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Documentation of decarbonisation scenarios for usage in the project

D2.1

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LOCALISED

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List of Abbreviations

GHG	Greenhouse Gas
FF55	Fit For 55 Package
MS	EU Member State
ICCT	International Council on Clean Transportation
LULUCF	Land Use, Land-Use Change and Forestry
CCS	Carbon Capture and Storage
ESR	Effort Sharing Regulation
ETS	Emission Trade System
RoW	Rest of the World
GTAP	Global Trade Analysis Project
ZEV	Zero Emissions Vehicles

Executive Summary

Deliverable 2.1 details how the EUCalculator model is used to reproduce the demand, energy supply and GHG emissions disclaimed in national decarbonization pathways. A total of three national decarbonization plans are reproduced for the countries of Portugal, France, and Germany as an example of what to expect as the process will be replicated for the remaining European Union member states. The process of reproducing the pathways is documented and the EUCalculator outputs on key indicators are compared to those available in the public-domain description of the national pathways. The resulting outputs of the EUCalculator model are made available internally and will be uptaken by WPs 3 to 8 for further work E.g., downscaling country results to administrative regions, providing preliminary data to assist tool design. The provided pathways constitute the first items of the library of model output to be constructed throughout the project. Finally, it should be noticed that the library of model outputs will evolve and the team does not discard that some pathways might be updated throughout the timeline of the project in case new technological, policy developments or interactions across WPs justify.

1 Introduction

The definition of a consistent set of country-level decarbonization pathways is needed for adequate downscaling and evaluation of local/regional mitigation/adaptation challenges in the European Union NUTS3 regions. While energy models provide researchers with ample room for experimentation and definition of multiple pathways, the challenge in LOCALISED is to guarantee that the set of decarbonization scenarios remains relevant throughout the project's 4-year time-frame and beyond. Accordingly, scenarios must both cover the most urgent climate policy needs, and incorporate elements of long-term structural changes in society and regional policies on fossil fuel use. The objectives of this deliverable are therefore two folds: The first is to establish a relevant set of MS-level decarbonization scenarios - from the point of view of current EU's policy trends - allowing the downstream work of downscaling (WP3); selection of relevant mitigation and adaptation measures (WP4); and the provision of activity, energy and emission indicators for WP's working at the intersection of data and knowledge provision to municipalities (WP5), society (WP6), and businesses (WP7). Secondly, to provide the quantification of such scenarios for 3 example countries, setting up the template for the model outputs, naming conventions, and data format for the full library of scenarios to be delivered as part of Del 2.2 (due in Jan 2023), in accordance with the project planning. It is important to highlight that since the initial drafting of the project proposal in 2019, the mitigation strategy of the EU has entered a state of flux. The political plea for even stronger mitigation commitments in the short-run[1], the imperative of a socially-fair and green post-covid recovery[2], and the consideration of EU energy security in response to recent geo-political crisis[3] need to be considered within Del 2.1. We integrate this need into a set of principles for scenario reproduction/generation[4], as well as for scenario evaluation. This will inform the future users of the project data about the rationale behind scenarios and provide a transparent evaluation of the main features and impacts entailed in each pathway.

The remainder of this Deliverable is structured as follows. In Section 2 the strategy to evaluate the scenarios, their consistency within the EU climate goals and their evaluation is detailed. Section 3 introduces the EUCalculator model, its main distinct features. In addition, this section explains how the scenarios will be generated and documented. Section 4 documents decarbonization scenarios for three countries (Portugal, Germany, and France) to provide concrete examples of how the generation and documentation of scenarios will work for other EU member states. Sections 5 and 6 close with brief considerations on access and storage of model outputs and conclusions. Given the current flux in energy systems and the foreseeable update of

[1] 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality.
[2] A fair transition towards climate neutrality.
[3] REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition.
[4] By reproduction we mean scenarios found elsewhere in the literature but reproduced by the energy modelling solution in the LOCALISED project. By generation we mean scenarios designed by the LOCALISED team.

national pathways in reaction to tighter climate regulation and contemporary geo-political concerns, the examples provided for the three countries are not to be seen as final but as the template for the detail and scope of the scenario documentation. In addition, the scenarios - and data provided - will provide WP's 3 to 8 with a good set of initial data upon which they can start developing the downscaling of model outputs and the integration of model results into these specific methodologies.

2 Decarbonization scenarios in LOCALISED

2.1 Ambition and consistency

For decarbonization scenarios to be relevant during the time frame of the project and beyond, their formulation needs to be nested in, and reply to, the most pressing mid-term challenge surrounding the decarbonization of the EU, that is, the *need for speed*. The most pressing and overarching mid-term climate target for the EU26 is embedded in the FF55 (14 July 2021) according to which a headline reduction of GHG [5]emission by 55% in the year 2030 (referenced to the year 1990) needs to be achieved[6]. Because of the tight carbon budget available, failing to achieve this intermediate climate target compromises almost irremediably the long-term vision of achieving territorial climate neutrality in the EU around 2045. Indeed, even under the most ambitious transport scenarios modelled by the ICCT, EU road transport alone would still emit nearly 4% of the remaining global carbon budget associated with a 67% chance of limiting warming to 1.5ºC, and the EU transport sector as a whole could emit more than the entire EU economy's share of the budget (Buysse, et al 2021). Overall the assessment of EU's progress in decarbonization is bleak and touted as *insufficient* to achieve the Paris agreement of stabilising global temperatures "well below 1.5 degrees" according to the climate action tracker[7]. But while the policies and actions currently in place are not enough to meet the EU's FF55 target, the block (that is the EU26 members) has been discussing a number of policy initiatives which, if adopted and implemented by Member States, could result in emissions reductions overachieving the 55% reduction target. For example, the renewable energy and energy efficiency targets tabled by the Commission in the May 2022 REPowerEU Plan, especially if ramped up during the subsequent legislative process by the European Parliament and the Council, create a viable opportunity for making the EU's domestic target Paris Agreement compatible. Beyond targets, there is something "bigger" at risk in failing to deliver the FF55 package. A huge amount of political capital has been committed by policy makers for Europe to become the world's first climate-neutral continent (Nakicenovic & Lund 2021). Failing to achieve the 2030 targets and hence the long term one as well, would forever undermine the global stance of the EU as a climate forerunner and weaken its moral bargaining power towards large emitters and emerging economies. Accordingly, for the purposes of this deliverable and the LOCALISED project, both existing or internally generated decarbonization pathways need to be aligned with the FF55 mid-term targets.

However, the main challenge is that under EU legislation there are no national targets for overall GHG reductions. For ETS, emission targets are set at the EU-level and not broken down nationally, but for ESR, and LULUCF national targets exist. In order to have consistent reduction targets allowing us to carry a speed test, LOCALISED adopts a disaggregation logic for GHG reduction targets that is used in the National GHG target

[5] REPowerEU
[6] Fit for 55
[7] EU country profile and progress in the Climate Action Tracker

calculator[8] from Oeko-Institut and Agora Energiewende (2021). As one can observe in Figure 1, achieving 55% reduction across the EU implies some countries to adopt higher efforts associated with their overall capacities, historical responsibility, and total weight in EU emissions[9]. This disaggregation allows us to consistently evaluate if the emission reductions in existing and newly generated pathways are aligned with the FF55 package and thus will be used in this deliverable.

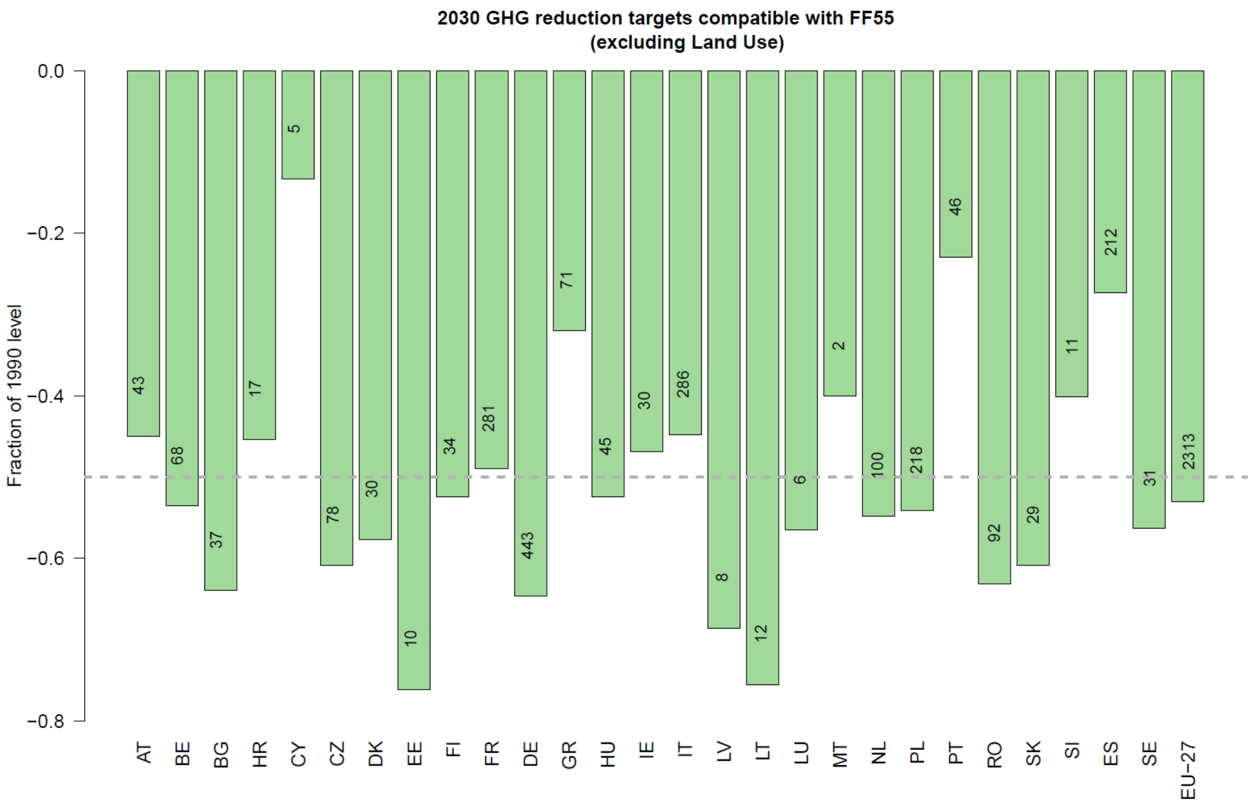

Figure 1 - GHG reduction by 2030 for EU26 Member states compatible with the FF55 package (data from footnote 5, Oeko-Institut and Agora Energiewende (2021), number in bars refer to absolute GHG reductions in Mt).

While multiple and equally fast decarbonization pathways are feasible within the realm of energy models - given the proper combination of assumptions - they will certainly have major consequences for social, ecological, and economic systems. The LOCALISED project does not discern on the *validity* of one decarbonization pathway against the other but it sees it as a core responsibility to warn the potential users of its outputs about the risks and opportunities entailed in each of the pathways provided. For this purpose, a scenario risk matrix is detailed and presented in the following section.

[8] National GHG target calculator (v0.1 - 06.07.2021)

[9] E.g., the ETS cap for the year 2030 is attributed to MS according to their share of the base value 2008-12, while the 39 % ESR reduction target compared to 2005 is distributed purely based on a GDP/capita distribution.

2.2 Pathway evaluation matrix

Decarbonizing the economy of the EU member states requires unprecedented levels of investment in the energy system, a cross-sectoral reach (in the sense that no sector can afford inaction), and the serious consideration of technologies with unproven feasibility and potentially low social acceptance. For example, insufficient knowledge about the physical-chemical properties of carbon dioxide strengthens a negative image of the CCS and raises public concerns and potential protest (Tcvetkov et al 2019). This, again, is not to say that the option for CCS is to be disregarded nor included, but rather to point out that a scenario including this option is more likely to generate social hesitancy when *push comes to shovel* than an alternative scenario in which such technologies are absent; and logically it follows that from the socio-political dimension alone such scenario could be harder to justify and operate on. In addition, one has to consider that the most recent push for decarbonization by the EU comes in the wake of reconfiguration of globalisation (Konomenko et al 2020) due to supply-chain disruption by the COVID19 pandemic that saw global trade fall between 10 and 16% according to the European Commission[10]. Recent geo-political crises have forced the EU to embark on a deep reconfiguration of its energy imports (mainly fossil) from outside the EU. Both geo-political fears and disruption in supply chains affect decarbonization efforts. Therefore, the impact of such technological risks and external geo-political shocks influence decarbonization efforts. For example, a gain in 1% on energy efficiency would decrease the EU's reliance on foreign gas by 2.6%[11], which is positive. On the other hand, the temptation of the EU reshoring some of its global supply chains in the aftermath of COVID to dampen the risk of future disruptions is counter-productive (both territoriality and globally) in sectors such as agriculture (Meijaard et al 2021). Accordingly, for each pathway the evaluation in Table 1 will be conducted.

Table 1: Pathway evaluation matrix

Scenario	**% difference to 55% reductions in 2030.**	**Requires the deployment of unproven/ low-social acceptance technologies.**	**Land vs energy vs. resource tradeoffs or synergies?**	**Net-zero ahead of 2050 (years)**	**Less material/ product imports to the country?**
A	-3%	Yes	Yes	5	Yes
B	+5%	No	No	3	No change
Logic	**Negative values preferable**	**"No" preferable to "Yes"**	**"Synergies" preferable to "Tradeoff"**	**Higher values preferable**	**No clear preference**

[10] The impact of the Covid-19 pandemic on global and EU trade (DG Trade).
[11] https://tinyurl.com/2p892hxu

3 Energy model & scenario documentation

3.1 The EUCalculator model

The EUCalculator is an energy-economy-climate model with a projection time frame covering the years 2015–2050. It is composed of 15 inter-dependent modules representing the supply and demand sides of activities, materials, energy and emissions; as well as different interfaces of the energy system with society and the environment. At its core, there are modules representing the energy-relevant sectors of agriculture, buildings, power/storage, transport and manufacturing (see Figure 2).

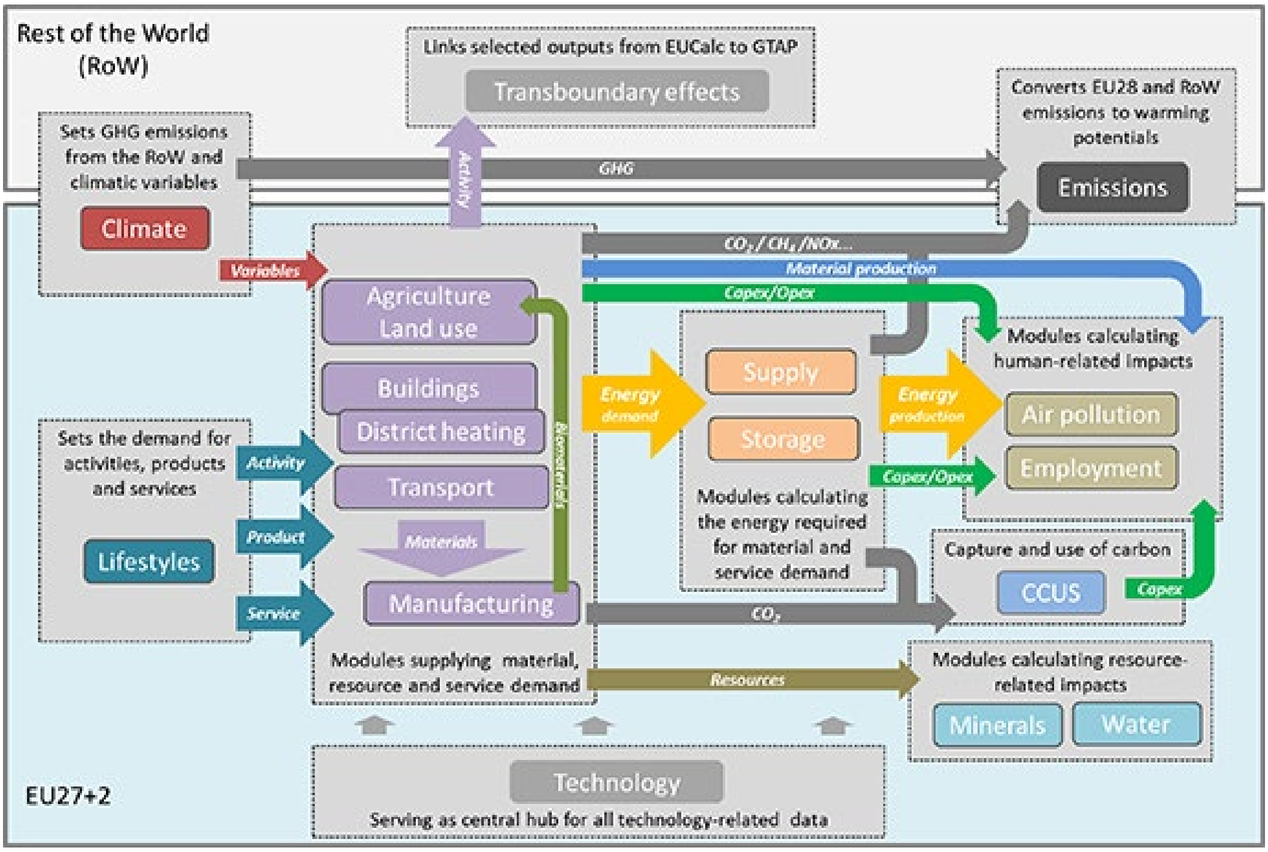

Figure 2 - Main flows of energy, materials and emissions and sectoral connections in the EUCalc model. Source: Costa et al 2020

The model is multi-country and cover, in the same level of detail, the current EU member states plus UK and Switzerland (EU27+2). The model inputs - in the form of a comprehensive ambition levers (see next section) - set the amount of EU27+2 activities, services and resource needs that ultimately influence the demand for final energy in sectors such as transport, industry, power and buildings. The energy system accounts for exhaustible energy resources and renewable energy potentials. Land-use, agricultural emissions, bioenergy and other land-based mitigation options are modelled explicitly in the EUCalculator. Social impacts such as employment and air pollution are also integrated in the model. Domestic supply of products, materials and food in the EU27+2 from the Rest of the World (RoW) is accounted for but not their associated embodied emissions. Total country-level emissions resulting from energy and material supply, are summed into annual EU27+2 totals for each of CO_2, CH_4, N_2O and SO_2. To find the global temperature response, the EUCalculator sums the emissions from the EU27+2 to pre-defined trajectories of emissions from the RoW.

Table 2 - Main impacts accessed in the EUCalculator model and spatial aggregations

	Impact	**Aggregation**
Energy	Total energy consumption Energy consumption by energy vector and sector	EU27+2 / country-level
Emissions	Total and sectoral GHG emissions	
Resource use	Crop and livestock production Land-allocation Forestry production Water consumption and withdrawal Mineral demand	
Pollution	Fine particulate matter	
Materials	Mineral demand	
Society	Mortality from PM25 Employment and skill	
Investments	CAPEX and OPEX	EU27+2
Water	Water stress	Sub-region
Climate	Temperature	Global

The EUCalculator model computes different types of impacts: the energy consumption and GHG emissions at a country level, resource depletion (water, fossil fuel, lands) and other environmental impacts such as biodiversity, and socioeconomic impacts such as employment and air pollution (see Table 1). For more details about the scope of those impacts' calculation and about the methodology, please refer to the related EU Calculator module documentation.

These modules respond to the demand for products, activities and services originated in the lifestyle module and, where relevant (e.g. agriculture and buildings), are impacted by changes in climate modelled by the climate module. The energy system interacts with the environment via modules simulating the supply and demand for water and minerals. The implications of air pollution and employment are also accounted for. Emissions captured in manufacturing processes or energy production are treated in the CCUS module. Finally, impacts on the trade of products, materials and food, as well as the carbon embodied in trade outside EU27+2 are modelled with a modified version of the GTAP (Global Trade Analysis Project) model in the Transboundary effects module.

The outputs of the EUCalculator model (see complete list following this link) are controlled by a wide and comprehensive range of levers representing changes one could make to mitigate climate change by 2050 (see complete list in Table A1 of the Annex section). A lever in the EUCalculator model represents an input to the model, a predefined trajectory of a quantity, e.g., distance travelled per person; insulation level for refurbished houses; efficiency and type of steel production; offshore wind capacity. In turn, these inputs to the model will drive energy demand and supply projections, and ultimately GHG emissions. Each lever has four different levels of effort that have been consistently defined across sectors. As a rule, when looked at in isolation, the higher the ambition levels of a lever, the higher its abatement potential. In detail, ambition Level 1 (see figure below) is a technical measure, key behaviour or management practice that would yield the lower abatement potential. In the EUCalculator model, this level is associated with the respective historical trends of technology deployment or consumption behaviour. Thus, this level of mitigation efforts will not go substantially above those associated with current policies and could even worsen GHG emissions. As illustration, consider the parameter "renovation rate of buildings" as part of the ambition lever "Building envelope" (see Table A1 in Annex action for the complete set of levers considered in the model). In the EUCalculator, ambition Level 1 for the yearly renovation rate is set at 1% as this better reflects the contemporary renovation rate for the full building stock across member states (Hermelink et al, 2019). On the other side of the spectrum, Level 4 is equated with the adoption of a transformation renovation rate of 3%, as this is the ambition required to renovate the majority of the buildings between today and 2050 (European Commission 2018). The ambition levels 2 and 3 are set as intermediate levels between historical trends and system transformation. Level 2 goes beyond historical trends but without reaching the full potential of available solutions, while Level 3 reflects the adoption of best practices/evolution found at regional levels. Regarding the latter in the EUCalculator Level 3 would equate to a yearly renovation rate of 2%, close to that observed in Austria (Anne Esser et al, 2019).

Level 1	*Level 2*	*Level 3*	*Level 4*
Projections of **historical trends.**	**Intermediate scenario**, more ambitious than a projection of historical trends but not reaching the full potential of available solutions.	**Very ambitious but realistic** scenario, given the current technology evolutions and the best practices observed in some geographical areas.	**Transformational requiring additional breakthroughs** or efforts such as cost reduction for key technologies, very fast deployment of infrastructures, technological advances, strong societal change, etc...

In the EUCalculator model all sectoral modulus are tightly integrated and none operates without inputs from another. In addition, it is not possible to set changes in two technologies or behaviours simultaneously. Once one technology level is set the model runs completely before the next change in technology (or consumer behaviour) can be changed. These characteristics minimise the potential overlapping emissions abatement/energy saving from measures introduced in the model across sectors. If for example heating habits are changed in the lifestyles module, then less energy for heating will be required for the building sector and this will be reflected on the abatement potentials of measures such as home retrofitting or shifting to renewables for space heating.

It is relevant to note that the process of defining the levels of ambition for any given lever consisted of three distinct steps i) a literature review which produced a "pre-read" brief followed by ii) a deliberative consultation with sectoral experts - governmental, private sector, civil society organisations and academia - across nine co-creation workshops designed to answer specific questions and specifically to test the acceptance across a broad range of stakeholders for suggested ambition values (Ranković and Kelly 2019). These workshops included stakeholders selected using proxies such as organisation type, geography, school of thought category and other relevant indicators intended to capture an array of expert judgements and perspectives for a given sector, to the level of levers. In several instances assumptions presented during co-design processes were adjusted in subsequent dialogues. Finally, iii) the entire data set, for each ambition level, for each lever in each sector was subjected to a review across all stakeholder groups through a scientific call for evidence followed by a general call for evidence process.

3.2 Exploring a wider option-space for decarbonisation

National decarbonisation pathways are determined at the country level and reflect national-specific preferences in energy technological composition, industrial strategies and societal evolution. Although the outcomes of national policies are framed by a set of common EU targets, the pathways to achieve them are heterogenous. In this sense, the national pathways are as much an exercise of common ambition as of countries asserting their socio-economic priorities.

It is not a given that a model running on top-down standard economic assumptions of cost-effectiveness of technologies or carbon pricing is able to consistently capture the planning heterogeneity emerging from these country-level exercises. Although the EUCalculator model assesses the cost implications of a decarbonisation scenario it does not use a cost optimisation approach to identify the least costly way of potential 2050 targets. Instead, its aim is to look at what is technically and physically achievable in each sector (see how ambition levers are defined in Section 3.1) over the next 30 years under different assumptions. This feature lends to the model a large latitude to explore different alternative pathways and technologies, including those that might not even be cost-effective but that countries resolve to pursue due to strategic or social preferences that are not always captured by economics, for example maintaining some coal industry at a loss due to its social relevance. Additionally, societal changes towards more sustainable ways of consumption are now increasingly gaining the interest of decision makers and being considered in national pathways as complement to technological change. In the EUCalculator model shifts in consumer preferences are a core feature and are integrated at the same level of importance in the model hierarchy as technological change without being bound by the usual constraints of optimisation models.

As the carbon budget decreases and time runs out, modelling the energy system is expected to become less of a cost-effectiveness exercise and more of an exploration of desirable futures rooted in moral, identity, and generational grounds - particularly at the level of a country. This means exploring what are sometimes economicallyunfeasible but socio-politically-desirable futures. In the EUCalc model such flexibility is embodied in independent 2020–2050 trajectories of behaviours (e.g. time spent using a computer or dietary choices) and technologies (e.g. the fuel mix in passenger transport or the intensification of agricultural production) that are relevant for the energy system and in turn, impact land, water, and other resources.

3.3 Pathway generation and documentation

National pathways

As mentioned beforehand both existing and internally-generated pathways to net-zero will be investigated in the context of this deliverable. In the case that the pathway originates from existing literature it will be reproduced via the EUCalculator model. In practical terms this implies selecting the ambition level in the EUCalculator model that best represents key assumptions/results of the scenario to be reproduced. In short, the procedure to compare the outcomes of the EUCalculator model involves the following steps:

1. Reading of the scenario documentation and extraction of the main assumptions on the evolution of activities and technology/policy deployment (not the final emission nor energy results). In case no specific assumption can be linked to a lever in the EUCalculator (see Table A1) the default value assumed is the one that matches as far as possible the baseline scenario published by the European Commission (European Commission 2018).
2. Selection of the lever level that would better represent the choice made in step 1 and documentation of the rationale.
3. Comparison of key energy indicators and GHG emissions in 2050 at sectoral level and explanation of the observed mismatches.

For example, say that in a given national pathway by 2045 the electrification of the passenger car fleet is 60%, that energy efficiency of the passenger car fleet increases by 30% and that travel demand drops to 1100 Million km per year (step 1). Then, step 2 will consist in choosing the technology trajectory and demand trajectories in the EUCalculator that more closely reproduces the boundary conditions published in the national pathway. In step 3 it is then evaluated what energy and emissions values are returned by the EUCalculator for the transport sector and the results compared to the national pathway. The alignment of the assumptions from national pathways in the model and the associated results will always contain a certain degree of disagreement. This is unavoidable and differences will be minimised as far as consistency and the impositions of the national pathways' documentation impose. In this regard it is important to underline that the original scenario documentation and model employed might not match one-to-one with the granularity of assumptions and levers available in the EUCalculator model. The differences can go both ways, that is, sometimes a particular module of the EUCalculator model is more detailed, other times the model that originated the pathway can be more detailed. In such cases the team is forced to make "best guesses" – taking into account the overall narrative of the scenario being reproduced – or derive relevant metrics indirectly using related proxies provided in the scenario documentation. Despite the significant flexibility of the EUCalculator in exogenously setting demand and technological evolution (see section 3.1), it cannot be assumed a-priori that any national pathway can be reproduced in an acceptable way. In case essential features of a pathway are not reproduced because the ambition levels in the EUCalculator falls short from that in the national strategy, the model will run using the most ambitious level available. In the final documentation it will be noted the respective assumption where alignment between the EUCalculator and the national pathway was not possible. This implies the level of ambition in the national pathway for a particular technology or behaviour is higher than the expert-level considerations on feasibility made in the EUCalculator.

Behaviour-change pathways

Recent bodies of literature point that behavioural change on key energy and emission drivers make it easier to achieve rapid mitigation while improving social outcomes, and should be explored by climate modellers (Hickel et al 2021). This is in contrast to the technologic-centred approach to mitigation in decarbonization pathways (Luderer et al, 2013). The generation of behaviour-change alternative pathways in LOCALISED for countries will be based on previous published pathways in Costa et al (2020). The behaviour-change pathways essentially mean smarter choices and lower demand 15 energy-relevant levers including activities, goods and services (e.g. living space, distance travelled, diet and food waste). These levers are marked in green in Table A1 (Annex section) and in the behaviour-change pathways are moved to maximum level of ambition in the EUCalculator. Broadly, maximum level of ambition in behaviour equates to a reduction in 50% of the time spent travelling to work/study through the full exploitation of remote-work/study and a decrease of 40% in travel for access to services due to progress in digitalisation is foreseen. In terms of diets it is assumed the widespread adoption of a flexitarian diet as proposed in Sringmann et al, (2018). This means that meat consumption is kept at 38g per day with 13g per day of red meat. Sugar and sweeteners are kept at below 5% of calorie intake; and fruits and vegetables consumption to be over 600g/day. Furthermore, there is a 22% decrease overall in the demand for freight transport, meaning a shift towards less consumed goods and travel distances, see Costa et al (2020) for further details on the quantification and scientific literature supporting the assumptions. In the behaviour-change pathways the technological assumptions (marked white in Table A1) are left to the level that best represents the assumptions of the national pathway. Finally, levers marked in red in Table A1 (which refer to trade relation between countries, demographics, and urbanisation) are kept constant at baseline population projection in Eurostat (2018) (for the case of demographics) and the net-import/demand ratio generated with the GTAP model reflecting a business as usual scenario projection in 2050 (for the case of trade relations).

4 Considered pathways

For producing country specific decarbonisation pathways, we gather the most recent, or nationally adopted, decarbonization scenarios available in the literature. If the decarbonization plan is aligned, or goes beyond the existing decarbonization pathway for the country, we proceed with its reproduction using the EUCalculator. For the purposes of this deliverable we exemplify how the scenario reproduction is documented and how the results are evaluated for three EU countries, namely: Portugal, France and Germany.

4.1 Portugal

Key scenario indicators on activity and energy

The most ambitious scenario from the Portuguese Roadmap for Carbon Neutrality[12] is presented in Table 2 (hereafter RNC2050), see Barata et al, 2019 and RNC 2019 for scenario details. This scenario was adopted.

Table 3- Key sectoral indicators on activities and emissions in the RNC 2050 pathway, and those used by the EUCalculator

Scope	RNC2050 pathway	Key levers/ambition	EUCalc pathway
General			
Population change	-1.3%	Population - 1.1	-1.2%
Population living in cities	81.2%	Urban population - 1.7	81.1%
Transport			
Total passenger transport	"1.7% GDP growth throughout 2045-2050" "... more medium range transport" but "lower short-range distances" "increases in remote working…"	Passenger distance - 2	No direct quantification from the pathway. Best guess based on economic growth and assumed reduction of travelling due to remote work and services by 10%.
Active transport	14%	Mode of transport - 1.8	14.5%
Share of ZEV sales (passenger)	100%	Passenger technology - 4	100%
Share of ZEV sales (freight)	100%	Freight technology - 4	100%
Total passenger mobility via carsharing and autonomous vehicles	33%	Car own or hire - 2.5	No direct quantification. Best guess based on the substantial share of total mobility
Vehicle occupancy	Not disclosed quantitatively but as a *"significant increase of public transportation rate"*	Occupancy - 2.5 (Increase of 30% in car occupancy)	Guarantees consistency with the choice for lever "Car own or hire" in which occupancy increases due to more availability of carsharing services.

[12] RNC 2050 documentation

Electricity share in transport energy	69%	Not set exogenously but responding to demand and technology	62%
Hydrogen share in transport energy	24%	Not set exogenously but responding to demand and technology	23%
Industry			
Material substitution	Glass replaces plastic in packaging; Increases in steel industries, replacement of cement by new construction materials, lower paper production	Material switch - 3 Material efficiency - 3.5	Material switches range from 7% (substitution of conventional wall insulation with cellulose) up to 40% (substitution of concrete with timber in buildings). In transport lightweight aluminium replaces steel and other components, in buildings natural fibres replace fossil-based chemicals, timber substitutes cement. Efficiency improvements range between 10 and 33% due to smart product and material design. Re-use of materials and circularity concepts of additive manufacturing.
Energy mix	Oil consumption residual, circa 12% of final energy consumption by Natural gas.	Fuel mix - 4	Full potential of electrification of heat, substantial switch to sustainable biomass in all manufacturing and production sectors, Very small shares of fossil-fuels in the energy mix.
Energy efficiency increases	25%	Energy efficiency - 4	Range between 10% (wood products) up to 35% (food, beverages and tobacco). In energy-intensive sectors the range is between 13% and 24%.
CCS	Not enough scale to be economically feasible.	Carbon Capture in manufacturing - 1	No commercially viable carbon capture technology option in place by 2050. Major research and development efforts are still required, as well as high investments.
Energy mix	Electricity - 55.5% Gas - 12.6% Biomass - 9.7%	Not set exogenously but responding to demand and technology	Energy mix of steel, glass, chemicals and cement industries: Electricity - 47.4% Gas - 13.6% Biomass - 26.7%
Buildings			
Fuel mix	Solar represents 12% of consumption and biomass 26%, strong phaseout of fossil fuels	Technology and fuel share - 4	Fossil fuel use reduction in 2050: gas -95%; coal -95%; oil -95%. These fuels are substituted by heat pumps (60%), biomass (20%), solar (12%), geothermal (4%), biogas (2%), biofuel (2%)
Thermal isolation in existing buildings	50% increase	Building envelope - 1.5	50% of the renovations are shallow (-30% energy demand), 38% are medium (-40%) and 18% are deep (-60%). 20% of new constructions have the lowest level of efficiency, 60% are medium efficient and 20% highly efficient.
Renewable energy in	66%	Not set exogenously but	73.4%

heating and cooling		responding to demand, technology and electricity mix	
Electricity (GW)			
Solar	26	Solar - 2.5	22.1
Wind (onshore)	12	Wind - 1.7	12.3
Wind (offshore)	0.2		0.03
Gas	0.2	Not set as ambition in the model but rather responds to the capacities of renewable energy and coal.	1.6
Hydro	8.5	Hydro and geo - 1	9.4
Geo	0		
Biomass/residues	1.8	Responds to the demand and fuel mix of sectors.	2.5
Coal	0	Coal - 4	0
Agriculture and forest			
Waste in agriculture	Reduced by 50%	Climate smart crop production - 3 Climate smart livestock - 3	In 2050 sustainable intensification crop production system is fully deployed. Food waste and losses are limited to about half the 2015 level. Decrease of inputs such as synthetic fertilisers and pesticides. Livestock yields are slightly higher by 2050 compared to 2015, due to an increase of the livestock slaughter age. As with crop production, food losses and waste are halved compared to 2015.
Reduction of synthetic-based fertilisers	57%		
Diets	Shift to more plant-based diet	Diet - 2	Consumption of meat, sugars and sweeteners decreases and fruits and vegetables increase towards WHO standards (but without fully reaching them). Significant departure from current diets.
Forestry	Sustainable management of forest with a view to increase the overall carbon pool. Fire risk reduction in 60%	Forestry practices - 2	Climate smart forestry practices are deployed in public forests by 2050 (approximately 40% of European forests), leading to increased biomass production and carbon pool potential. Fire dynamic not included in the EUCalculator. Hence this feature of the RNC 2050 cannot be mirrored

General indicators of population and percentage of urbanization are matched quite well to the ambition levers in the EUCalculator (see Table 2). In RNC 2050, population in

Portugal is assumed to decline by -1.3% while urbanization (measured in the % of population living in cities) will reach 81.2%.

For transport, no specific quantification was found for the number of km driven per person in the time frame of the RNC 2050 but it was explicitly noted in the economic scenario formulation (see Barata 2019) that a strong economic growth is observed until 2030 (1.8%/annum, and 1.7% in 2050), which increases travel demand (Schafer 2009) and that due changes in urbanization (with more concentration of population) short range distances decline while long range ones increase. There is also a focus in promoting remote work, which should decrease travel demand. All summed up, the evolution of transport demand is assumed to grow significantly in the time frame 2020-2035, slowing thereafter until 2050 (see Figure A1 panel B, in Annex). By 2050, RNC 2050 reports the amount of active travel, that is, transport done by foot or bicycle, to be 14% of total passenger transport. The latter is matched rather well with the EUCalculator at 14.5% by choosing ambition level 1.8 for the lever mode of transport (see Figure A1 panel A, in Annex). The pace of electrification in the RNC 2050 is very fast and by 2050 it has the "potential to 100% of transport demand". In the EUCalculator we cannot set the final share of energy consumption by fuel in the transport sector but we can set the target sales of electric and other Zero Emission Vehicles ZEV by adjusting the levers of passenger and freight technologies (see Table X). In both cases we set the sales of ZEV's to be 100% in the year 2050. Automation and sharing economy are said in the RNC 2050 to cover about 33% of passenger mobility, we align this with the EUCalculator by allowing the number of passenger kms done in hired cars by about 30% (in opposition to private transportation), see lever car own or hire in Table X. For coherency, the levels of vehicle occupancy are also raised by similar amounts.

Traditional industries in the RNC 2050 are said to undergo a decline, being substituted by more knowledge-based ones as the Portuguese economy becomes more integrated. As a result, production of paper (a stronghold of the Portuguese economy) declines. In the EUCalculator we adjust material imports so that the Portuguese industry loses competitiveness and as a result, paper production declines between 2020 and 2050 by about 11% (see figure A2). Energy efficiency is set to increase overall by about 25%, which is aligned with the most ambitious energy efficiency evolutions in the EUCalculator (see lever energy efficiency in Table 2). Specifically, the lever assumes an increased energy efficiency of 10% (wood products) up to 35% (food, beverages and tobacco). In energy-intensive sectors the range of improvements is between 13% and 24%. There is no large-scale deployment of Carbon Capture and Storage (CCS) given the relatively small overall dimension of the Portuguese industry and economy. Accordingly, the lever CCS of the EUCalculator is set to 1, that is no commercially viable carbon capture technology option will be in place by 2050. Finally, we align the fuel mix in manufacturing to level 4, (see Table 2) as this level assumes the full electrification of heat, the use of zero-carbon hydrogen, and the switch to sustainable biomass in manufacturing and production sectors, leaving very small shares of fossil-fuels in the energy mix. Comparing the energy mix of industry in Table 2, one observes that the level of electrification in the EUCalculator is somehow below the RNC 2050 (47.4% vs 55.5%), while the level of biomass use is higher (26.7% vs 9.7%). This is a feature of the model that prioritizes the use of sustainable biomass to that of electricity. This carries no consequences for emissions as sustainable biomass is managed in order to be climate neutral but it does carry consequences for ecosystems. On the other hand, the share of gas obtained for the energy intensive industries is well aligned with both the RNC 2050 and the EUCalc reproduction (13.6% vs 12.6%).

The documentation of the building sector in the RNC 2050 is not very detailed. In terms of fuel mix the document is clear in stating that solar represents 12% of consumption and biomass 26%, indicating a strong phaseout of fossil fuels. In the EUCalculator we align this with level 4 in the lever technology and fuel share. Under this lever there is a strong phaseout of fossil fuels in the building sector by 95% (for coal the decarbonization is even larger because of the complete decarbonization of the electricity grid (see table 2 section electricity). According to the same lever, solar achieves a penetration rate of 12% (very close to the RNC 2050 level) while biomass 20% (slightly lower than in the RNC 2050, 26%). Thermal isolation is said to lead to energy saving gains of about 50%. In the EUCalculator the lever building envelope controls both the pace (how many existing buildings are renewed) and depth (energy standards of renewed/new buildings) of retrofitting. This lever is set at level 1.5 with 38% of the renovations achieving 40% better energy efficiency and 18% achieving 60%. As a result of the strong focus on renewables in the RNC 2050, clean energy share in heating and cooling of buildings reaches 66%. In the EUCalculator reproduction this same indicator is returned at 73.4%, a bit higher but not far off.

Electricity generation in the RNC 2050 archives deep carbonization in 2050 with large capacities of solar, wind and hydro power. The EUCalculator matches rather well to the installed capacities of wind and goes only 0.9 GW higher for hydropower. For solar the EUCalculator delivers an installed capacity of 22.1GW while in the RNC 2060 it is around 26 GW. Although gas capacities decrease considerably in the EUCalculator (above 85% in 2050 compared to 2020, see Figure A3), the model cannot lower its capacity of 0.2 GW in the RNC 2050. The production of gas in the EUCalculator is not controlled by a lever but is a response to the capacity of renewable energy installed.

Finally, in regard to agriculture and forest, the RNC 2050 suggests that waste in farm operation is reduced by 50% and the evolution of the agricultural system towards precision agriculture. We align this with smart crop and livestock production levers in the EUCalculator under the level of sustainable intensification. Diets move towards less meat intensive and towards more fruits and vegetables (see Table 2). Forests are managed in the view of increasing the overall carbon pool of the ecosystem and fire reduction, a common feature of Mediterranean ecosystems, is targeted for a 60% reduction. It must be said that this last feature of the RNC 2050 cannot be mirrored in the EUCalculator because fire dynamics are not included in the model.

Evaluation of sectoral emissions

Despite some minor mismatches in some sectors (see buildings), in the aggregation the level of 2050 GHG emissions, measured in CO2eq, returned by the EUCalculator matches well that of the RNC 2050, differing only by ~3.6% (see Table 3). In terms of negative emissions from land use and forestry, the EUCalculator representation of the RNC 2050 returns a total sequestration of -11.07 MtCO2eq, this is well within the RNC 2050 proposed range of -9 to -13 MtCO2eq.

Table 4 - Comparison of GHG in the RNC 2050 and its reproduction using the EUCalculator

Sectoral emission (MT CO2eq)	RNC2050 pathway	EUCalculator pathway
Energy	0.7	0.58
Industry	5.5	5.10
Buildings	1.5	1.70
Transport	0.2	0.28
Agriculture	3.5	3.90
Waste/others	1.4	0.78
Total	***12.8***	***12.34***
Land use	-9 to -13	-11.11

Given the proximity of the values in terms of emissions, and the overall agreement between energy mixes and assumptions (see Table 2), the representation of the RNC 2050 by the EUCalculator is deemed satisfactory.

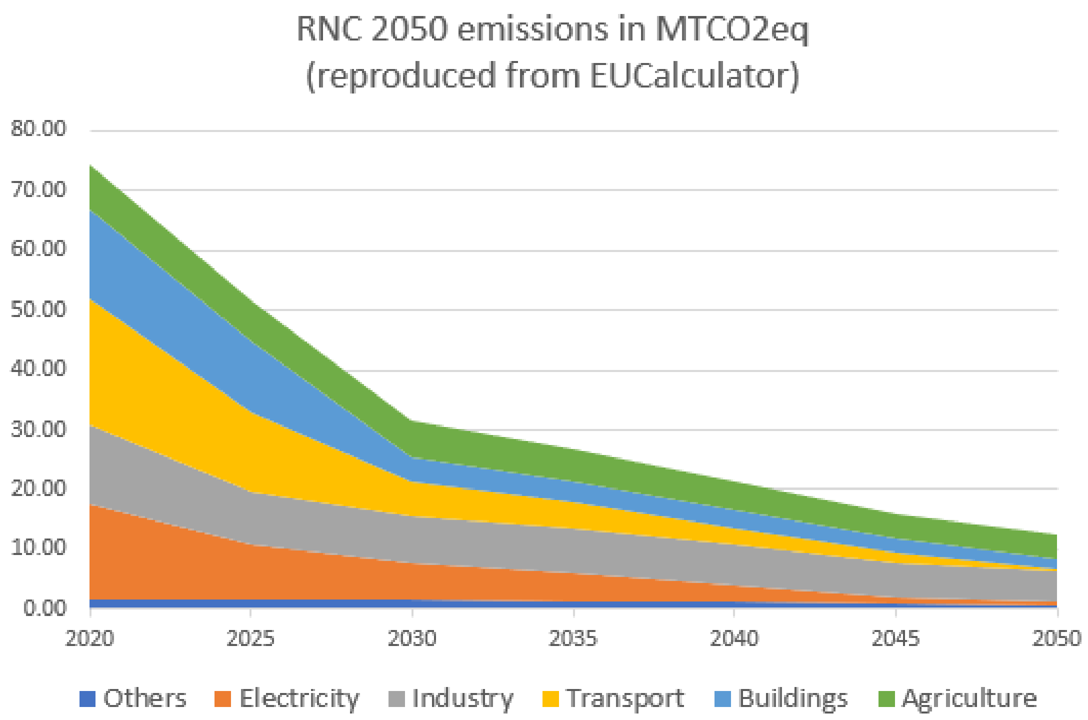

Figure 3 - Time development of GHG emission reproduced to match the RNC 2050

Taking advantage of the EUCalculator in inducing substantial behavioural shift towards less consumption and material demand, a variation of the RNC 2050 scenario is simulated. In this variation, named *RNC 2050 BC* (Behavioural Change) and its consumption assumptions largely taken from those in Costa et al, 2021. The original RNC 2050 assumption of technological and energy deployments remain unchanged from those in Table 2 but consumption attitudes change dramatically in relation to the demand for transport, material consumption and diets (see section Behaviour-change pathways). The extra speed of decarbonization brought about significant changes in behavioural change makes the RNC 2050 BC more compatible with the FF55 targets of 55% reduction by 2030 than the original scenario. Under RNC 2050 BC a relative decrease of 57.3% is achieved by 2030. The stronger decrease of emission over the short term and the slight increase of negative emissions in the RNC 2050 BC scenario (11.31 vs 11.11 MTCO2eq in the RNC 2050) improve in about 3 years the point in time when carbon neutrality is achieved (see Table 4).

Table 5 - Evaluation matrix of the RNC 2050 and RNC 2050 BC pathways

Pathway	**Difference to 55% reductions in 2030.**	**Requires the deployment of unproven/ low-social acceptance technologies.**	**Land vs energy vs resource tradeoffs or synergies?**	**Net-zero ahead of 2050 (in years)**	**Less material/product import to the country**
RNC 2050	+3.4%	No	No explicit tradeoffs	~0	Yes
RNC 2050 BC	-2.3%	No	Stronger synergies between land freed land and carbon uptake	~3	Yes
Logic	**Negative values preferable**	**"No" preferable to "Yes"**	**"Synergies" preferable to "Tradeoff"**	**Higher values preferable**	**No clear preference**

4.2 France

Key scenario indicators on activity and energy

The National Low Carbon Strategy (Stratégie Nationale Bas-Carbone[13]), SNBC2050 hereafter and associated documentation, describes a road map for France on how to steer its climate change mitigation policy. It provides guidelines to enable the transition to a low carbon economy in all sectors of activity. It sets out objectives for reducing

[13] Stratégie Nationale Bas-Carbone (English version)

greenhouse gas emissions in France in the short/medium in order to achieve carbon neutrality by 2050[14].

Table 6 - Key sectoral indicators on activities and emissions in the SNBC2050 pathway, and those used by the EUCalculator

Scope	SNBC2050 pathway	Key levers/ambition	EUCalc pathway
Transport			
Passenger transport	"passenger-km for all modes together will rise by 26% between 2015 and 2050" "private car traffic which will decrease by around 2% between 2015 and 2050"	Passenger distance - 1.4 Mode of transport - 2.7	Total pkm increase from 1160 to 1550 Billion (~ 25.2%). Reduction of car transport of ~3.1%
Freight transport	"tonnes-km will grow by 40%" "loading rates of heavy goods vehicles will increase"	Freight distance - 1.3 Freight utilisation rate - 4	Increase of ~41% Trucks have a 15% higher load in 2050 with respect to 2015 and trucks will run 10% more km per year than in 2015.
Modal share of cycling	"multiplied by 4 after 2030"	Mode of transport - 2.7	Multiplied by ~2 after 2050
Sales for cars	"100% of sales for new cars will be electric after 2040" "In 2030, the scenario attains a 35% share for private electric cars and a 10% share for private rechargeable hybrid cars in sales of new vehicles"	Passenger technology - 4	100% ZEV in new car sales by 2050 and 35% by 2030.
Efficiency for thermal vehicles	"4L/100km in real consumption for new vehicles sold in 2030" *4L/100km = 1.368Mj/km*	Passenger efficiency - 4 Freight efficiency - 3	By 2035 passenger vehicle efficiency is of 1.382 Mj/km
Freight transport	"A more balanced mix (renewable gas, electricity, biofuels)"	Fuel mix - 2.5	Biofuels reach 50.4% of total road fuel.
Heavy goods vehicles	"improvements in efficiency of 35-40% " by 2050	Freight efficiency - 4	By 2050, trucks' energy consumption (MJ/tkm) decreases by 41.5%.
aviation	50% biofuel by 2050	Fuel mix - 3.5	Biofuels reach 52.5% of total aviation fuel.
Final energy consumption for domestic transport	Total: ~200TWh Electricity: ~100TWh Biofuel: ~50TWh	Not set exogenously but responding to demand, technology and electricity mix	Total: 193 TWh Electricity: 109 TWh Biofuel: 34 TWh
Industry/Waste			
Efficiency	"In 2030, the scenario assumes gains of between	Energy efficiency - 3.5	The estimated range of increased energy efficiency is

[14] SNBC2050 summary and highlights

	10% and 30%. In 2050, the gains will rise by between 20% and 40%."		between 10% (wood products) up to 35% (food, beverages and tobacco). In energy-intensive sectors the range is between 13% and 24%.
Electrification	"rate will rise slightly between 2015 and 2030 (from 38% to 41%) then more rapidly until 2050 to reach over 70% of final consumption at this point."	Fuel mix - 4	Full potential of electrification of heat, use of zero-carbon hydrogen and a switch to sustainable biomass are expected to take place in all manufacturing and production sectors, leaving very small shares of fossil-fuels in the energy mix.
Recycling	"Incorporation rates of recycled raw materials that increase drastically to around 80% in 2050, particularly for steel, aluminium, paper, plastics and glass, thus making production processes more efficient."	Technology efficiency - 4	For seat scrap-EAF technology will reach a share of 70% on average in Europe. Paper production from recycled fibres could reach a maximum of 90% Secondary aluminium reaches a maximum of 55%. Recycled paper reached 90% and glass 100%.
Material	"using more materials with low carbon impacts (low carbon cement, bio-based chemicals, carbon-free hydrogen, etc.). A more systematic use of wood as a material should also reduce reliance on materials with a higher carbon footprint"	Material shift - 4 Material efficiency - 4	Material switches range from 10% (substitution of conventional wall insulation with cellulose) up to 60% (substitution of concrete with timber in buildings). In transport lightweight aluminium replaces steels and other components: 50% substitution of steel by aluminium in cars and 45% in trucks. Improvement in material efficiency ranges between 10 and 33% in 2050 due to smart product and material design, re-use of materials and circularity concepts of additive manufacturing. This results in 31% reduction in CO2 intensity.
Buildings			
Behaviour	"proper individual behaviour (heating temperature reduced by an average of 1°C by 2050)."	Space cooling and heating - 2	indoor temperatures are set at 1°C degree more/less than the observed comfort temperature
Renovation	700000 equivalent complete renovations on average over the 2030-2050 period in the residential sector. The tertiary sector will also undergo a similar rate of renovation.	Building envelope - 3	Renovation rates of residential and non-residential buildings reach 2%. (700000 equivalent complete renovations in a universe of 35 million dwellings in 2015 results in ~2% renovation rate.)

Efficiency	"100% BBC (Bâtiments Basse Consommation/ Low Consumption Buildings) on average in 2050"	Building envelope - 3 (both residential and non-residential buildings)	Only 10% of the renovations are shallow (-30% energy demand), while the remaining 90% and medium/deep resulting in energy cuts of -40 to -60%
Energy Mix	"totally carbon free by 2050" "electrifying all uses apart from heating and a more varied energy mix for this latter use, with particularly significant recourse to heat pumps and urban heat networks."	Technology and fuel share - 4	Fossil fuel use reduction in 2050: gas -95%; coal -95%; oil -95%. These fuels are substituted by heat pumps (60%), biomass (20%) , solar (12%), geothermal (4%), biogas (2%), biofuel (2%).
Forest/Land sector			
Forestry practices	"Intelligent and sustainable forest management will allow us to preserve the carbon pump effect while improving its resilience to climate risks and better conserving biodiversity."	Forestry practices - 2	Climate smart forestry practices are deployed in public forests by 2050 (approximately 40% of European forests), leading to increased biomass production and carbon pool potential.
Forest area	"The forest area will increase through afforestation."	Not set exogenously but as result of material demand/forest practice levers	25.6% increase in forest area between 2015 and 2050.
Forest harvest	"from 48 Mm^3 in 2015 to 65 Mm^3 in 2030 and 83 Mm^3 in 2050"	Not set exogenously but as result of material demand/forest practice levers	
Agriculture			
Diets	"domestic demand will be modified (in line with nutritional indicators for 2035" "nutritional recommendations, leading to a limiting of excess consumption of meat products and meat in particular, and increasing the consumption of legumes, fruit and vegetables.	Type of diet - 3 Food waste - 4	assumed that countries aim to fulfil the healthy dietary requirements set by WHO 2003 and WCRF 2017. This means that countries converge to a diet where meat consumption does not exceed 90g/day (of which only up to 71g/day is red meat); where sugars and sweeteners are kept below 10% of calorie consumption and where fruits and vegetables consumption is of at least 400g/day. Countries achieve a 75% food waste reduction at the consumer level by 2050.
Management practices	Agricultural systems will evolve (towards agroforestry, agro-ecology, organic agriculture, grass-fed livestock and limited land take)	Climate smart crop production - 4 Climate smart livestock - 4	Production system follows the agroecology standards. Food waste and losses are limited to a third of the previous level or about 6 times lower compared with 2015. The extensive approach leads to yield decline by 20-40% compared with 2015, but the agricultural land potential for carbon storage is fully exploited. Grasslands are used extensively, with a maximum

			livestock population of 1 Livestock Unit per hectare (LSU/ha). Livestock yields are constant compared with the level of 2015, and an increase of the livestock slaughter age is set to meet organic farming standards.
Energy production and carbon capture and storage			
Electricity mix	By 2035 50% of electricity generation from nuclear	Nuclear - 3.8	Nuclear production ~ 62.7% of electricity production in 2035
Total electricity consumption	~ 600TWh	Not set exogenously, results of the sectoral demand	~ 554TWh
Final energy consumption	Total ~ 1060TWh Industry ~ 250TWh Transport ~ 200TWh	Not set exogenously, results of the sectoral demand	Total ~ 732TWh Industry ~ 221TWh Transport ~ 270TWh
CCS	"allow us to avoid around 6 MtCO2/year in industry and to annually achieve around 10 MtCO2 of negative emissions with energy production installations using biomass (BECCS for bioenergy with carbon capture and storage)"	Carbon capture in manufacturing - 4 Carbon capture to fuel - 4 Carbon capture ratio in power - 4	By 2050 a total of 10.9 MtCO2/year are removed

In regard to the transport sector the SNBC2050 document foresees a strong total increase of passenger transport in the order of 26% between 2015 and 2050, the decrease of private car transport by 2% and four-fold increase in the share of active transport done with bicycles. In the EUCalculator model these key indicators are controlled by the levers Passenger distance and Mode of transport (see Table 5). Adjusting these levers, the EUCalculator model is able to return very close values; for total passenger transport an increase of 25.2% is obtained, as well as a drop of 3.1% in car usage (see Figure A4 in the Annex section). Bicycle transport also increases substantially, practically doubling (1.9x) as result of the lever combination; nonetheless the 4-fold increase in SNBC2050 is not realised. Freight transport is assumed in the SNBC2050 pathway to increase 40% between the years 2015 and 2050. In the EUCalculator we adjust the lever's freight distance (which controls the total demand for freight transport in tonne-km) to 1.3, obtaining a freight increase for France of about 41%. At the same time, the French pathway states - qualitatively - that "loading rates of heavy goods vehicles will increase", making the overall freight transport more efficient. We reflect this in the EUCalculator by assuming that trucks have a 15% higher load in 2050 with respect to 2015 and trucks will run 10% more km per year than in 2015, which equates to the most ambitious setting of the lever freight utilisation rate. Very much in line with other pathways the SNBC2050 foresees ZEV sales to be 100% electric by 2050. Similar to the case of the Portuguese pathway the lever passenger technology is aligned to level 4 in order to reflect the fast uptake of electric vehicles. This results in a fast turn-over of the French vehicle fleet throughout 2020 and 2050 so that by mid-century 6% of private cars run exclusively on diesel and gasoline (see Figure A5 of the Annex section). Assumptions regarding the efficiency of thermal engines in the EUCalculator is aligned with the in the SNBC2050 at 1.382 Mj/km by means of the lever passenger efficiency (see Table 5), for efficiency trucks the EUCalculator assumes that trucks energy consumption (MJ/tkm) decreases by 41.5% in relation to that of 2015, which is aligned with the top-end of the 35-40% range for efficiency improvements in freight transportation assumed in the SNBC2050 documentation. Finally, biofuels are foreseen in the SNBC2050 to play an important role in the future of transportation in France. In particular, biofuels will compose 50% of fossil fuels used in aviation by 2050 and contribute to a diversified fuel mix in the freight transportation sector (see Table 5). The level fuel mix in the EUCalculator is aligned with level 3.5 which delivers by 2050 a penetration of 52.5% of biofuels in the aviation sector (as share of total fuel usage) and roughly the same in freight transport. As a result of these assumptions the final energy demand per fuel is returned by the EUCalculator (see Table A2 of the Annex section) and compared to the respective key indicators in Table 5. Total demand from the EUCalculator reaches 198 TWh which is only 7% of the 200 TWh obtained in the SBNC. Electricity demand is calculated at 109TWh in 2050, a 9% overestimation from that in the SNBC2050. The largest discrepancy between the SNBC2050 pathway and the SNBC2050 is observed in the biofuel demand (34TWh vs 50TWh in the SNBC2050). This discrepancy is driven in part by overall energy demand in transport running ~7TWh lower, and the slightly higher pace of electrification in passenger transport in the EUCalculator.

The assumptions of material and technology in SNBC2050 are very ambitious and their representation in the EUCalculator requires nearly all levers of the manufacturing module (see Figure 2) to be pushed towards level 4 (see Table 5). The SNBC2050 envisions that "recycled raw materials will increase drastically to around 80% in 2050, particularly for steel, aluminium, paper, plastics and glass". In the EUCalculator scrap-EAF technology[15] (the recycled route for steel) will reach a share of 70% on average in Europe. Paper production from recycled fibres could reach a maximum of 90% while recycled paper reached 90% and glass 100%. Secondary aluminium route (recycled) is assumed to reach a maximum of 55%, which is rather far-off the "around 80%" mark in the SNBC2050. In the EUCalculator it is assumed that considerable shares of high-quality primary route aluminium will be needed to supply the energy transition. Importantly, the SNBC2050 foresees around 6 MtCO2/year in industry plus about 2Mt in the energy sector to be removed via the deployment of carbon capture and use technologies. In the EUCalculator this requires the levers carbon capture in manufacturing and carbon capture ratio in power to be set at level 4, which results in negative emission of about 10.6MtCO2/year in 2050 (see Figure A6 in the Annex section for the corresponding time trajectory).

Similar to the manufacturing sector the ambition of changes required in the building sector is high in the SNBC2050 pathway. Individual behaviour towards a more rational

[15] A process in which strap steel is melted in an electric arc furnace (EAF).

use of heating and cooling is foreseen by assuming that inhabitants heat their homes by 1 degree less in 2050 than in 2015. In the EUCalculator such progression is simulated 1:1 via the choice of ambition level 2 in the lever space cool and heating (see Table A5). Energy renovation of existing building stock is foreseen to be substantial. Over the 2030-2050 period circa 700000-equivalent renovations are projected in the SNBC2050, which accounting for the circa 35 Million dwellings in France (see Table A5) results in about a 2% renovation rate. Accordingly, in the EUCalculator the lever building envelope (that controls the renovation rate of buildings) is set at level 3, which results in a 2% renovation rate at the end of 2050. Unfortunately, in the EUCalculator the lever building envelope also controls the depth of renovations in addition to the pace of renovations. That means that the adequate level to represent the pace of renovation (e.g., 2%) might miss-represent the depth of renovation (that is, the level of energy efficiency of the renovated building). The SNBC2050 assumes that a "large majority of the building stock" will be renovated in order to achieve the goal of 100% Low Consumption Buildings. This "large majority" is nevertheless not quantified. In the EUCalculator the depth of renovations is bound to that of level 3. This means that only 10% of the renovations are shallow (-30% energy demand), while the remaining 90% and medium/deep resulting in energy cuts of -40 to -60%.

Agricultural practices and forestry are both set in the SNBC2050 pathway to evolve as to enhance the uptake of carbon and increase the resilience of ecosystems. As a result of strong demand for construction and a policy that sets to increase the carbon pool, forest cover is set to expand in France as well as the harvest of forest products from 48Mm3 to 65 and 83 Mm3 respectively in 2030 and 2050. In the EUCalculator the material demand from the building and the material switch in manufacturing sector (see Table 5) lead to an increase of harvested products in the EUCalculator of 60Mm3 in 2030 and 72Mm3 in 2050. These are respectively only ~7.7 and 10.8% off from those reported in the SNBC2050 (see Figure A6 of the Annex section). An increase of forested area of 25.6% compared to 2015 is also observed in the EUCalculator when running with the specifications that better match the SNBC2050. Agricultural systems in the SNBC2050 are projected to evolve (towards agroforestry, agro-ecology, organic agriculture, grass-fed livestock and limited land take). This feature of the pathway is aligned in the EUCalculator by level 4 in both the lever climate smart crop production and climate smart livestock. The combination of these two levers results in a production system following agroecology standards where waste and losses are 6 times lower compared with 2015. Furthermore, chemicals are fully banned, replaced by integrated pest management. In raiders to livestock, grasslands are used extensively, with a maximum livestock population of 1 Livestock Unit per hectare (LSU/ha). The SNBC2050 also accounts for changes in domestic demand of agricultural products via a change in personal preferences for animal and plant-based products. The SNBC2050 pathway limits excess consumption of meat products and increases the consumption of legumes, fruit and vegetables. The specific quantities of each food group are those in the French National Nutrition and Health Program's dietary guidelines, or PNNS[16] (see also

[16] Programme National Nutrition Santé

Hercberg 2011). The guidelines in PNNS are well in line with the ones in the lever diet level 3, countries converge to a diet where meat consumption does not exceed 90g/day (of which only up to 71g/day is red meat); where sugars and sweeteners are kept below 10% of calorie consumption and where fruits and vegetables consumption is of at least 400g/day. In regard to food waste, the SNBC2050 envisions food waste to drop 50% by 2025. In the EUCalculator we align this trajectory with level 4 that leads to food waste reductions of 75% in 2050 compared to those of 2015 but only a drop of 25% in the year 2025.

Attending the evolution of demand, technology and efficiencies across all sectors, a total of about 600TWh will be requested from the electricity system by 2050 (see Table 5). After aligning the highlighted EUCalculator levers to those that better reflect the demand and technology deployment across sectors in the French pathways, the model returns a total need for electricity generation of 554 TWh in the year 2050, a 7.7% underestimation to the consumption in SNBC2050. In addition, by 2050 the EUCalculator projects that 62.7% will be supplied by nuclear power (with lever nuclear set to 3.8), somehow higher than the 50% projected in the SNBC2050. In the EUCalculator, strong nuclear phase out needs to be orchestrated across countries in order to preserve grid stability, hence, the decline is less pronounced. Nevertheless, nuclear capacity in France does decline in the EUCalculator projections from 2035 onwards as more renewable capacity is added. In the year 2050 about 40% of electricity demand in France is supplied by nuclear power. In total, the SNBC2050 pathway is set to supply 1060TWh by 2050 while in the EUCalculator projections the total amount reaches only 733TWh (see Table 5).

Evaluation of sectoral emissions

Mid-century sectoral emissions in the SNBC2050 with those in the EUCalculator representation are provided in Table 6. Emissions in the energy sector are higher in the EUCalculator representation mostly due to a higher reliance on natural gas while in the SNBC2050 by 2050 there are only so-called renewable gas (including hydrogen). In industry the emission in the EUCalculator runs a bit higher due to a less reliance on electrification as that foreseen in the SNBC2050 while for the transport and buildings sectors the emissions are very comparable, and so is for agriculture. Emissions from waste are not directly modelled in the EUCalculator but rather subsumed under the agriculture production system. In terms of negative emissions, the removals by land use/forestation and CCUS are very much identical to those in the SNBC2050. The respective time evolution of emission per sector is shown in Figure 4.

Table 7 - Comparison of GHG in SNBC2050 and its reproduction using the EUCalculator

Sectoral GHG emissions in 2050 (MT CO2eq)	SNBC2050 pathway	EUCalculator pathway
Energy	2	2.72
Industry	16	17.83
Buildings	5	4.88
Transport	4	4.82

Agriculture	47	50.69
Waste/others	6	0.26
Total	***80***	***81.02***
Land use and forestry	-68	-69.62
CCUS	-10	-10.9

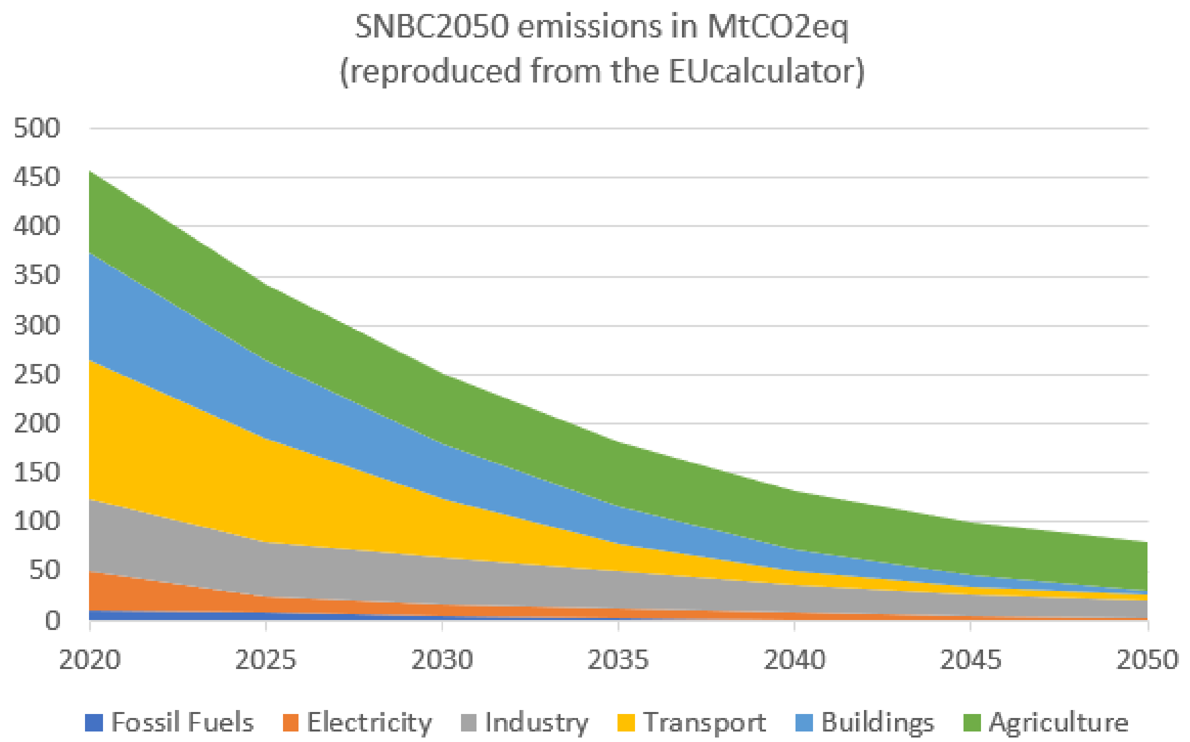

Figure 4 - Time development of GHG emission reproduced to match the SNBC2050

Similarly, to the described case of Portugal, we evaluate the SNBC2050 scenario along the proposed evaluation matrix, as well as a variation of it (SNBC2060BC) in which behavioural change toward less and more sustainable form of consumption. The extra speed of decarbonization brought about significant changes in behavioural change makes the SNBC2050BC even more compatible with the FF55 targets of 55% reduction by 2030 than the original scenario (which is also broadly compatible). Under SNBC2050BC FF55 targets are outperformed by a further 16% mostly due to drastic reductions in the transport sector driven by a decrease in total amount of passenger and freight transport. Due to substantial changes in consumption less energy is needed in manufacturing and accordingly the need for CCUS is reduced by 14% in comparison to that assumed to be needed in the SNBC2050. Furthermore, strong dietary shifts in the SNBC2050BC boosts natural carbon removal by forest a further 9% (see Table 7). As a result, net-zero would be achievable 2 years ahead of 2050 in the SNBC2050BC compared with the original SNBC2050. Importantly, because of the extra leeway on emission caused by behavioural change and the boosted sequestration of carbon in ecosystems in the SNBC2050BC scenario, CCUS technologies could be disregarded completely and net-zero still be feasible in 2050.

Table 8 - Evaluation matrix of the SNBC2050 and SNBC2050BC pathways

Pathway	Difference to 55% reductions in 2030.	Requires the deployment of unproven/ low-social acceptance technologies.	Land vs energy vs resource tradeoffs or synergies?	Net-zero ahead of 2050 (in years)	Less material/product import to the country
SNBC2050	+0.6%	Yes, CCS and BECCS, but with caution and incrementally.	No, mainly because of land freed due to changes in diets	~0	Unclear
SNBC2050BC	-16%	No. But even if deployed it require 14.3% lower effort than in SNBC2050	Stronger synergies with 9.3% more carbon uptake from spared land.	~2	Yes
Logic	**Negative values preferable**	**"No" preferable to "Yes"**	**"Synergies" preferable to "Tradeoff"**	**Higher values preferable**	**No clear preference**

4.3 Germany

Key scenario indicators on activity and energy

The transformation pathway proposed by the ARIADNE project[17] sets to push the Germany energy and societal system to net zero by around 2045. To our knowledge the pathway proposed[18] (from hereafter KAP2045) is the most recent and ambitious national pathway available at the time of writing, see Kopernikus Ariadne Projekt (2021).

Table 9 - Key sectoral indicators on activities and emissions in the KAP2045 pathway (technology mix variant), and those used by the EUCalculator

Scope	KAP2045 pathway	Key levers/ambition	EUCalc pathway
Transport			
Passenger transport	1360 Mpkm	Passenger distance - 1.1	1373 Mpkm
Bicycle Rail	84 Mpkm 174 Mpkm	Mode of transport - 1.5	91 Mpkm 143 Mpkm
Total freight transport	29% increase compared to 2020	Freight distance - 1.8	26% increase
BEV fleet share (passenger)	74%	Passenger technology - 4	70%
BEV fleet share (freight)	44%	Freight technology - 3.6	47%

17 Kopernikus Ariadne Project website

18 Scenarios and pathways (full report)

Passenger transport efficiency	2.4x increase	Passenger efficiency - 2.1	By 2050, car energy consumption (MJ/tkm) decreases by 27%, bus energy consumption by 20%, rail energy consumption by 25%, aviation energy consumption by 11%. Resulting in a 2.4x improvement
Freight transport efficiency	2.0x increase	Freight efficiency - 2.1	By 2050, truck energy consumption (MJ/tkm) decreases by 17%, rail energy consumption by 13%, aviation energy consumption by 7% and shipping energy consumption by 13%. Resulting in a 2.2x improvement
Energy demand	358 TWh	Not set exogenously but depending on the demand and technology settings	330.9 TWh
% of electricity in overall demand	55%	Not set exogenously but depending on the demand and technology settings	48.3%
% of hydrogen	14%	Not set exogenously but depending on the demand and technology settings	15.1%
Buildings			
Rate of retrofitting	Between 1.5 and 2% a year	Building envelope - 2.5	The annual renovation rate is 1.8%. 8% of the renovations are shallow (-30% energy demand), 50% are medium (-40%) and 20% are deep (-60%). The demolition rate is 0.5%/annum.
Renewable share in heating and cooling	96%	Technology and fuel share - 4	Fossil fuel use reduction in 2050: gas -95%; coal -95%; oil -95%. These fuels are substituted by heat pumps (60%), biomass (20%) , solar (12%), geothermal (4%), biogas (2%), biofuel (2%).
Energy efficiency gains	1.9x increase	Heating and cooling efficiency - 3	The efficiency of boilers increases slowly across the stock to an average of 91% for gas boilers, 87% for oil boilers and 69% for wood boilers.
Energy demand	608 TWh	Not set exogenously but depending on the demand and technology settings	612.9TWh
Fuel mix	Electricity - 380 TWh Heat - 201 TWh Biogas - 10 TWh Natural gas 0.03 Twh	Not set exogenously but depending on the demand and technology settings	Electricity - 329.4 TWh Heat - 133.3 TWh Biogas - 10.1 TWh Natural gas - 2.8 TWh
Industry			
		Technology efficiency - 3 Material efficiency - 2 Material switch - 2	In energy-intensive industries a more rapid shift from energy-intensive production technologies to emerging, low-carbon technologies are observed. For example, in the steel sector, the secondary route (scrap EAF), HIsarna and Hydrogen DRI gain shares (65% in total), geopolymer cement production becomes significantly more important (10%).

Production	Non-ferrous metals - 2Mt Non-metallic min. - 63Mt Chemicals - 44Mt Steel - 40Mt	Not set exogenously but depending on the demand and technology settings	Non-ferrous metals - 1.7Mt Non-metallic min.- 44.1Mt Chemicals - 31.3Mt Steel - 35.7Mt
Primary vs secondary steel	50%	Technology efficiency - 2.3	46%
Energy	672 TWh	Not set exogenously but depending on the demand and technology settings	467 TWh
% of electricity	44%	Fuel mix - 4	29.8%
Electricity generation			
Solar	29%	Coal phase out - 4 Solar - 3 Wind - 3 Hydro, geo and tydal - 1 Nuclear - 4 Bioenergy capacity - 1	22%
Wind	62%		63%
Nuclear	0%		0%
Hydro	2%		5%
Geo	0.55%		0.20%
Biomass	1%		3%
Coal	0		0
Others	5%		0.1%
Gas	0%		6%
Agriculture			
Not explicitly modelled		Climate smart crop production - 2 Climate smart livestock - 2 Food waste - 3	In 2050 sustainable intensification crop production systems remain limited compared to conventional practices. The intensification of the crop production system enables to increase the yields and input uses in line with historical trends. Land requirement is lower per output unit. In 2050 sustainable intensification livestock production system remains limited compared to conventional practices. The intensification of the livestock production system enables to increase the yields and input uses following historical trends. Given the intensification, the land requirement is lower per output unit. 50% food waste reduction at the consumer level, thus complying with Sustainable Development Goal (SDG) target 12.3

The alignment of the KAP2045 demand and technology assumptions in the EUCalculator model (see Table 8) follows the same logic and procedure as described extensively for the cases of the Portuguese and French decarbonization pathways. In the transport sector, unabated growth in freight and passenger demand continues well into 2045, resulting in an increase of 29% (compared to 2020) for the first and a total of 1360 Mpkm for the latter. In the EUCalculator, setting freight and passenger distance to 1.8

and 1.1 levels respectively results in an increase of freight demand of 26% and passenger demand of 1373 Mpkm (less than 1% difference to the in the KAP2045). In terms of active and rail passenger modal split, the EUCalculator returns respectively slightly higher (8.4%) and lower (18%) demands for transport done using bicycles and rail, see Figure A7 for the passenger transport evolution per mode in Germany from the EUCalculator model reflecting the KAP2045 pathway. In terms of penetration of electric vehicles in freight and transport, setting the EUCalculator lever of passenger and freight technology to 4 and 3.6 respectively, results in about 70 and 47% of fleet electrification, which is in line with the 74 and 44% assumed in the KAP2045. As a result of this overall good matching between demand and technologies, the final transport energy demand delivered by the EUCalculator is of about 331TWh, only 7% down from that published in the KAP2045. See Figure A8 of the Annex section for the evolution of the energy demand in time and the respective gains in passenger and freight efficiency aligned with those of the KAP2045. In terms of the energy vectors supplying the transport demand, the EUCalculator returns 48% electricity and 15% hydrogen as dominant vectors. The latter is virtually identical to the transport mix in KAP2045 while the share of electricity is slightly lower in the EUCalculator (which is in line with the 4% lower penetration of electric passenger vehicles).

The key energy efficiency driver of the building sectors in the KAP2045 is the renovation rate. The rate is set at "between 1.5 and 2%". In the EUCalculator model we opted to set the rate of renovation in both residential and non-residential buildings at 1.8% (lever building envelope = 2.5). This assumption, together efficiency improvements set by level 3 of the heating and cooling efficiency lever, resulted in a total energy demand of 612.9TWh, only about 1% higher than then one from KAP2045 (see Figure A9 of the Annex section for the time evolution of energy demand returned by the EUCalculator). The matching of the energy vector supplying the demand in buildings was less successful. The EUCalculator underestimates the use of the electricity and heat vectors compared with the KAP2045 while matching nearly perfectly the supply with biogas. Importantly, about 2.8TWh of gas (~0.5% of demand) are still required in the EUCalculator to supply the building sector which is not in line with the near absence of gas in the KAP2045. Which will have consequences for the final sectoral emission accounting.

The final industrial production values in the KAP2045 are approximate in the EUCalculator by means of the demand generated from the building and transport sector and by setting the levers technology efficiency, material efficiency and material switch off the levels shown in Table 8. Overall, yearly production for energy intensive industries is comparable between that in the KAP2045 and the one reproduced with the EUCalculator. This is particularly true for the case of non-ferrous metals (1.7 vs 2Mt) and steel (35.7 vs 40Mt). In addition, the fraction of recycled route for steel (secondary steel, see Table 8) is also identical between both the KAP2045 and the reproduction done with the EUCalculator model (50 vs 46%). Regarding the production of non-ferrous minerals and chemicals, the production returned by the EUCalculator is lower than that noted in the KAP2045. The underestimation for both cases is about 29%. As a result of this mismatch, the final energy demand in industry returned by the EUCalculator is 467TWh, about 30% lower than that in the KAP2045. Finally, the penetration of electricity in the sector is about 30%, which is lower than the 44% in the KAP2045.

The electricity mix in the KAP2045 is characterised by high penetrations of solar and wind at respectively 29 and 62% of the total electricity supply. Aligning the set of electricity generation technologies in the EUCalculator according to those in Table 8 returns shares of solar and wind of 22 and 63% respectively. The remaining shares of energy generation technologies in the grid are also very comparable between KAP2045 and the EUCalculator pathway apart from gas. In the EUCalculator gas is a very small but not non-residual technology in the Germany electricity mix. Mostly it is used for the purposes of balancing as nuclear and coal are taken off grid.

The agricultural system is not explicitly modelled in the KAP2045 and the emission from land use and forests not accounted for the emissions neutrality objective. Agricultural emissions in KAP2045 are given at 30.3Mt. Without a detailed characterization of the evolution of practices in the sector given by the KAP2045, we assume agricultural practices evolve along the level 2 of the levers climate smart crop production and climate smart livestock. This means that in 2050 sustainable intensification crop production systems remain limited compared to conventional practices, as so does livestock production. The slight intensification of the crop production system enables to increase the yields and input uses in line with historical trends. Land requirement is lower per output unit. This increases the overall efficiency of the sector. In addition, food waste is set at 50% reduction from 2015, thus complying with Sustainable Development Goal (SDG) target 12.3 (an assumption commonly found in the other national pathways).

Evaluation of sectoral emissions

Sectoral emissions in the KAP2045 are compared with those in the EUCalculator representation are provided in Table 9. In terms of overall emissions, the pathway derived from the EUCalculator model is only +1.3% off the numbers in the KAP2045 (50.8 vs 50.1). This slight over estimation is reflected homogeneously across the sectors apart from transport. This is mostly driven by very low but rather persistent use of gas for electricity production and in buildings. In the latter, gas remains in use for cooking purposes as it is not fully replaced by electricity. In the electricity mix gas is used as a balancing strategy in the EUCalculator until 2050. In industry, the lower rate of electrification achieved (see Table 8) is the main driver behind the 10% higher emissions in the EUCalculator pathway than that in the KAP2045. The respective time evolution of emission per sector is shown in Figure 5.

Table 10 - Comparison of GHG in KAP2045 and its reproduction using the EUCalculator

Sectoral emission (MT CO2eq)	KAP2045 pathway	EUCalculator pathway
Energy	2.2	2.8
Industry	9.2	10.1
Buildings	0.5	1
Transport	0.7	0.6
Agriculture	30.3	36.2
Waste/others	7.2	NA
Total	**50.1**	**50.8**
BECCS	-41.8	-46.8
CCS (power)	-5.0	
LULUCF	NA	-47.5

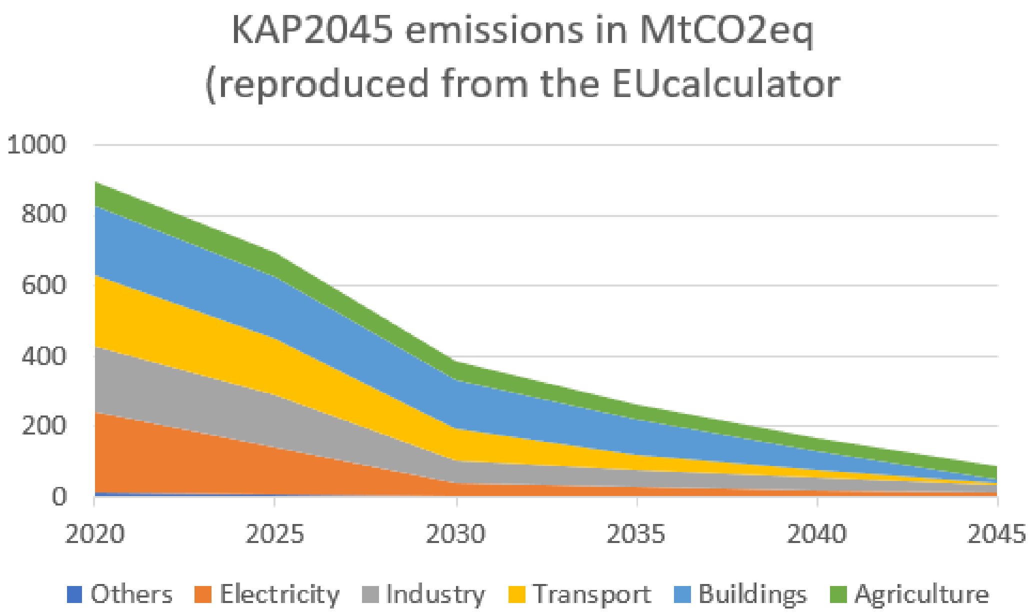

Figure 5 - Time development of GHG emission reproduced to match the RNC 2050

Similarly, to the described case of Portugal and France, we evaluate the KAP2045 scenario according to the proposed evaluation matrix, as well as a variation of it (KAP2045BC) in which behavioural change towards less and more sustainable form of consumption, see Table 10. The KAP2045 easily archives the FF55 reduction targets and keeps land/energy tradeoffs in check with the limited deployment of biomass capacity. On the other hand, the scenario relies on the economic feasibility of CCS. Because the energy system decarbonizer by 2045 the carbon uptake by ecosystems would be enough to make Germany carbon negative by then or even earlier. The event of behavioural change in the KAP2045BC is similar to that shown for the pathways of Portugal and France that assume substantial shifts in human behaviour. Because the KAP2045 is so ambitious, additional mitigation potential from behavioural change only slightly improves the FF55 reduction targets. The KAP2045BC would allow for about 39%.

Table 11 - Evaluation matrix of the KAP2045 and KAP2045BC pathways

Pathway	**Difference to 55% reductions in 2030.**	**Requires the deployment of unproven/ low-social acceptance technologies.**	**Land vs energy vs resource tradeoffs or synergies?**	**Net-zero ahead of 2050 (in years)**	**Less material/product import to the country**
KAP2045	-12%	Yes, CCS and BECCS	No substantial tradeoffs as biomass plays a small overall role.	~5	Unclear
KAP2045BC	-15%	CCS and BECCS are not strictly necessary but if implemented the uptake would be similar to that in the KAP2045.	Stronger synergies with 39% more carbon uptake from spared land.	~2 (if CCS and BECS are not deployed)	Yes
Logic	**Negative values preferable**	**"No" preferable to "Yes"**	**"Synergies" preferable to "Tradeoff"**	**Higher values preferable**	**No clear preference**

5 Pathway library

All energy, material and emission outputs from the EUCalculator model entailed in both scenarios evaluated are made available to WP3 by means of a .json file. A detailed listing of the model outputs can be accessed following this link. The library of model outputs to be elaborated throughout the project is made available internally to all partners through the PIK cloud following this link. Upon request, interested third party elements to the project can also access the database. Nevertheless, it is noted that the database will evolve and the team does not discard that some pathways might be updated throughout the timeline of the project in case new technological or policy developments, or interactions between WP's justify.

6 Conclusions

This deliverable describes how the EUCalculator is used to reproduce country-level decarbonization pathways adopted by countries or available in recent literature. It documents the key assumption on demand and supply of the energy systems available in the public-domain description of the pathways and evaluates how close the EUCalculator model is able to reproduce the final patterns of energy and emissions. In order to exemplify the process, the national decarbonization pathways for Portugal, France and Germany are reproduced in the EUCalculator and associated documentation provided. The output of the EUCalculator representing the national pathways for the selected countries is made available internally for further usage by WPs3-8.

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8 Annex

Table A1: List of levers in the EUCalculator modes, their scope and definition.

Domain	Scope	Lever	Definition
Key behaviour	Travel	Passenger distance	This lever sets the total average distance people will travel in one year. It includes travel distance by land, water and air.
	Travel	Mode of transport	The transport mode lever sets the mode by which passenger transport is undertaken (walking, cycling, motorbike, car, bus, train, aeroplane and boat).
	Travel	Occupancy	This lever sets the occupancy of passenger vehicles, i.e., the number of people in the average car and bus.
	Travel	Car own or hire	The passenger car utilisation rate lever sets the average number of kilometres travelled by a vehicle every year.
	Homes	Living space per person	This lever sets the amount of residential floor space per person.
	Homes	Percentage of cooled living space	This lever sets the per-capita fraction (percentage) of residential living space cooled.
	Homes	Space cooling	This level sets the room temperature within residential buildings.
	Homes	Appliances owned	This lever sets the number of white and black goods found in each household and comes expressed as appliance/cap.
	Homes	Appliance use	This lever sets the number of hours an appliance (washing machines, dishwashers, dryers, fridges, freezers, computers, TV's and phones) is used in households.
	Diet	Calories consumed	This lever sets the intake of daily calories consumed by individuals and comes expressed in kcal/cap/day.
	Diet	Type of diet	This lever sets the composition of individual diets expressed as daily calorie demand for 26 food groups.
	Consumption	Use of paper and packaging	This lever sets the use of paper for printing and sanitary purposes, and the plastic, paper, aluminium and glass used for packaging.
	Consumption	Appliance retirement timing	This lever sets product substitution rate, the amount of time a consumer wishes to shorten/extend the use of appliances owned beyond their expected lifetime. The appliances considered in households are dryers, washing machines, dishwashers, televisions and computers. Mobile phones are considered on a per capita level.
	Consumption	Food waste	This lever sets the number of calories wasted at the consumer level and comes expressed in kcal/cap/day.
	Consumption	Freight distance	This lever sets the total demand for freight transport (in tonne-km).
Technology and fuel	Transport	Passenger efficiency	This lever sets the efficiency of passenger vehicles. It controls efficiency improvements for all vehicle types (both fossil fuel-powered and low-carbon).
	Transport	Passenger technology	This lever sets how passenger technology in the transport sector will move from fossil fuels to lower emission vehicles. These include hybrid, electric or hydrogen vehicles and their use for passenger, freight and international transport.

Transport	Freight efficiency	This lever sets the efficiency of freight vehicles and controls efficiency improvements for all vehicle types (both fossil fuel-powered and low-carbon).
Transport	Freight technology	The freight vehicle technology mix lever sets the technology mix (e.g. Internal Combustion Engine (ICE), Battery Electric Vehicle (BEV), Plug-in Hybrid Vehicle (PHEV), Fuel Cell Electric Vehicle (FCEV), etc.) in the new vehicle sales for road, rail, sea and air. Based on this lever, and on historical fleet data, the model can compute the share of each technology in the total vehicle fleet and then compute the vehicle-kilometres by mode into vehicle-kilometres by mode and by technology.
Transport	Freight mode	The transport mode lever sets the proportion of freight transport made by road, rail, sea and air.
Transport	Freight utilisation rate	This lever sets the load factor for trucks, which is the weight of goods carried by each type of truck and sets the average number of kilometres travelled by a truck every year.
Transport	Fuel mix	The fuel mix lever sets the share of biofuels and efuels in each fuel type (e.g. gasoline, diesel, kerosene, gas, etc.).
Buildings	Building envelope	This lever sets the average heat loss reduced with insulation and affects the energy needed per floor area.
Buildings	District heating share	This lever sets the percentage of heating energy demand covered by district heating.
Buildings	Technology and fuel share	This lever sets the mix of technologies used for space heating.
Buildings	Heating and cooling efficiency	This lever sets the average energy loss in heating, cooling and ventilation systems.
Buildings	Appliances efficiency	This lever sets the average rate of energy use for appliances, cooking and lighting. The appliances modelled are fridges, freezers, washing machines, laundry dryers, dishwashers, computers, TV’s, and phones.
Manufacturing	Material efficiency	This lever sets material efficiency. It controls decrease in material demand due to activities such as smart design, use of more efficient materials and smart manufacturing.
Manufacturing	Material switch	This lever sets the percentage of materials substituted by other, more sustainable materials in products.
Manufacturing	Technology diffusion	This lever sets the percentage of manufacturing materials produced with low-carbon technologies. It also accounts for recycled material used in the production process.
Manufacturing	Energy efficiency	This lever sets the decrease in energy consumption through technology-based energy efficiency measures.
Manufacturing	Fuel mix	This lever sets the percentage of energy used along each energy carrier (electricity, coal, oil, gas, biomass, waste, and hydrogen) for each technology.
Manufacturing	Carbon Capture in manufacturing	This lever sets the percentage of CO2 equivalent carbon emissions captured within the manufacturing industry.
Manufacturing	Carbon Capture to fuel	This lever sets the percentage of utilisation of carbon captured.
Power	Coal phase out	This lever sets the phase-out and installation of new coal power plants.

	Power	Carbon Capture ratio in power	This lever sets the ratio of emissions captured in the power sector.
	Power	Nuclear	This lever sets the phase-out and new capacities of nuclear power plants.
	Power	Wind	This lever sets the new on- and off-shore wind power capacities.
	Power	Solar	This lever sets Photovoltaic (PV) and Concentrated Solar Power (CSP) capacities.
	Power	Hydro, geo & tidal	This lever sets the new hydropower, geothermal and marine power capacities.
	Power	Balancing strategies	This lever describes a portfolio of balancing and storage technologies, including: pumped hydroelectric storage, battery, flywheel, compressed air storage and power-to-X technology.
	Power	Charging profiles	This lever sets the charging patterns of electric vehicles, thus influencing when charging happens and its ability to shift demand.
Resource and land	Land and food	Climate smart crop production	The lever sets the ambition regarding the crop production system, from intensive to agroecology approach.
	Land and food	Climate smart livestock	The lever sets the ambition regarding the livestock production system, from intensive to agroecology approach.
	Land and food	Bioenergy capacity	The lever sets the ambition regarding the bioenergy domestic production capacities per energy-type.
	Land and food	Alternative protein source	The lever sets the share of insect and microalgae-based meals for each livestock type, and disable/enable by-product feedstock for other markets.
	Land and food	Forestry practices	The lever sets the ambition regarding the deployment of climate smart forestry.
	Land and food	Land management	The lever sets the ambition level for land-use allocation and dynamics.
	Land and food	Hierarchy for biomass end-uses	The lever sets the hierarchy regarding the agri-food industry by-products and waste uses.
Demo-graphics	Long-term	Population	This lever sets the amount of population living in the EU28+Switzerland.
	Long-term	Urban population	This lever sets the fraction of total population living in urban areas
Domestic supply	Domestic supply	Food production	The lever sets the self-sufficiency ratio for each food group.
	Domestic supply	Product manufacturing	This lever sets the import of products and the impact of trade.
	Domestic supply	Material production	This lever sets the import of manufactured materials.
Mitigation outside Europe	Constraints	Global mitigation effort	This lever sets how the rest of the world may decarbonise.

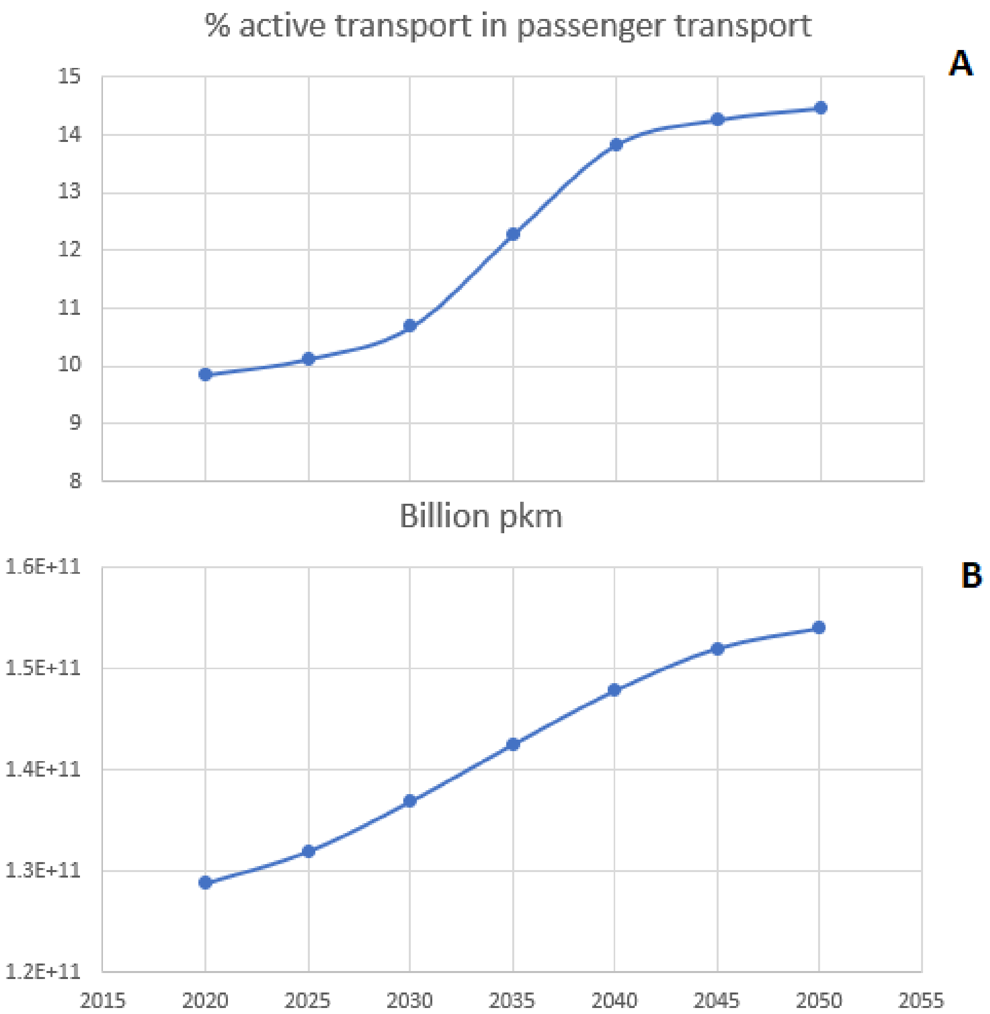

Figure A1 - pkm and % of active transport in the EUCalculator representing that of RNC 2050.

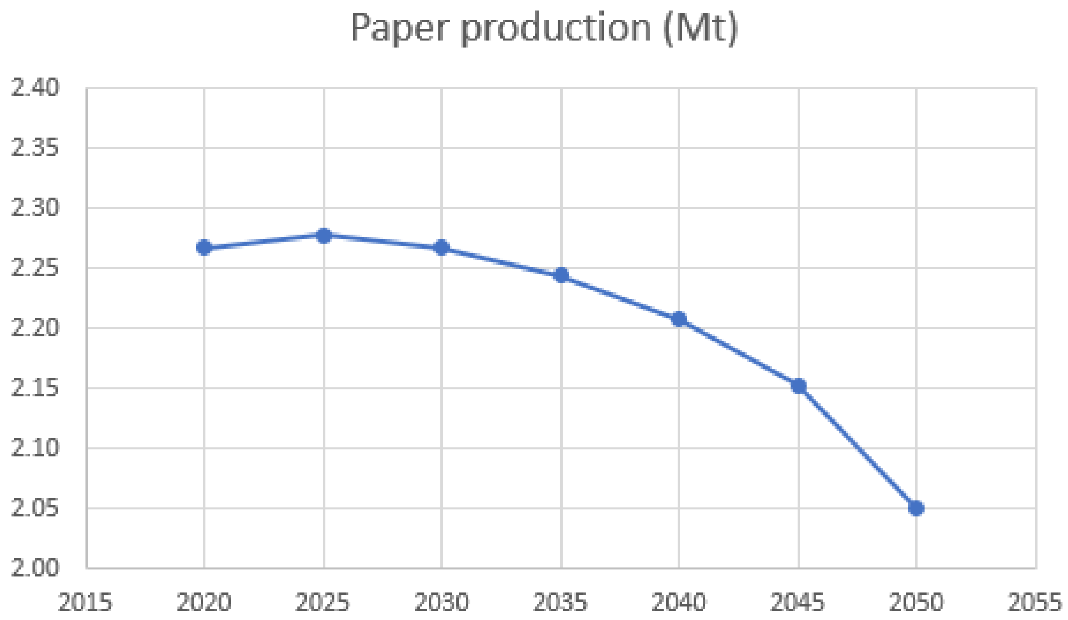

Figure A2 - pkm and % of active transport in the EUCalculator representing that of RNC 2050.

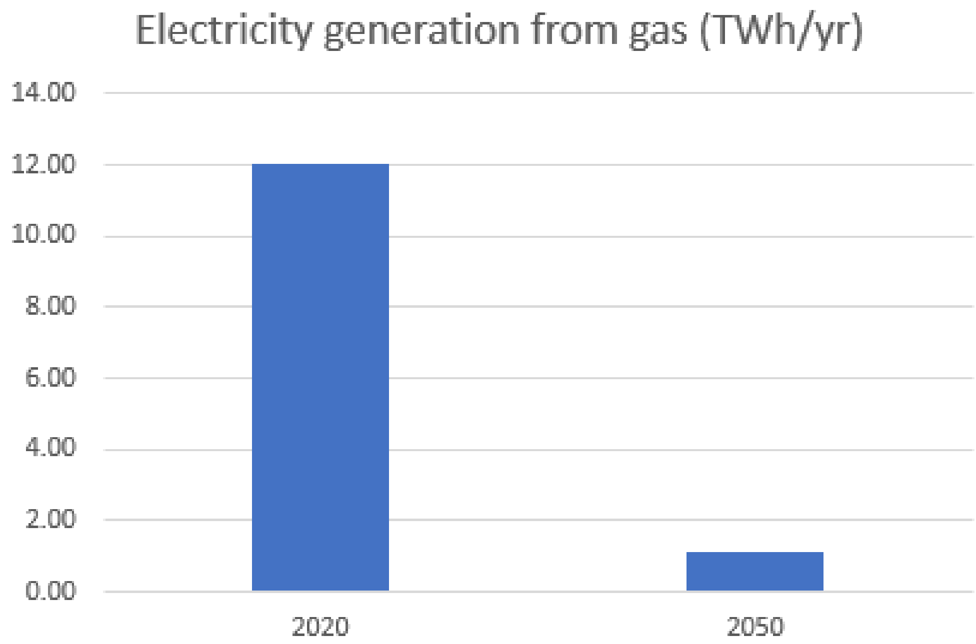

Figure A3 - Electricity generation from gas in Portugal.

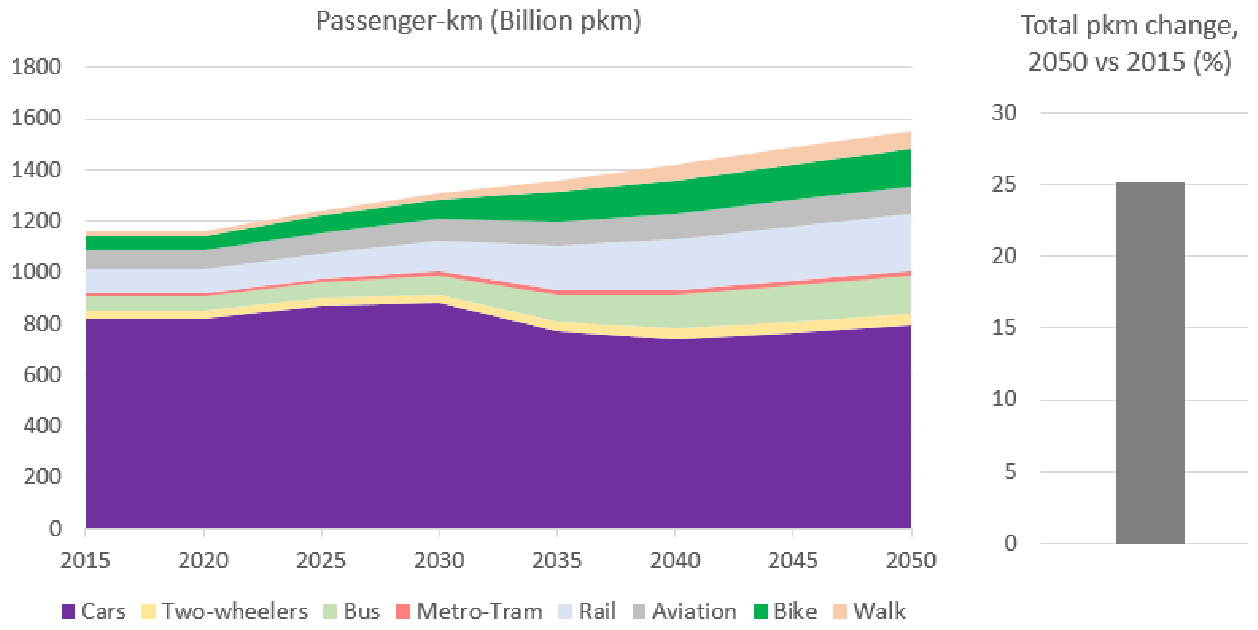

Figure A4 - Passenger transport evolution per mode in France from the EUCalculator model reflecting the SNBC2050 pathway.

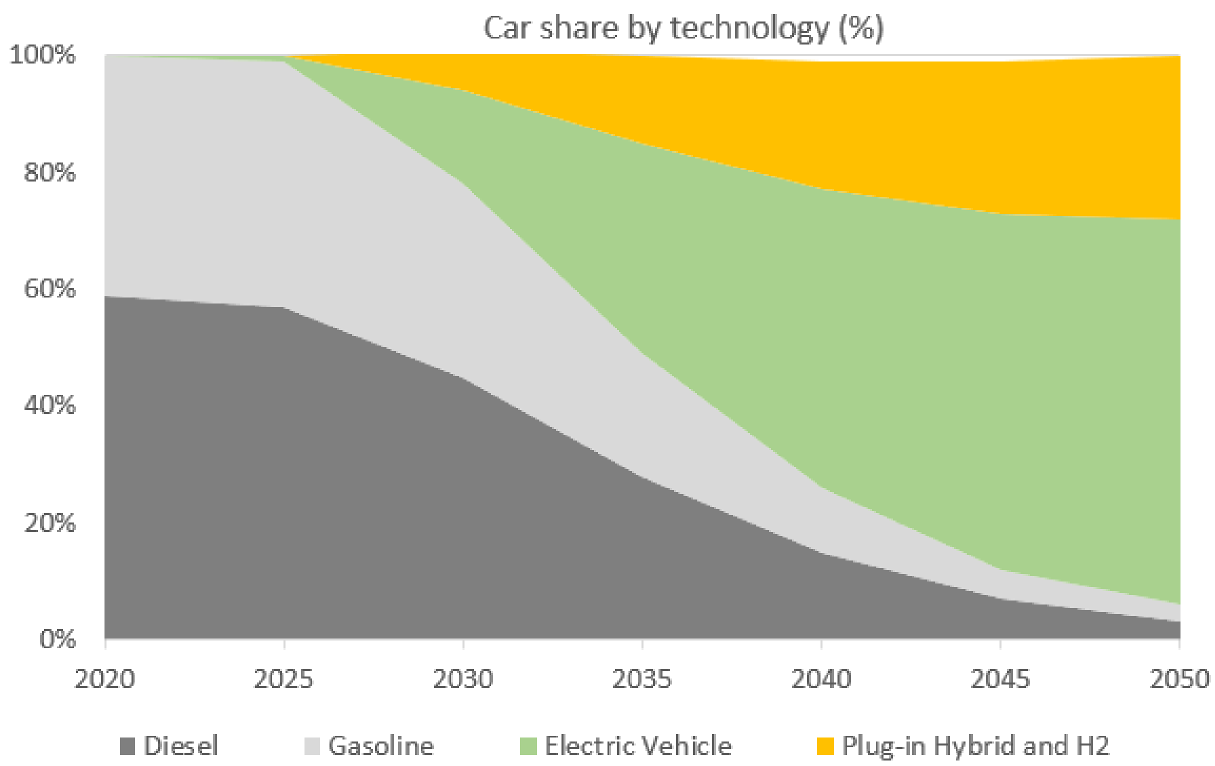

Figure A5 - Car share per technology in France from the EUCalculator model reflecting the SNBC2050 pathway.

Table A2 - EUCalculator reproduction of energy demand per fuel in the transport sector according to the SNBC2050 assumptions (key indicators highlighted).

TWh	Passenger	Freight	Total
Electricity	84.6	24.1	**109**
Biofuels	19.2	15.2	**34**
Diesel	2.6	2.7	5.4
Gasoline	1.1	0	1.2
Hydrogen	20.7	4.9	25.6
Kerosene	16.1	1.2	17.4
Marine fuel oil	0	0.5	0.6
Total			**193**

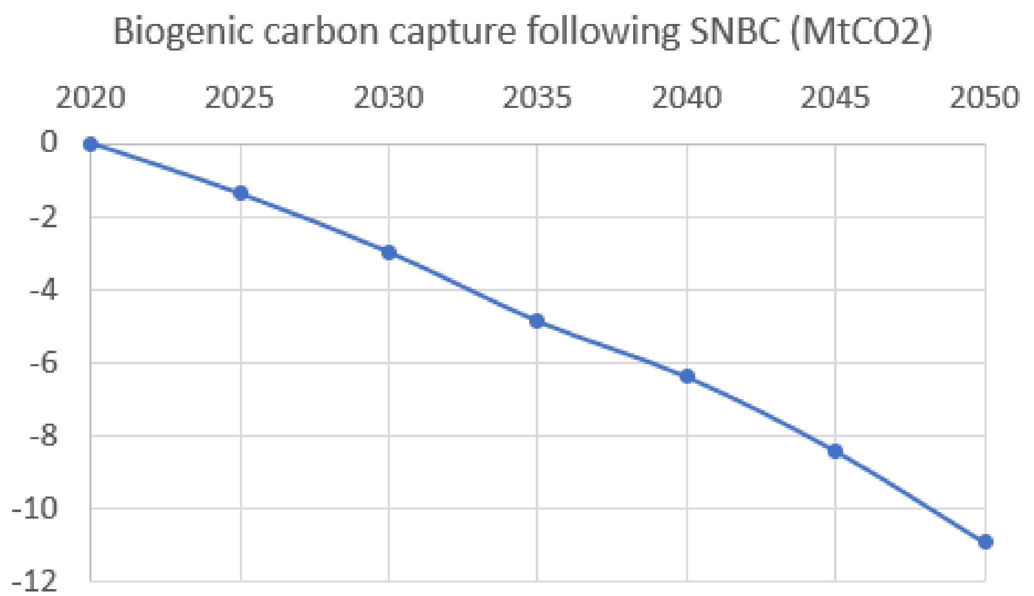

Figure A6 - Negative emission in industry and power sectors from the EUCalculator following the assumptions in SNBC2050.

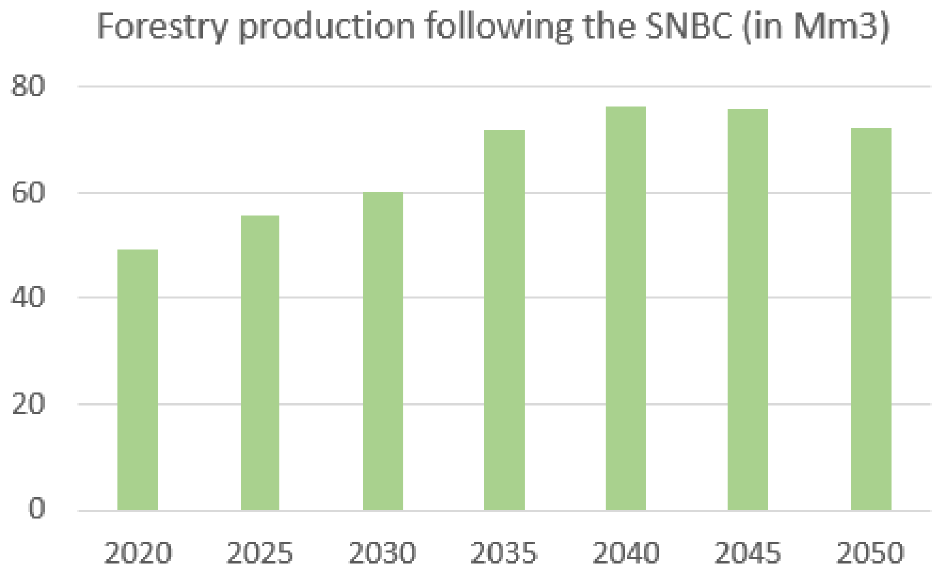

Figure A6 - Forestry production from the EUCalculator following the assumptions in SNBC2050.

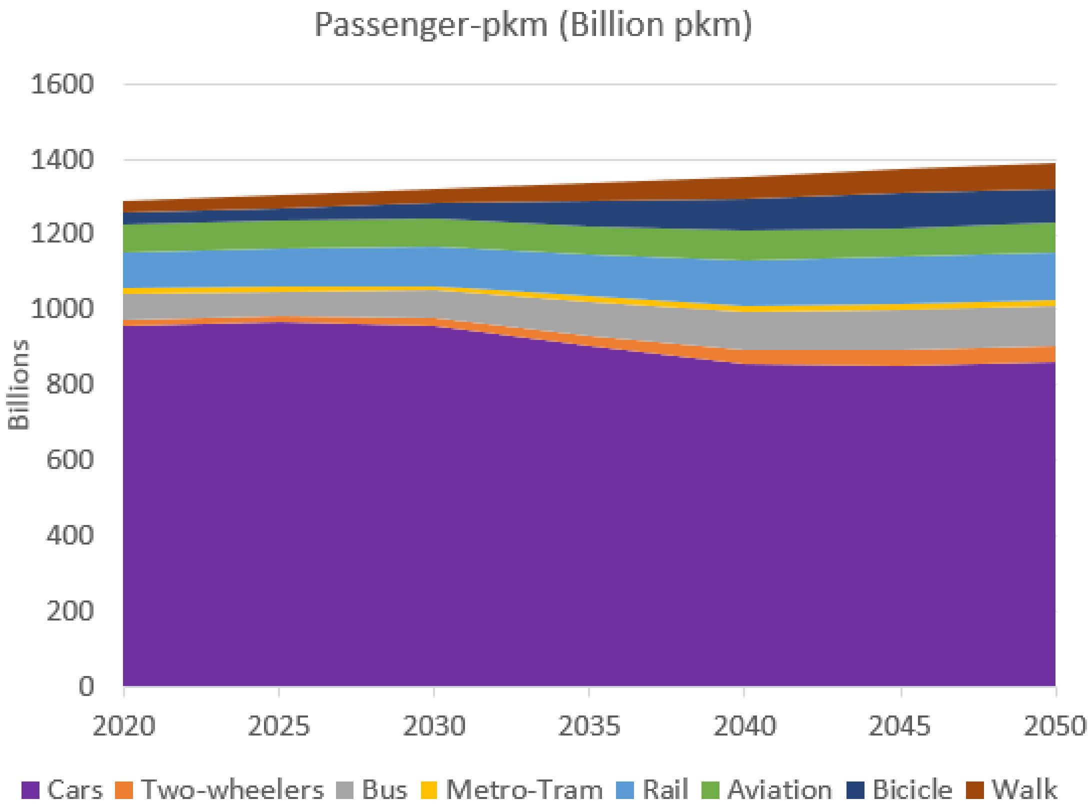

Figure A7 - Passenger transport evolution per mode in Germany from the EUCalculator model reflecting the KAP2045 pathway.

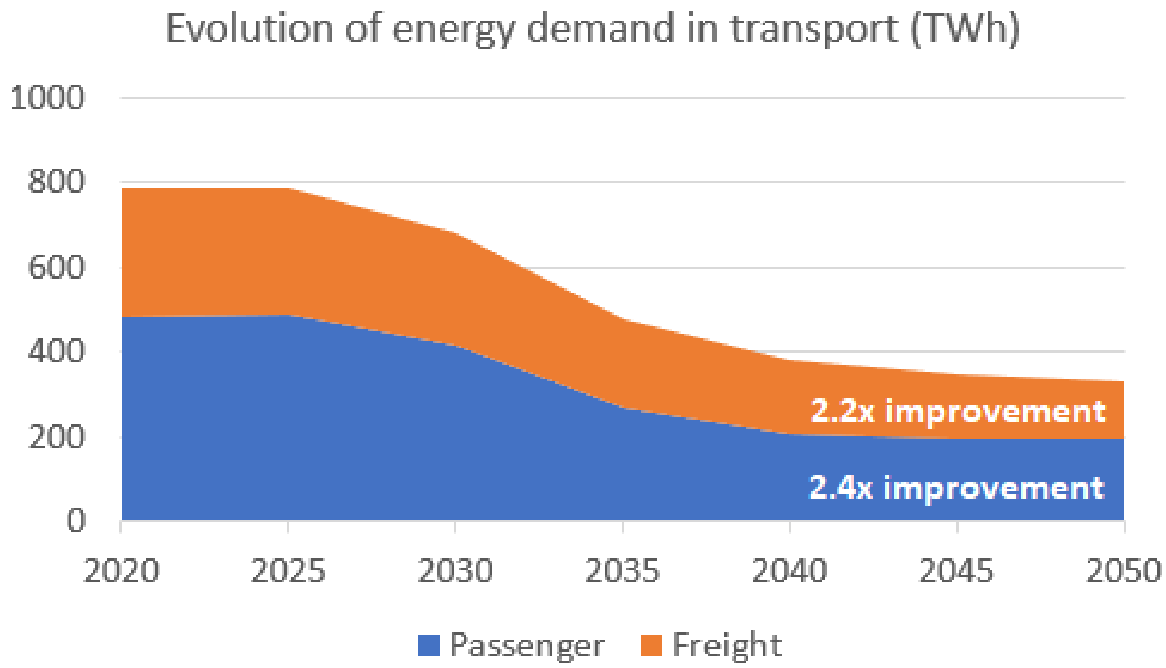

Figure A8 - Evolution of energy demand in transport in Germany from the EUCalculator model reflecting the KAP2045 pathway.

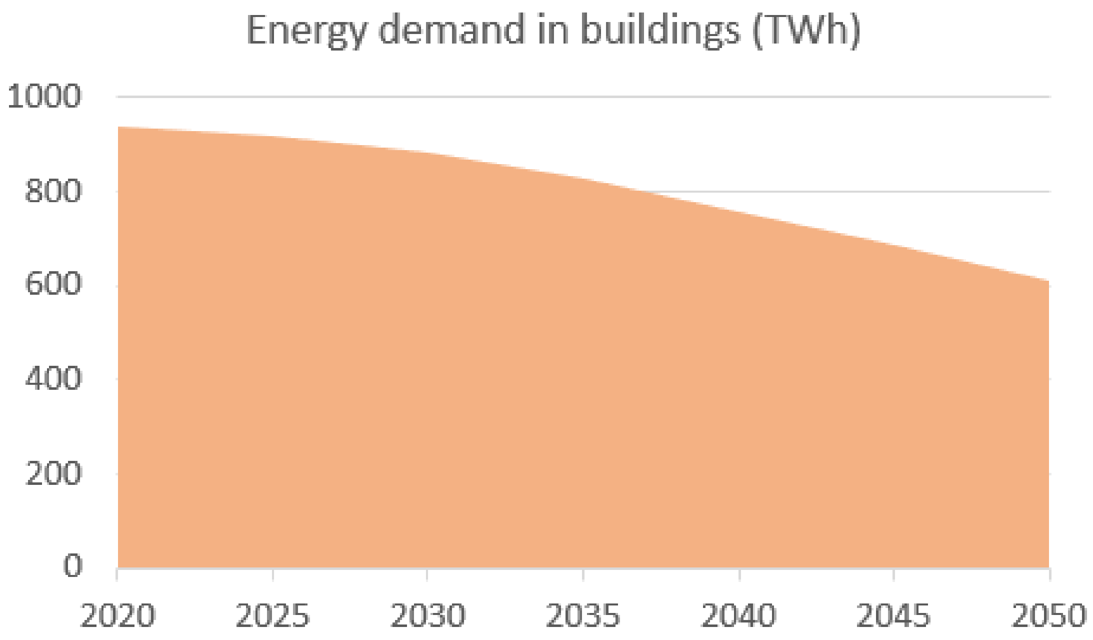

Figure A9 - Evolution of energy demand in buildings in Germany from the EUCalculator model reflecting the KAP2045 pathway.

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