WHY

D5.1

Report on the integration of the WHY Toolkit with the energy models

LEGAL DISCLAIMER

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EXECUTIVE SUMMARY

This report includes the definition and the development of the five Use Cases of the WHY project, which capture a wide diversity of contexts from the local to energy community, national, European, and global level. These Use Cases play a central role in the project, as through their application in diverse situations, the WHY Toolkit and models will be tested and validated. This deliverable (**D5.1**) aims to provide a detailed definition for the design and development of the Use Cases, based on the soft-linkage of the WHY Toolkit with large-scale Energy System Models (ESMs). In this direction, the impacts of WHY modelling enhancements on energy and climate strategies at different jurisdiction levels are assessed from the local level up to the European and global levels.

The design of all Use Cases has been greatly benefited from the active engagement of stakeholders and end-users, including policy makers, public authorities, businesses, and utilities. This has taken various forms, depending on the specificities of each Use Case ranging from the organisation of (online and in-person) stakeholder workshops to interviews, focus groups on online questionnaires. In all cases, stakeholders helped to define the most important aspects, questions, and policy interventions to be assessed in each Use Case. An active communication channel with stakeholders has been established and will be extensively used to discuss the results of the Use Cases and identify policy-relevant recommendations.

This report also includes the relevant information needed for the implementation of the scenarios and policy interventions with the WHY Toolkit and the links with large-scale ESMs (PRIMES, TIAM-ECN, PROMETHEUS), focusing on the European and global Use Cases where the use of ESMs was identified as important. Furthermore, this report provides key input assumptions, policy framework, definitions, and policy interventions that are used for the actual development of the five Use Cases through scenario implementation, simulations, and policy impact assessment using the WHY Toolkit.

The Positive Energy District Use Case in Maintal is discussed in Chapter 2 of this report. This case study focus on the creation of a positive energy district and optimizing it for energy consumption and provision. The original Use Case was designed as a Micro-Grid Use Case in Austria's hamlet of Gniebing, but it was cancelled due to high energy prices that led to massive problems for the Gniebing Grid Operator. Then, the focus shifted to positive energy districts, which share some resemblance with microgrids. The WHY-project will assist to reduce the uncertainty by providing more detailed information on the energy consumption of the households. The Use Case is separated into three phases: draft planning phase, technical planning phase, and post-planning phase. The blackout-simulation model will be created using the Maintal data. The WHY-Toolkit generates the baseline load profiles for normal uninterrupted power supply and operation of the system, and the results of the WHY-Toolkit will provide the load profiles of the households in general but also the load profiles of the individual devices. Using the data from the survey and the preferences of the inhabitants on which devices and energy services are most important to them, a distribution of used services and devices amongst the inhabitants will be used to identify which devices will be running during the time without power supply. The distribution is then applied on the households that are part of the simulation, which will finally create a matrix. The goal is to create a self-sustainable positive energy district in Maintal, which will be achieved

through the analysis of the behavioral change of the potential inhabitants in a disruption of the energy supply. The Maintal Use Case is expected to provide insights into the design and operation of future positive energy districts.

The Energy Cooperative case in **Chapter 3** is focusing on the usage of the WHY-Toolkit to simulate the behavioral change of residential consumers to obtain a deeper knowledge of the load behavior of these consumers and the way they will change their behavior in response to modification of changes in the electric tariff structure. The main goal is to assess the impacts of the modification of the tariff structure, including the load profile, the purchase strategy they need to follow, and the impact on achieving long-term goals such as reducing energy consumption, increasing distributed generation assets for self-consumption, reducing energy poverty, and increasing community empowerment. The Energy Cooperative Case uses quantitative and qualitative pre-post analyses of interventions, and surveys were sent to all the partners of Goiener to gather socio-economic information of households. The validation method includes bootstrapping techniques to estimate the replicability of the results. Finally, this Case describes the scenario design with new energy and climate policies implemented to reduce emissions, improve energy efficiency, expand renewable energy generation capacity, and improve the electric system, based on specific interventions that impact the load behavior of the consumers.

The role of energy communities is discussed in **Chapter 4** as a means of achieving the European Union's goal of becoming climate neutral by 2050. Energy communities can support a clean energy transition at the local and citizen level by encouraging democratic decision-making and self-sufficiency, social innovation, and collaborative social transformation. Energy communities can take many diverse legal, organizational, and financial forms, depending on local circumstances and needs, and the available policy and regulatory support. Energy communities have gained momentum through public investment and support schemes, and the awareness of sustainable advantages for local populations. The main objective of this use case is to show the way that new energy community-based business models can advance the energy communities and lead to climate neutral cities. A methodology is outlined for assessing the setup of an energy community, which involves answering questions related to the technical, economic, environmental, and social aspects of the community. Two assessments are carried out: a top-down assessment where a stakeholder decides to sell energy directly to the neighborhood instead of selling it to the market, and a bottom-up assessment where a group of people is interested in producing their own energy. The assessments conclude that energy communities can play a vital role in achieving climate neutrality by 2050 and that new energy community-based business models can help to make energy communities even better.

The European Use Case is a study that aims to explore the impact of EU-wide policies on achieving the EU's goals on climate change mitigation and energy efficiency (**Chapter 5**). To achieve its goal, the WHY Toolkit is soft linked with the PRIMES modelling suite to provide a granular representation of load profiles of energy consumers and model the specificities of different building types. The PRIMES-BuiMo model simulates the future development of the buildings sector in the EU Member States and projects energy consumption, fuel mix, equipment choice, renovation rates, investment, and CO2 emissions under alternative policy scenarios. The model splits the stock of buildings in many categories, by geographic locations, age of construction, income classes and service sector sub-sectors. The soft-link of PRIMES-BuiMo with the WHY Toolkit will enable an improved assessment of households' energy demand and a better representation of factors like income, preferences, weather, access to loans, location, and household composition. This Use Case provides an improved understanding of the role of energy consumers towards the systemic transformations required to reach the EU Green Deal goals by exploring the effects and feasibility of climate neutrality in the buildings sector with unprecedented temporal and spatial granularity, while capturing system interlinkages between energy demand, supply, prices, grids, fuel mix, and storage. Behavioral changes, such as transitions to sustainable lifestyles, can contribute significantly to achieving decarbonization and the Sustainable Development Goals (SDGs). However, ESMs have limited sophistication and theoretical and/or empirical validation in representing lifestyle changes as these variables are mostly exogenous. As a result, they offer limited insights into consumer-side transitions and the associated implementation barriers for policy. This Chapter also presents a methodological framework to integrate consumer-led transitions into ESMs, focusing on the transport and residential sector. The methodology used in the EU Use Case involves integrating data from the WHY toolkit into PRIMES-BuiMo, creating an interface that matches the categories of buildings in PRIMES-BuiMo to building categories that are simulated with the WHY Toolkit. PRIMES-BuiMo represents the market and non-market barriers as well as hidden costs and perceptions that affect consumer behavior together with various policy instruments that influence the decisions of individual consumers. The non-market barriers can be broadly split into two categories: *a) (lack of) information and knowledge*, and b) *technical and regulatory uncertainty*. The EU Use Case aims to understand the implications of enhanced energy efficiency and electrification in EU buildings towards achieving climate neutrality by mid-century. It assesses the impact of policy interventions and incentives on energy consumption and the uptake of low and zero-carbon solutions. The analysis provides key performance indicators related to emission trajectories, energy efficiency, uptake of renewable energy, building renovation strategies, energy system costs, and affordability.

Chapter 6 discusses the Global Use Case which investigates under which circumstances ambitious climate policies and energy efficiency targets affect the global energy mix and the future development of the buildings sector. Two integrated assessment models, **TIAM-ECN** and **PROMETHEUS** are used and linked with the WHY-Toolkit to improve their simulation properties. This use case aims to bring the global dimension into the WHY project and contributes to the scientific literature on global energy scenario analysis. The scenario design as well as the selection of the input data and the output indicators are based on consultation with several stakeholders, the extensive literature research, and the internal expertise of the two modeling teams. Based on policy dimensions identified through the stakeholder input, internal and external variables are considered, and several scenarios are designed and implemented with the models. The validation of the global scenarios is also discussed in this chapter by presenting key results obtained from the PROMETHEUS and TIAM-ECN models. The projections obtained under the diagnostic scenarios are presented for the global energy system development and CO2 emissions. Furthermore, the trends observed in both models are compared, highlighting the differences in their projections. The validation process aims to demonstrate the advancements realized in the global energy system and Integrated Assessment models as part of the WHY project.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Long text
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
EU	European Union
EC	European Commission
EV	Electric Vehicle
CO2	Carbon Dioxide
EE	Energy Efficiency
DR	Demand Response
ESM	Energy System Model
UCM	Use Case Manager
IDEA	Institute for Diversification and Saving of Energy
REC	Renewable Energy Community
CEC	Citizen Energy Community
KPI	Key Performance Indicator

1. Introduction

Energy systems are crucial components of the model societies as they provide essential power and energy resources to cover the daily needs. However, these systems are facing significant challenges, including the reduction of carbon emissions to mitigate climate change, the transition to renewable energy sources and the increased demand for energy to cover heating and mobility needs in emerging economies. The comprehensive understanding of energy systems and the evaluation of the impact of policy interventions seems to be prerequisite component to meet the above challenges.

The design and development of use cases is an important tool to address these challenges. A use case is a real-world scenario that describes a specific problem that stakeholders face related to the energy systems. The impact of policy interventions can be evaluated by designing and developing use cases which can finally identify potential solutions.

The Use Cases are an important part of WHY project ambition to create an improved and transparent energy modelling framework to improve the understanding for energy consumption and potential energy efficiency improvements in the buildings sector. The five WHY Use Cases will serve to test, validate, and demonstrate the WHY Causal modelling toolkit and its links to leading Energy System Models, through the creation of model plug-ins. To ensure consistency and transparency, the data and information required for the definition and design of the five Use cases are presented in detail in this report. The analysis provides details for the Use cases, which demonstrate the relevance and adequacy of the WHY modelling toolkit to enhance the modelling of energy consumption in the residential sector and illustrate the ability of the proposed approach to answer specific questions related to the evolution of the energy consumption and energy efficiency at local, national, European, and global levels. The use cases will also act as a real-life proof of concept of the WHY research methodology. Through the five Use Cases, the modelling enhancements and linkages with ESMs will be validated through a comparison of modelling results with previous studies (without the use of WHY Toolkit) to re-assess policy instruments and interventions. The WHY Use cases provide an in-depth analysis on specific topics (e.g., energy community, energy cooperative) and geographical regions (local level, national, global), which are important in the current EU energy policy landscape.

The five Use Cases developed through the WHY Toolkit share a similar use context, acting as proof of concept and testing/validating the modelling improvements. Their objective is to assess in detail the impacts that a set of interventions (e.g., policy measures) may have on the energy system development, energy costs and prices and CO2 emissions using the WHY modelling tools. To support policy decisions, the actor or entity (modeler, researcher, policymaker, utility, energy community or other) uses the WHY toolkit to assess the policy impacts before the actual policy is implemented. The WHY Use Cases that are described extensively in the next Chapters of this report are:

- ✓ **The Positive Energy District Use Case in Maintal.**

The Maintal Use Case aims to access the positive energy district in Maintal, which is currently being developed with a mixed allocation of the available space within the buildings (companies, households, etc). The district will be planned to address the topic of energy consumption and energy provision. The objective of this Use Case is to reduce uncertainty in energy consumption of households. The WHY-Toolkit will be used to generate individual load profiles for different types of households.

- ✓ **Energy cooperative Operation and Planning**.

Energy retailers want to know as precisely as possible how much energy end users will need. This allows them to optimize the purchase of energy, reduce deviations, risks and therefore penalties and secure futures in a more accurate way, which means tariffs that are fitting for the customers. Having an accurate view of consumer demand is also critical for setting the margin in electricity rates, especially when making tighter purchases. Currently consumer demand is estimated based on the existing consumer portfolio (aggregate consumption profile) and extrapolating considering the growth forecast based on indices of previous years, the annual consumption curve, and the weather conditions. With the use of WHY Toolkit, Goiener will be able to perform more accurate demand forecasting by taking into consideration not only climatic factors but other non-climatic factors that are difficult to simulate on a massive scale. This Use Case will assess the improvements of using the WHY Toolkit in the daily operation and on the strategic planning of new incentives, tariffs, actions, or campaigns of Goiener.

- ✓ **Energy Communities**.

In recent years, energy communities are widely discussed, attracting attention in national and EU energy policy debates. However, despite manuals and best practice guidebooks becoming increasingly available, there is still a lack of tools to help municipalities in the setup of Energy Communities in line with the Electricity Market Directive and Renewable Energies Directive. This Use Case will develop tools to support municipalities on setting up Energy Communities. The primary objective is the selection of the policy mix that increases the likelihood of achieving an optimal energy community, along with the development of tools that enable the operation of the energy community, i.e., the tariff systems, business model, etc. Using the WHY toolkit, a set of practical recommendations to build and operate energy communities will be developed. The platform allows simulating the energy needs of citizens, the use of household appliances and the impact that citizen demand has on different distribution networks.

- ✓ **The European Use Case**.

Energy efficiency and decarbonization of the European building stock are hailed as key drivers of Europe's transition to climate neutrality by mid-century, as part of the EU Green Deal and Fit for 55 policy package. However, most analyses on emission reduction targets in buildings are based on large-scale models that do not include a granular representation of load profiles of energy consumers and do not model the specificities of different building types. To overcome these challenges, in this Use Case the WHY Toolkit will be soft-linked with the PRIMES modelling suite (especially PRIMES-BuiMo), one of the most widely used and well-established models at EU level. It has been used to provide quantitative model-based assessment of benchmark EU energy and climate policy impact assessments (Energy Efficiency directive, Fit for 55 package, "Clean Planet for All" strategy). A two-way interlinkage of the WHY Toolkit with the PRIMES model will be carried out based on data interface and a disaggregation of PRIMES-BuiMo results to capture consumer differences, idiosyncratic behaviours and load profile granularity provided by WHY Toolkit. The Use Case will offer quantitative evidence on different pathways to decarbonize the EU buildings sector by 2050, that promote energy efficiency, electrification, fuel switch, and deep renovations, smart appliances/grids, demand-side management, and co-benefits to achieve climate neutrality by 2050. Based on detailed load modelling and consumer representation, the EU Use Case will re-assess various policy instruments (as identified in the targeted stakeholder workshop) consistent with the revised Energy Efficiency Directive, the Fit for 55 package and the EU's commitment to become climate neutral by 2050.

- ✓ **The Global Use Case**.

The Paris Agreement has set the goal of limiting global warming to well below 2°C and pursuing efforts to bringing it down to 1.5°C, which requires a substantial drop in global Greenhouse Gas (GHG) emissions. This can be achieved only through large and rapid changes in the energy system leading to net-zero emissions by or slightly after 2050. Key drivers are the uptake of renewable energy, the electrification of end uses, and energy efficiency improvements which are commonly assessed using large-scale Integrated Assessment Models. However, these models typically do not represent in detail energy demand, consumer behavior and energy efficiency measures. To improve the modelling of energy demand in global mitigation scenarios, the Global Use Case will link the WHY Toolkit with the integrated assessment models TIAM-ECN and PROMETHEUS, which have a global coverage and represent the energy system dynamics disaggregated in more than 20 distinct regions. A scenario-based analysis is presented comparing the outcomes of the global models when a soft link with WHY Toolkit is activated. This Use Case aims to assess the systemic effects of the improved representation of energy demand from the built environment on long-term global energy scenarios, in line with the Paris agreement.

The report is structured as follows: Chapter 2 provides details on The Positive Energy District Use Case in Maintal, Chapter 3 discusses the Energy Cooperative, Chapter 4 the Energy Communities, Chapter 5 the European energy strategy, Chapter 6 the global energy scenarios while Chapter 7 concludes and suggests next steps.

2. The Positive Energy District Use Case in Maintal (The Maintal Use Case)

This use case is based on the assessment of the positive energy district in Maintal.

2.1. Objective and Scope of the Use Case

In the first iteration of this Use Case, it was designed as a Micro-Grid Use Case featuring the hamlet of Gniebing in Austria (see Deliverable 1.3). The plan was to get a better grasp of household consumption to better operate the micro-grid and analyse the potential of running it during a black out scenario. Over the course of multiple discussions with the Grid Operator of Gniebing the Use Case has been defined with an increasing degree of detail. Unfortunately, the Use Case has had to be cancelled due to the energy crisis and the high energy price situation which led to massive problems for the Gniebing Grid Operator, who is not unbundled, due to its small size and had to shift its manpower and focus on tackling the challenges arising from the new market situation. Thus, this use case had to be changed.

As a result, the consortium was looking for a similar setting, while it was not possible to identify another grid operator who has already prepared his grid for a similar task, the focus was changed on positive energy districts, as they share some resemblance with microgrids. Through the project partner Climate Alliance, the consortium was put in contact with the City of Maintal.

The city of Maintal is currently developing a new positive energy district with a mixed allocation of the available space within the buildings (companies, households, etc.). The district will be planned by a technical bureau, which will also have to address the topic of energy consumption and energy provision within the district. Normally the planner will rely on standardised values for energy consumption and generation, both for thermal and electrical energy, which would result in an uncertainty. Planners mostly work with annual values for generation and consumption and do not investigate the details of high-resolution load profiles. Thus, if the energy generation is greater than the annual consumption, the plus energy criterion is fulfilled. But it gives no indication of whether the generated energy is used by the consumers.

The WHY-project will help to reduce the uncertainty by providing more detailed information on the energy consumption and consumption profiles of the households. For that purpose, the planners will provide the WHY consortium with the general data on the potential occupants of the buildings.

During the detailed planning phase of the positive energy district, the planners will decide on what heating technology to implement for the entire district. During that phase the WHY Building Sizer, a model library which is part of the WHY-Toolkit and responsible for sizing components (see Deliverable 3.2), will be used to optimise the setup and provide the planners with the means to validate their results. Additionally emergency energy supply is a topic that is not part of the planning process but will be addressed by the WHY consortium.

The Use case is separated into three phases:

- **Draft planning phase:** During this phase the WHY consortium uses the WHY-Toolkit to generate individual load profiles for types of households which will inhabit the positive energy district. The number of households to be considered will depend on the definitions made by the Maintal city planners, which is not available at this point in time (but will be presented in deliverable D5.2). The input data on the occupancy of the households and the technical parameters will be provided by the Maintal planners. As a result, the Maintal planners will receive household load profiles with a temporal resolution of 15 minutes for their calculations.

- **Technical planning phase:** In this stage of the planning of the Maintal district, the WHY consortium will use the WHY-Toolkit in combination with the building sizing tool to validate the technical options for heat supply in the district chosen by the Maintal planners. The results of the validation and the effects on the energy consumption through the use of the chosen technology will be provided to the Maintal planners for further consideration.

- **Post planning phase:** During the post planning phase, when everything is set, the WHY consortium will use the Causal Model in combination with the WHY-Toolkit to analyse the behavioural change of the potential inhabitants that would result from a disruption of the energy supply and whether the district could work in a self-supply mode during the period of disruption. The results will be provided to the city of Maintal for further consideration.

2.2. Specifics of the Black Out simulation

The simulation of Blackouts is a difficult approach as knowledge on how people would react in such a case is not given. Back-Up Power Supply has only recently reached the household sector through the combination of PV and Battery storage systems. The approach to simulate Black-Outs follows the idea that if people would have a backup power supply in a black-out case, they would use certain energy-related services trying to keep up their usual practices as much as possibles. As such the WHY consortium has conducted a survey on the "services" for household inhabitants, that they would like to have even during a situation with a prolonged unavailability of electrical energy.

The blackout-simulation model will be created using the Maintal data. The WHY-Toolkit will generate the baseline load profiles for normal uninterrupted power supply and operation of the system. Thus, no curtailments to the load-behavior of the inhabitants will be considered. The results of the WHY-Toolkit will provide the load profiles of the households in general but also the load profiles of the individual devices that are used during the day.

Using the data from the survey, and the information of the preferences of the inhabitants on which devices and services are most important to them, a distribution of used services and devices amongst the inhabitants will be used to identify which devices will actually be running during the time without power supply. The distribution will be applied on the households that are part of the simulation which will create a matrix of devices used amongst the different households in the simulation. These data will then be applied to the load profiles generated by the WHY-Toolkit as part of post processing. As mentioned, the WHY-Toolkit provides the load profiles of individual devices, if those individual devices are not to be considered, as the inhabitants do not plan to use them, their load profile will be set to zero. With the matrix of priority use for different devices in the individual households, new consumption profiles are generated for the positive energy district.

As part of the Maintal Positive Energy District development, energy generation capacities and potentially storage systems will be considered. The planned technologies will then be used in a power supply simulation, where the generation profiles will be matched against the (now reduced) consumption load profiles. The following simulations will be made:

- Simulation with generation systems as planned by the Maintal planners and without battery storage systems and full load (no change in behavior).
- Simulation with generation systems as planned by the Maintal planners and without battery storage systems and reduced loads.
- Simulation generation systems and battery storage systems as planned by the Maintal Planners (it is at this point not certain if this will be implemented).
- Simulation with battery storage system with increased generation and storage capacities to ensure back-up supply.

The simulation model will go through every day of the year and start a 7-day black-out simulation starting at four different times of the day (6:00, 12:00, 18:00, 24:00). That way different starting points of the blackout will be considered, and thus different effects will be assessed depending on seasonal or daily load variation, holidays, etc. For each of the timesteps within the 7-day window the following KPIs will be calculated. Parts of these KPIs were already mentioned in D1.3 but due to the change of the use case, the KPIs had to be adapted:

- Duration without power supply
- Number of timesteps the system needs to reduce power or shut down renewable energy sources in order to prevent overproduction (KPI G_2)
- Duration with power supply (KPI_G_1)
- Amount of energy lacking
- Amount of excess energy.
- Number of users that would need to be switched off in order to maintain operation.
- Number Consumers that can be supplied during a Blackout Situation (KPI_G_10).
- Number of timesteps the system needs to shed loads in order to prevent underproduction (KPI_G_3).

The results of the simulation will then be analysed, and the different cases described above will be compared.

2.3. Quantitative data used as an input to the model

As the Maintal Use Case is currently (02/2023) in development and the tender of the city Maintal on who will be the planner of the positive energy district is to be published soon, the specifics of the data used are not yet fully defined. At this point a first assumption of the data can be described here:

- **Draft planning phase:** Technical parameters of the buildings within the district, such as building standards, sizes of the flats, insulation, number of flats, number of stories, etc. Occupancy of the flats, described by age distribution, family settings, etc.
- **Technical planning phase:**
    - Technical parameters of the buildings within the district for the detailed planning phase, such as building standards, sizes of the flats, insulation, number of flats, number of stories, etc.
    - Occupancy of the flats, described by age distribution, family settings, etc.
    - Technical parameters of the options to be considered for thermal energy generation.
- **Post planning phase:**
    - Results of a survey conducted with 1500 participants on the requirements on the provision of services that they would have, when it comes to a short-term disruption of energy supply or when it comes to a long term disruption of energy supply. A short-term disruption relates to a couple of hours maximum with the rest of the energy system around the disruption still working, for instance a small-scale disruption of supply in a part of the city. A long-term disruption indicates a duration of more than 2 days (7 days are considered in the simulations) with a total failure of large parts of the energy supply.

2.4. Validation Method

The validation of the generated load profiles will be made in two steps. First, the annual consumption values will be benchmarked against a) comparable annual consumption value from measured data, literature and expert knowledge and b) the data provided by the Maintal planners. If there is a substantial deviation between these values, an in-depth discussion between the Maintal planners and the project consortium will be required. Minor deviations will of course occur, due to the nature and higher degree of detail from the results of the WHY-Toolkit.

Secondly the load profiles will be matched against measured load profiles from comparable households taken from the data already gathered by the WHY-consortium.

2.5. Description of scenario co-design process with stakeholders

For the Maintal two distinct scenarios are defined: Normal Operation and Emergency Supply Operation. The first scenario describes the day-to-day operation of the Positive Energy District. The second scenario describes the situation during a prolonged period of lacking power supply.

1) Normal Operation:

The “Normal Operation” scenario describes the day-to-day situation of households in the Maintal Positive Energy District. The scenario aims to capture the expected household energy demands and load profiles. For that purpose, the information on the inhabitants of the Maintal Positive Energy District will be considered. The number of households is not yet defined, as the tender-process for the definition of the Maintal planner is still ongoing.

The “Normal Operation” scenario is developed to support the city of Maintal in the planning phase of the Positive Energy District. The scenario development is not yet fully concluded as the decision on who will be the technical planner of the Positive Energy District has not yet been made by the city of Maintal, thus one relevant stakeholder for the detailed development of the scenario is missing.

As a result of the discussions with the City of Maintal the scenario will be split into two phases, the Draft Planning Phase and the Technical Planning Phase, the specifics of both phases are described above. For the Planning Phase the focus of the scenario will be on creating load profiles for households with a high temporal granularity. For the Technical Planning Phase, the focus will be on a detailed analysis of technical components for thermal energy supply of the households.

2) Emergency Supply Operation:

The “Emergency Supply Operation” scenario describes a situation where the superordinate power supply fails because of a black-out or a regional or even local disruption of the power supply. In this scenario the supply fails and an emergency supply by the power sources of the Positive Energy District in Maintal is initiated. This scenario evaluates the effects of a massive intervention for the household inhabitants. The general reaction to such an intervention, which as was estimated through a large-scale survey, will be the input for the scenario. Based on these inputs, load profiles with a high temporal resolution will be created and matched against the generation and (potential) storage capacities within the district.

The scenario will be split into different sub-scenarios, which describe the technical setup and the reaction of the inhabitants of the Maintal Positive Energy district, as described above.

The “Normal Operation” scenario is developed to provide the City of Maintal with information on what to expect during a disruption of the energy supply. The scenario development is also not yet fully concluded as the decision on who will be the technical planner of the Positive Energy District has not yet been made by the city of Maintal.

2.6. How Stakeholder input modified the use Case content?

As mentioned above the Maintal Use Case was developed due to the changes in the Gniebing Use Case in order to have a similar small scale Use Case in the WHY project. The consortium was put in contact with the Maintal administration via the project partner Climate Alliance. The clerk responsible for the tender of the Maintal Positive Energy District was a former employee of Climate Alliance who also has worked on the WHY project, which provided a good starting point for the initial discussions.

The WHY consortium was contacted by the city of Maintal to provide insights for the new positive energy district to be developed in Maintal. At a first meeting with the clerk responsible for the tender, the project WHY and the possibilities of the WHY toolkit were discussed. During this discussion a preliminary draft on how the WHY project could support the city of Maintal was drafted. This initial draft suggested that the WHY consortium would provide the city of Maintal with the energy related data and suggestions for devices to be implemented at the Maintal Positive Energy District. Initially the consortium thought, that the WHY project would work directly with the city and provide data to them. Over the next couple of weeks, the city's administration consulted over the possible cooperation leading to a second meeting with the Maintal city clerk. During that meeting the Maintal Use Case was reworked. Instead of initially providing an overall analysis of the positive energy district, the focus was to be set on providing support for the Maintal planners. In a third meeting, this time with decision makers of the city of Maintal, the Use Case was discussed again and the exact inputs of the WHY Toolkit and the timeframe of the Use Case were defined.

3. The Energy Cooperative case

3.1. Objective, Progress and Methodology

This Use case focuses on the operation and development of the Energy Cooperative case. In this Use Case, the Spanish energy cooperative Goiener will perform better estimations and load demand forecasts using the WHY Toolkit, considering not only the climatic factors but also other non-climatic factors that are difficult to simulate on a massive level. For Goiener, it is necessary to foresee the short-term consumption of its consumer partners in order to be able to buy energy in a more adjusted way in the daily market. But it is also very important to be able to calculate consumption forecasts in the medium and long term. Based on a good demand forecast, Goiener will be able to know the exact amount of energy that is going to supply. In this way, Goiener will be capable of stabilising the prices of the electricity tariffs. Moreover, it will allow Goiener to enter into long-term power purchase agreements (PPA) with small renewable energy producers.

The main goal of this use case is to use the WHY-Toolkit to simulate the behavioural change of the residential consumer partners in order to obtain a deeper knowledge of the load behaviour of these consumers and how they will change their behaviour in response to modification of the environment conditions. One of the main conditions is the electric tariff. Goiener is interested on assess how a change in its tariff structure will modify:

- The load profile of its partners (individually and as a group).
- The purchase strategy they need to follow.
- The impact on achieving its long-term goals: reduction of energy consumption, increase of distributed generation assets for self-consumption, reduction of energy poverty and increase of community empowerment.

To analyse these aspects, the use case exploited data from two different tariff changes that were implemented in Spain. The first electric tariff change was implemented on the 1st of June of 2021. The objective of this tariff change was to shift the load curve from peak to flat and valley hours in order to improve the electric system. So, the aim of this first part was to analyse if Goiener partners were following this expected behaviour. The second change was adopted in order to face the high prices of electricity as a result of the EU energy crisis. The Royal Decree Law 10/2022, from the 13th of May of 2022, develops a temporary mechanism that limits the impact that the increase of natural gas prices is having on the wholesale electricity market, because of its marginalist design. With this mechanism the production cost of marginal fossil fuel technologies was adjusted. This has the effect of a reduction equivalent to the adjustment in the offers that marginal fossil technologies make in the market, with the consequent reduction in the wholesale market price. The amount corresponding to the adjustment is financed by those consumers who benefit from the reduction. So, the aim of the second part will be to analyse the effect that Royal Decree Law

10/2022 has in the consumption behaviour of the partners. This intervention has not been yet analysed, because of its recent implementation.

3.2. Quantitative data used as an input

Both a quantitative and a qualitative pre-post analysis of the interventions is formulated. Anonymized datasets from 22 851 electric meters were analysed in the first intervention. With the aim of achieving socio-economic information of these households, a survey was sent to all the partners of Goiener. This survey was answered by 691 people. Moreover, 311 answers gave the necessary information to de-anonymize the results, so that a more detailed analysis was possible to be done in these cases.

In the second intervention, the same number of electric meters were analysed. A similar survey was sent to the partners, with the aim of obtaining the socio-economic profile of the partners and the investing intentions that they had. This second survey was answered by 634 people. Moreover, 292 answers gave the necessary information to de-anonymize the results.

3.3. Validation method

As the results of the use case will be a set of KPIs emerging from the two surveys, we plan to use bootstrapping techniques to estimate the replicability of the results. In this sense, we will simulate hundreds of surveys using different samples of different sizes and calculate the panel of KPIs on each sample. If the variance of each one of the bootstrapped KPIs is reasonable, we will validate the method. If not, we will look for the potential reason for such a phenomenon.

3.4. Description of scenario design

In the last few years, new energy and climate policies are implemented in order to reduce emissions, improve energy efficiency, expand the renewable energy generation capacity and improve the electric system. The Goiener Use Case has taken advantage of two recent policies that have been applied in Spain. The first one was implemented on the 1st of June of 2021. With this new policy a change of electric tariff was implemented in all of Spain. Before that time, there were 6 different tariffs for households. The modification simplifies the tariff structure and now there is just one, which has 2 periods for power access and 3 periods for energy consumption. The main objective of this policy was to improve the use of the national electric system by shifting the load curve from peak hours to intermediate and valley hours, reducing the thermal gap as much as possible.

Aside from the policy interventions, non-policy-driven interventions also have an important role in this use case. To measure its impact, all 14000 consumer-members were included in an experimental setup with three experimental conditions and a control group. All of them received basic advice on moving loads. Furthermore, each one of the experimental groups received extra information about: environmental impact, extra tips on moving loads, and finally, energy efficiency related advice. The intervention lasted 6 months. The general message was sent once a month and the reinforcement messages after 15 days. The aim of this intervention is to identify which kind of messages make the biggest effect on the energy consumption and on the shift of the load.

The second policy was implemented on the 15th of June of 2022. A temporary mechanism that limits the impact that the rise in natural gas prices is having on the wholesale electricity market, because of its marginalist was adopted. Apart from the policy intervention, another non-policy-driven intervention was carried out. The cooperative partners were added in a telegram bot, in which they were sent daily information on electricity prices, with the aim of moving their load to the cheapest hours. The intervention lasted, also, 6 months. The aim of this intervention is to identify and measure the impact that an economical signal has in the consumption behaviour.

3.5. How stakeholder input modified the Use case content?

Various meetings with the Spanish Institute for the diversification of energy supply and energy savings (IDAE) were carried out, before, during and after the first intervention. In the first part, the meetings were mainly focused on the preparation of the survey. Therefore, it was possible to include the vision of IDAE in the survey. Afterwards, the meetings were focused on the analysis and interpretation of the results.

After the analysis of the second intervention, another meeting will be conducted with the same institute, in order to share the results and add their ideas to the final conclusions.

4. The Energy Community use case

4.1. Objective and Scope of the Use Case

The European Union aims to become climate neutral by 2050. All parts of society and economic sectors will play an important role in achieving this goal. While this objective has been defined at the EU or Member State level, its implementation will take place locally, involving all European cities, villages, communities, and citizens.

In that context, energy communities can be instrumental in changing the energy landscape and enabling the clean energy transition at the local and citizen level. Community-based clean energy projects have rapidly gained momentum with the help of public investment and support schemes, and the awareness of sustainable advantages for local populations. Energy communities have encouraged democratic decision-making and self-sufficiency, social innovation, and collaborative social transformation. Beyond the community-specific lens, energy communities can bring increased flexibility and resilience to the main energy grid, and from an economic perspective, they can be also seen as socially innovative enterprises, engaging in economic activity that lowers energy costs while providing financial returns to the local community. Therefore, they will activate the local economy.

Against this backdrop, energy communities can take many diverse legal, organisational, and financial forms, subject to local circumstances and needs, while also depending on the available policy and regulatory support. From a technical standpoint, energy communities traditionally focused on only energy generation, but this is growing dynamically to include storage, supply, and energy efficiency. Organisationally, they can be created either in a top-down or a bottom-up approach, with initiatives including communities of place, whose values are shared within a landscape, and communities of interest, who come together by their shared principles, financial position, and problems. Spatially, energy communities are present in both rural and urban areas, even forming collaborative partnerships. This multidimensional potential has been acknowledged by the European Union that already via the Clean Energy for All Europeans package has sought to empower citizens and communities to become active participants in the energy transition, promoting prosumers involved in energy generation, consumption and trading in energy markets.

The main objective of this use case is to show how new energy community-based business models can make the energy communities 'better' and lead to climate neutral cities.

4.2. Methodology

In particular, we plan to show how the WHY toolkit could be used to plan the setup of an energy community from the technical, economic, environmental and social perspective providing tools to answer the following questions:

- Who should be involved and how to involve them?

- How to size the different components (generation, storage, control strategy, etc.)?
- What legal entity is the most effective / robust?
- What is the best business model / tariff system to be deployed?
- How to manage new contracts and cancellations after the set up?

We will carry two assessments:

Top-down assessment:

A stakeholder (a public authority or an SME) decides to share some space in their facilities to include some distributed renewable energy generation and/or storage. In order to increase the profitability of the system (or to fulfil their statutes, their corporate social responsibility activities or just for greenwashing) the stakeholder decides to sell the energy directly to the neighbourhood (including its own self consumption) instead of selling it to the market. The stakeholders could also be interested to go further and promote energy efficiency and conservation actions or provide power to heat (district heating) or power to transport (fast charging stations) services over the same infrastructure.

For the first assessment we will replicate the energy community that Goiener is helping to start at Hernani city. Hernani is a small industrial city situated in the Euskadi region (north of Spain) and has around 20 000 inhabitants. At that city, Goiener is proposing to build an energy community that involves the entire municipality including citizens, SME, public authorities and even industries in different types of memberships such as consumers, service providers, collaborators, investors, or workers.

The aim of this use case is to create a tool that could be used in the technical part of an energy community use case. The tool is prepared to make fast calculations in collective self–consumption. For that, the clusters obtained in the Task T2.1 have been used. So, the percentage of each cluster that corresponds to Goiener has been translated to the collective self-consumption. With this tool the following parameters can be calculated in a fast way just knowing the amount of people that is going to be consuming from the collective self-consumption:

- Production (MWh/year)
- Power (kWp)
- Self-consumed energy (MWh)
- Buyed energy (MWh)
- Surplus energy (MWh)
- Savings (€/year)
- Payback period (years)

Moreover, a comparison with a storage system has been done for each of the calculated parameters. At the moment, the tool is in a validation process.

Bottom-up assessment:

In this case, a group of people is interested in producing its own energy for different reasons. A description of the physical use case is provided in Deliverable D1.3. Two meetings have been carried out with the stakeholders of this use case, namely, the citizens involved in the creation of the community. The objective of the meetings was the definition of the master action plan.

The result of the co-creation activity was the prioritisation of the actions to be carried out by the following order:

1) Assess the installation of a self-consumption based on PV.
2) Assess how to reduce the use of gas in the heating and DHW system installed.
3) Look for potential ways to heat the swimming pool.
4) Install batteries and energy management systems.
5) Assess how is the best way to deploy electric charges in the community.

In parallel, the stakeholders agreed on becoming an energy community.

With this prioritisation several activities are planned:

- Hire an engineer to check the physical boundaries and size (and budget) an installation taking into consideration these aspects.
- Start the discussion about the legal figure and the governance structures to be deployed.
- Simulate using the WHY Toolkit the building complex

4.3. Validation method

For the top-down assessment, we have taken advantage of the energy communities that are still thinking about installing a collective PV installation. Therefore, all the used information to dimension the installation has been used to validate the tool. The results obtained with the tool are compared with real numbers and the error of each case is calculated.

For the bottom-up assessment, the results of the report from the engineer will be compared with simulations carried out using the WHY Toolkit in order to validate the tool.

4.4. Description of scenario design and input data for the model

For the top-down approach, the necessary data to dimension a PV installation has been used, such as, the load profiles of the partners, the available surface and the maximum voltage that the transformer can support. The information was obtained from the first PV installation that was designed for EnHerkom (Energy Community of Hernani). So, apart from all the technical information, personal information from all the people who were participating in the collective self-consumption was used, thus, Universal Supply Point Code

(USPC), ID number and the exact location of the home where they live. In the near future, a similar activity will be carried out but with a different installation.

For the bottom-up approach, as with the top-down one, it was collected the individual load profiles of the households as well as the load profile of the different energy services of the buildings (illumination of shared spaces, elevators, heat pumps, ventilation systems, antennas, water pumps, etc.). Moreover, the technical parameters (power of the boilers and heat pumps, sources of heat, volume of the hot water reservoirs, etc.) of all the systems already in place in the building and the dimensions of the potential spaces for installation of the different assets considered where collected.

5. The European use case

The European Use Case explores the impact of EU-wide and national policies on achieving the EU goals on climate change mitigation and energy efficiency.

5.1. Objective and Scope of the Use Case

Energy efficiency and decarbonization of the European building stock are considered as key drivers of Europe's transition to climate neutrality by mid-century, as part of the EU Green Deal and the Fit for 55 policy package. However, most analyses on emission reduction in buildings are based on large-scale models that do not include a granular representation of load profiles of energy consumers and do not model the specificities of different building types. To overcome these challenges, in this Use Case the WHY Toolkit will be soft-linked with the PRIMES modelling suite (especially PRIMES-BuiMo model), one of the most widely used and well-established models at EU and Member State level (Fotiou et al 2019). It has been used to provide quantitative model-based assessment of major EU energy and climate policies (Energy Efficiency directive, Fit for 55 package, "Clean Planet for All" strategy). A two-way interlinkage of the WHY Toolkit with the PRIMES-BuiMo model is implemented based on data interface and a disaggregation of PRIMES-BuiMo results to capture consumer differences, idiosyncratic behaviours and load profile granularity provided by WHY Toolkit. The Use Case offers quantitative evidence on different pathways to decarbonize the EU buildings sector by 2050, based on accelerated efficiency improvements, electrification, fuel switch, net-zero energy buildings and deep renovations, smart appliances, and demand-side management, to achieve climate neutrality by 2050. Based on detailed load modelling and consumer representation, the EU Use Case will re-assess various energy and climate policy instruments (as identified in the stakeholder workshop) consistent with the revised Energy Efficiency Directive, the Fit for 55 package and the EU's commitment to turn climate neutral by 2050. This Use Case will provide an improved understanding of the role of energy consumers towards the systemic transformations required to reach the EU Green Deal goals by exploring the effects and feasibility of climate neutrality in the buildings sector with unprecedented temporal and spatial granularity, while capturing system interlinkages between energy demand, supply, prices, grids, fuel mix, and storage.

5.2. Methodology

5.2.1. Brief description of PRIMES BuiMo model

The PRIMES-BuiMo model simulates the future development of the buildings sector (residential and commercial) in the EU Member States, projecting energy consumption, fuel mix, equipment choice, renovation rates, investment and CO2 emissions under alternative policy scenarios (Fotiou, T. et al., 2019). It focuses on the dynamic simulation of the renovation decisions and the choice of the energy depth of building renovation as well as on the choice of technology type to cover the energy end-uses. Market and non-market barriers are represented as well as hidden costs and perceptions affecting consumer behaviour together with a variety of policy instruments influencing decisions of individual and possibly removing barriers. PRIMES-BuiMo combines the detailed representation of economic behaviours with engineering aspects and technical constraints embedded in the integrated model-based decision framework. It includes a detailed database of many building classes and explicit energy-related technologies distinguished by type and vintage.

PRIMES-BuiMo splits the stock of buildings in many categories, by geographic locations, age of construction, income classes and service sector sub-sectors. This allows the simulation of the behavioural heterogeneity of energy consumers which depends (among others) on several factors, including income, preferences, weather, access to loans, location, and household composition. Instead of a single representative actor, the model includes a variety of actors with distinct behavioural patterns. Discount rates differ by income class with low-income classes typically facing higher discount rates, representing their difficulty to access to low-cost loans. Through the differentiation of discount rates based on real-world estimates, the model can address the drawbacks of the representative consumer assumption. Further modelling improvements are required especially on how consumer behaviour is represented, which factors influence the decisions of energy consumers, and how new markets and business models are integrated (e.g. prosumaging, distributed generation, smart appliances). The soft-link of PRIMES-BuiMo with the WHY Toolkit will enable an improved assessment of households' energy demand and a better representation of all the above factors while considering the complex interactions of energy demand, supply, fuel prices and investment dynamics.

The modelling of renovation is based on dynamic discrete choices, where heterogeneous agents choose the most cost-efficient renovation strategies. Dynamic strategies are endogenously determined in the model and may potentially involve renovation of building envelope, technical equipment selection, including electricity self-production equipment, premature replacement of equipment, and fuel switching. PRIMES-BuiMO estimates the useful energy demand by building type to be met by the purchase of energy products, which is then translated to the final energy consumed (keeping track of equipment vintages) by the space heating system. The choice of the space heating strategy depends on the timing and depth of the envelope renovation, while the strategy for hot tap water and cooking equipment depends on the space heating system. Keeping track of technology vintages, PRIMES-BuiMo determines the fuel mix for the technical building equipment and derives energy consumption by fuel, associated CO2 emissions, operating costs, and investment expenditures. Electricity use in households is also included based on the energy service to be provided and the selection of the type of technology to purchase to meet the desired level of energy use. The turnover of the stock of appliances is dynamic and endogenous to the model and is influenced by policy instruments and eco-design regulations.

Energy labelling and other policies are represented in the model and facilitate the uptake of highly efficient, yet more expensive, technology types through reducing the uncertainty and lack of information. PRIMES-BuiMo can represent various policy instruments including economic policies, regulatory instruments, taxes and subsidies for energy products, financial facilitation for renovation and purchase of low-carbon technologies, Information campaigns, eco-labelling of technical equipment, eco-design standards, Building code standards, Energy efficiency standards, carbon pricing (EU and national), white Certificates and targets for RES heating and cooling. Particularly for the residential sector, the model represents several market and non-market barriers, to improve the representation of the so-called “energy efficiency gap” (Fotiou, Capros, & Fragkos, 2022).

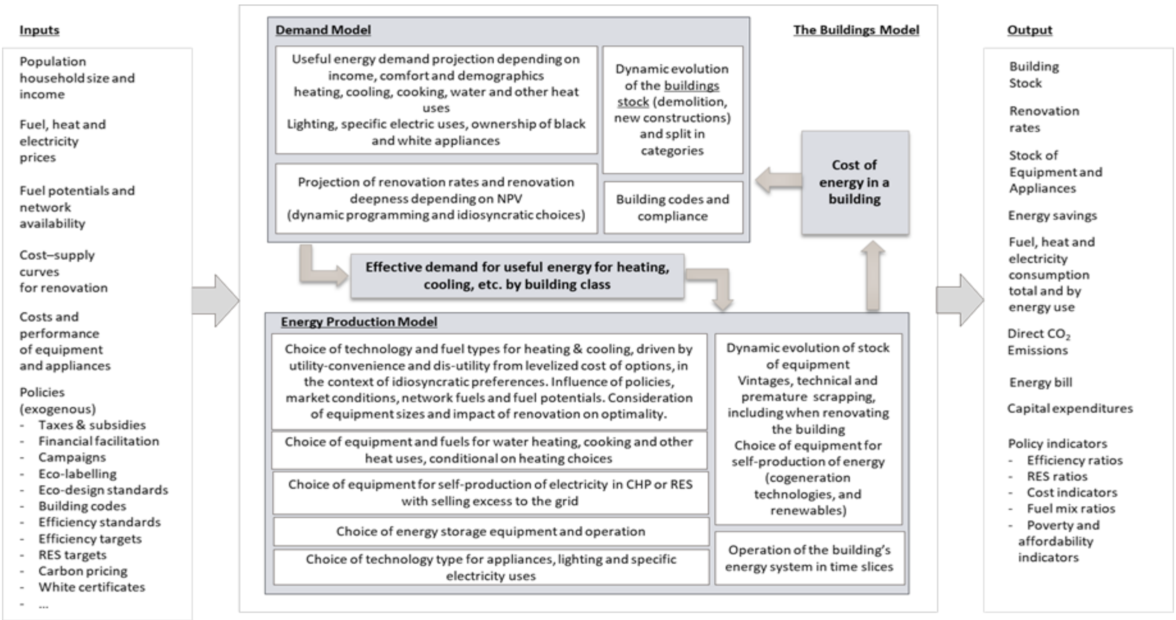


Figure 1: Flowchart of the PRIMES-BuiMo mod

5.2.2. Integration of behavioural transitions and lifestyle changes

Mitigation pathways consistent with the ambitious goals of the Paris Agreement (PA) often signify the role of behavioral changes to reduce emissions for sectors like transport and buildings. The IPCC 6th Assessment report confirms that demand-side strategies can reduce emissions across all sectors by 40–70% by 2050 (Creutzig et al., 2022). Thus, demand-side transformations can play an important role in Paris-compatible scenarios, alongside supply-side transformations (IPCC, 2014). The significant contribution of behavioural change in achieving decarbonization targets and wider SDGs is stressed by recent studies, such as the 1.5 °C warming report by the IPCC (Rogelj et al., 2018) and the Net Zero by 2050 report (IEA, 2021a, 2021b). As an example, Figure 2 shows that for the IEA’s net-zero pathway, about 24% of carbon dioxide (CO2) emission reductions in 2050, can be attributed to changes in behavior changes and energy efficiency.

Integrated assessment and energy-system models are central to climate-change mitigation research (Krey, 2014) and have been systematically utilized to assess potential trajectories towards meeting decarbonization goals (Levesque et al., 2021) and broad SDGs (van Vuuren et al., 2015). However, despite the strong evidence for the importance of demand-side transitions (Creutzig et al., 2016; Grubler et al., 2018), the representation of lifestyle changes in energy–economy models lack sophistication and theoretical and/or empirical validation, and it is mostly exogenous (Trutnevyte et al., 2019). As a result, while energy-system models adequately capture supply-side emission-reduction options (Iyer et al., 2015), they are often criticized for the limited insights they provide about consumer-side transitions (van den Berg et al., 2019). This prohibits a comprehensive analysis of the specific drivers and effects of behavioural change, as well as of the associated implementation barriers for policy. This is slowly changing recently through the emergence of new scientific evidence on the large contribution of lifestyle transformations towards meeting ambitious climate goals, and how these lifestyle changes can be represented in large-scale quantitative models.

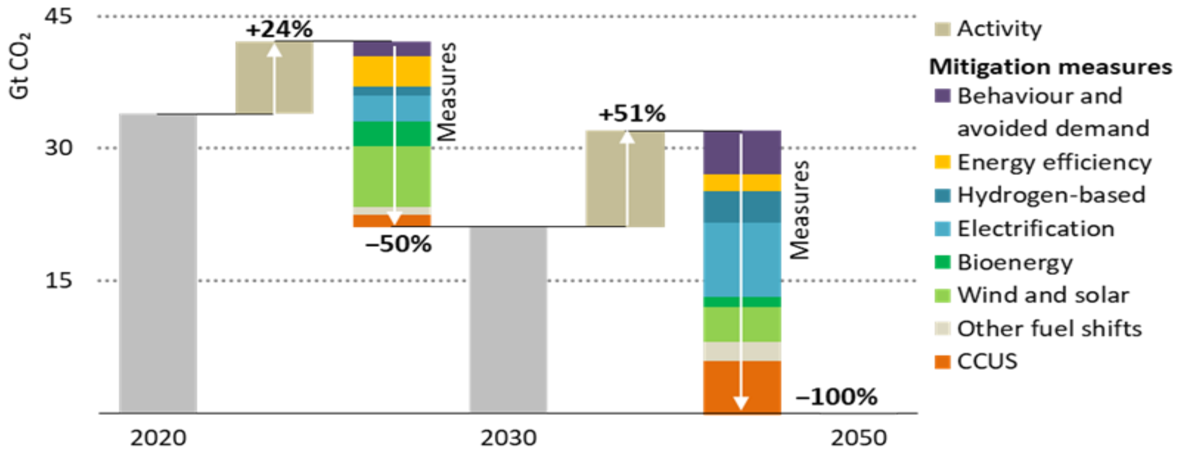


Figure 2: Decomposition of CO2 emission reductions in 2030 and 2050 by mitigation measure according to the Net-Zero emissions scenario of the IEA (International Energy Agency, 2021). CCUS: Carbon Capture, Usage, Storage.

Through a comprehensive literature review (which is presented in detail in the peer-reviewed article -Andreou et al 2022- included in the Annex 2), we identified the most common and important lifestyle transitions taking place in the transport and residential sector and developed a general methodological framework to integrate consumer-led transitions in energy-systems modelling, which is described below:

- "Avoid" actions: Several voluntary actions (listed in Table 1) can reduce service demand in the residential sector, especially through conserving hot water, residing in smaller dwellings, and adjusting thermostats for heating and cooling in buildings. Commonly "avoid" actions in the residential domain are not modelled explicitly in ESMs, but their effect on energy use is indirectly captured through adjusting relevant model parameters. For water-conservation measures, their impact is usually modelled by simply applying a reduction factor on the overall water-heating demand (25% in global studies (van Sluisveld et al., 2016; Van Vuuren et al., 2018; van den Berg et al., 2021), 10% in a US study for California (Yeh et al., 2016), based on the assumption that daily shower time is reduced. A more elaborate analytical approach was described in Levesque et al (2019): in addition to cutting down showering time, the authors assumed changes in the number of showers per person per day and showerhead flow rates, both reducing water-heating demand. Aside from showering, the authors investigated the impact of low-demand practices in clothes and dish washing by imposing assumptions about the number of wash cycles and temperature elevation. The household floor area is generally projected to increase as incomes grow across the globe in ESM-based scenarios (IEA, 2020). Limiting unnecessary floor area per capita through, for example, compact city and building designs, is represented by setting a cap on household areas in most lifestyle-led mitigation pathways (Costa et al., 2021; Cabeza et al., 2022) according to living standards in selected developed economies. Contrary to the customary approach, the authors of Le Gallic et al (2017) and Millot et al. (2018) established a statistical relationship between housing floor area and a set of factors, such as cohabitation practices and dwelling location, based on information from national surveys in France. The authors simulated the potential effects of lifestyle changes on household floor area, which were then fed as inputs to an energy-system model to analyse the wider effects. Finally, adjustments to the temperature at which consumers heat or cool their household because of changing habits has a direct effect on the energy demand for space heating and cooling. The most common approach to quantifying thermostat adjustments for heating/cooling in ESMs is to exogenously reduce/increase the base temperature based on which heating/cooling degree days are calculated (e.g., by 1 °C in van Sluisveld et al. (2016), van de Ven, et al (2018) and Van Vuuren et al. (2018)). Degree days are a measure of heat or cold stress, as they capture the daily deviation of the mean outdoor temperature from a pre-established baseline value (Mourshed, 2012). Rodrigues et al. (2022) estimated the heating-energy demand (using the PRIMES-Buimo module (Fotiou, et al 2019) via bottom-up calculations based on various factors, including U-values and the ventilation characteristics of building classes, encompassing indoor thermostat settings. However, none of the large-scale model assessments have used real-world data to assess the energy-saving potential of changing thermostat behaviours and potential rebound effects.

- "Circular economy" practices aim to increase the efficiency of resource use, without compromising the level of the provided service (Creutzig et al., 2022). The most common circular-economy measure studied in integrated assessment models is waste management and recycling, such as that of plastic (van Sluisveld et al., 2016), paper, metal, and organic waste (van de Ven, González-Eguino and Arto, 2018). Recycling occurs at the disposal phase of consumer goods, but its effect is propagated through the production output in industrial sectors, as the requirement for raw materials and products declines. Reductions in industrial energy demand are also achieved through the re-use of materials and by extending the life span of consumer goods (Girod, van Vuuren and Hertwich, 2014). The effect of waste management and recycling on GHG emissions is studied in large-scale ESMs by decreasing industrial production (e.g., lower activity in non-energy industries from reduced plastic demand (EC, 2018; Grubler et al., 2018; Fragkos, 2022).

The review showed that modelling tools, such as IAMs and ESMs, that are used systematically to assess climate policies and the potential of net-zero transitions, have often limited representation of lifestyle transitions, especially with regards to their drivers, implementation costs and true mitigation potential. Other challenges arise from the coarse representation of consumer groups and their behaviours in current models and the absence of a feedback mechanism translating sustained changes in energy and material use to economy-wide impacts.

When combined with energy efficiency, changing consumer behaviours are strong facilitators of (a) deep emission reductions in buildings and transport, (b) downsizing the scale of the investment required by supply-side transformations, and (c) progressing towards key environmental and socio-economic SDGs. Significant potential for emission savings in the residential sector stems from actions curtailing the demand for energy services, such as space heating and cooling, the most influential being *managing the demand for hot water*, *limiting the size of dwellings*, and *adjusting thermostats for heating and cooling.* Moreover, circular-economy practices, including *recycling* and *waste management*, are also effective ways to reduce the demand for energy. Energy system models typically capture lifestyle changes by using simplistic and aggregate approaches, which mainly involve ad hoc modifications to existing model parameters exogenously based on stylized assumptions without integrating theoretical insights, empirical evidence, or real-world data. These modifications can alter the behavioural dynamics embedded in the mathematical formulation of models by allowing the relaxation of specific model constraints (e.g., travel-time budget), applying caps on internal parameters (e.g., household floor area), or directly correcting end-user demand (e.g., useful water-heating demand). Furthermore, the treatment of lifestyle changes via simplified application of exogenous scenario-dependent assumptions that reflect only the average behaviour of consumers in a region poses inherent challenges to policy analysis:

Table 1 Summary of most important lifestyle changes for energy-system and IAM-based modelling studies for the transport and residential sectors.

Sector	Domain	Lifestyle Change Category	Most Important Lifestyle Changes
Transport	Mobility	Transport-mode shifts	• Shift from private cars to public transport (e.g., buses, railways) • Shift from airplane to high-speed trains (reduction in flights) • Shift to active modes of transport (cycling, walking)

		Shared-mobility practices	• Carpool commuting • Car-sharing schemes (mobility-as-a-service)
		Driving habits	• Eco-driving practices (e.g., lower speeds)
Residential	Thermal Comfort	"Avoid" energy-demand actions	• Conservation of hot water for showering, clothes, and dish washing • Adjustment of thermostat-temperature set points • Living in smaller dwellings
	Consumer goods	Circular economy practices	• Re-cycling, re-using, and extending the lifetime of consumer goods

- **Challenge 1**: The true cost of the transition to low-demand societies cannot be reliably estimated, as the costs to overcome behavioural, and infrastructural and institutional lock-in effects and barriers through policies are not quantified (Ivanova *et al.*, 2020).
- **Challenge 2**: Large-scale models with long time horizons often have a coarse representation of consumer groups and their decision-making process and thus they do not capture consumer heterogeneity (Keppo *et al.*, 2021). Ignoring consumer heterogeneity when studying social phenomena prohibits the assessment of responses for different consumer groups (based on different income classes and locations, for example), and the effect of interactions between different groups (through social learning, for example). Recent assessments have updated and expanded modelling frameworks to overcome some of these caveats, e.g. in the PRIMES-BuiMo model (Fotiou, Capros and Fragkos, 2022).
- **Challenge 3**: Demand-side transitions can shift consumption patterns for services and materials (such as people buying fewer cars due to carpooling and the provision of fewer household devices due to extended product lifetimes), which affects both the demand for (and production of) industrial products and the overall economic growth. Lifestyle changes will shift the economic activity from carbon-intensive sectors to services that could offer new, high-quality jobs to support future digitalization and green growth (Grottera *et al.*, 2020; Costa *et al.*, 2021).

In order to consistently address all the above challenges of current modelling frameworks, the PRIMES-BuiMo model is further developed and enhanced in the EU Use Case to better reflect behavioural changes in the EU residential sector, based on a detailed integration of bottom-up data through the soft-link with the WHY Toolkit and the representation of consumer heterogeneity multiple building types and income classes in the EU Member

States. The next section presents the methodology used in the EU Use Case to improve the representation of consumer behaviour in the PRIMES-BuiMo model.

5.2.3. Methodology used in the EU Use Case

As described in the section above, PRIMES-BuiMo splits the stock of residential buildings in many categories, by geographic location, age of construction, type of building and income class. To integrate the data from the WHY Toolkit in PRIMES-BuiMo, an interface has been created that matches the categories of buildings in PRIMES-BuiMo to building categories that have been simulated with the WHY Toolkit. To that end, building typologies included in the international research project **TABULA** have been considered.

For each of the building categories, which are included in the interface to integrate the data from the WHY toolkit to PRIMES-BuiMo, there will be provided the unit energy consumption (in terms of final energy consumption in kWh/building) by end-use and energy carrier, in two contexts: in the first context the end-user energy prices will have "normal" or "baseline" values, whereas in the second context the end-user prices will have increased values. Using data for each building category in the two price contexts as explained before, there will be defined a relationship regarding energy consumption behaviour of each building category relative to the average building and how this is influenced by the increased energy prices.

PRIMES-BuiMo represents the market and non-market barriers as well as hidden costs and perceptions affecting consumer behaviour together with various policy instruments influencing decisions of individual consumers and possibly removing barriers. Based on the relationships defined through the data from the WHY-Toolkit for each building category, the modelling parameters representing market and non-market barriers will be modified so that PRIMES-BuiMo can reproduce more realistically the actual consumer behaviours assessed in the WHY Toolkit. Below we give examples of modelling parameters that will be modified in the context of data integration from the WHY Toolkit to PRIMES-BuiMo and potential barriers.

Market barriers include hidden up-front investment costs, as well as the difficulty of households to access capital funding (i.e., high interest rates for loans). Hidden up-front investment costs are not directly related to material or labour costs but are nonetheless true payable costs. In the case of the renovation of the building envelope, these include costs incurring to avoid disturbances to neighboring flats, complicated waste removal, or the requirement for internal insulation work in multi-story buildings. The cost accounting should further consider high investment costs for very old houses, for which the status of the buildings' structure is uncertain. Similarly, historic buildings, particularly in urban areas, also entail very high costs due to renovation constraints resulting from architectural guidelines and other limitations. In the case of remotely located buildings, the additional transportation costs of the materials (and possibly labour) to the remote locations should also be considered in the cost accounting.

Hidden up-front investment costs are also considered for the consumer decision about heating and cooling systems. They include installation costs, which involve not only labour and material costs but also costs related to the transition from the already installed technology to the new one (i.e., drillings in case of geothermal technologies, chimney availability when fuel switching, new radiator or pipe construction work for the installation of heat pumps, etc.).

The non-market barriers can broadly be split into two categories: a) (lack of) information and knowledge, and b) technical and regulatory uncertainty. Lack of information, low accuracy of available information, lack of incentives to gather the necessary information, lack of knowledge or capacity to draw correct conclusions (i.e., about future energy savings), as well as asymmetric information (sellers vs. buyers) are important features often observed in case studies related to energy efficiency. Technical and regulatory uncertainty stems from the unknown and uncertain evolution of energy prices and technological costs in the future and the uncertain performance of the investment and technologies. Furthermore, there is generally a reluctance by consumers to invest in new technologies that are not yet fully mature or have limited market penetration due to the low "imitation factors" (Fotiou, Capros, & Fragkos, 2022).

5.3. Inputs to the modelling framework

5.3.1. External variables

The future development of exogenous input assumptions and external variables influences the model-based projections for endogenous variables. In the EU Use Case the main input variables are: a) Socio-economic developments (GDP, population, household income, household size), b) prices of energy products and potential carbon taxes, c) Assumptions on technology costs and performance (e.g., heat pumps, boilers, storage etc.), d) climate related parameters (e.g., Heating and Cooling Degree Days), e) energy and climate policies and targets, f) Parameters influencing technology adoption (e.g., fuel potentials, network availability, renovation costs, discount factors). The current section provides the quantitative projections for the main exogenous drivers, which are largely based on the EC Reference scenario 2020 (European Commission 2021).

The macroeconomic outlook provides the framework projections on how the European economy will evolve in the coming decades and offers a view of the future development of the European economy by sector. The macroeconomic outlook builds on recent demographic and economic projections for the EU countries provided by Eurostat and the joint work of the Economic Policy Committee and the European Commission. The impacts of the COVID-19 pandemic are reflected in the socio-economic projections for Europe as well as in the sectoral composition of GDP.

According to EUROSTAT projections, the EU population is projected to slightly increase until 2030 and then decline in the long term. However, there are differences between national population trends, as in several EU Member States the population is projected to increase by 2050. The old-age dependency rate, i.e. the ratio between people aged above 65 years and those aged between 20-64, is projected to continue rising sharply by 2050 influenced by the dynamics of fertility, life expectancy and migration. The GDP projection is based on the European Commission's 2021 Ageing Report and the Spring 2021 Economic Forecast and includes the short-term effects of Covid-19, especially in sectors like aviation and tourism facing the largest impacts. The macro-economic projections are highly uncertain both due to potential new outbreaks of COVID-19 and the trends emerging regarding remote work, fewer business trips and changes in global supply chains (European Commission 2021), but also due to the Russian war in Ukraine and the energy crisis. In the medium and long-term, European GDP is projected to constantly increase with an average annual growth rate of 1.5% per year.

The shares of major components of EU GDP are projected to record minimal changes by 2050. Current trends continue with high and increasing shares of private consumption (increasing from 54% of EU GDP in 2015 to 56% in 2050), followed by investments (representing about 22% of EU GDP in 2050) and government consumption. The contribution of government consumption to the EU's GDP is projected to marginally decline, reflecting adjustments in the aftermath of the COVID-19 crisis and contraction of government spending. Trade surplus with non-EU regions continues to account for about 2%-3% of the EU GDP in the next decades.

In terms of sectoral composition, the services sector is projected to dominate the economic activity generating about 70% of EU's GDP by 2050. Industry and construction are projected to decline slightly by 2030 and more so by 2050 due to structural shifts in the economy and reduced investments resulting from lower economic growth. Industries linked to construction, such as cement, record improvements in sectorial activity to 2050. Energy-intensive industries maintain their shares in gross value added over time. The share of the fossil fuel sector is projected to decline as a result of energy efficiency improvements and the implementation of climate policies.

The cost development of technologies relevant for the buildings sector is provided exogenously, namely for heating and cooling equipment, electric appliances, and the renovation of buildings' envelope. In the modelling framework, the decisions of consumers related to the purchase and use of appliances, technical building system equipment and heating technologies largely depend on the relative total costs of the competing options and energy forms. The total costs are driven by the evolution of technology purchase costs, the prices of energy products, the technology efficiency, and the potential carbon emission costs. In the Reference scenarios, the technical and economic characteristics of technologies and appliances related to the buildings sector change over time driven by economies of scale and learning-by-doing effects. In the EU Use Case, the techno-economic assumptions incorporated in the modelling framework have been revised following recent literature research. The Figure 3 below presents the future development of the purchasing costs for heat pump technologies in the EU.

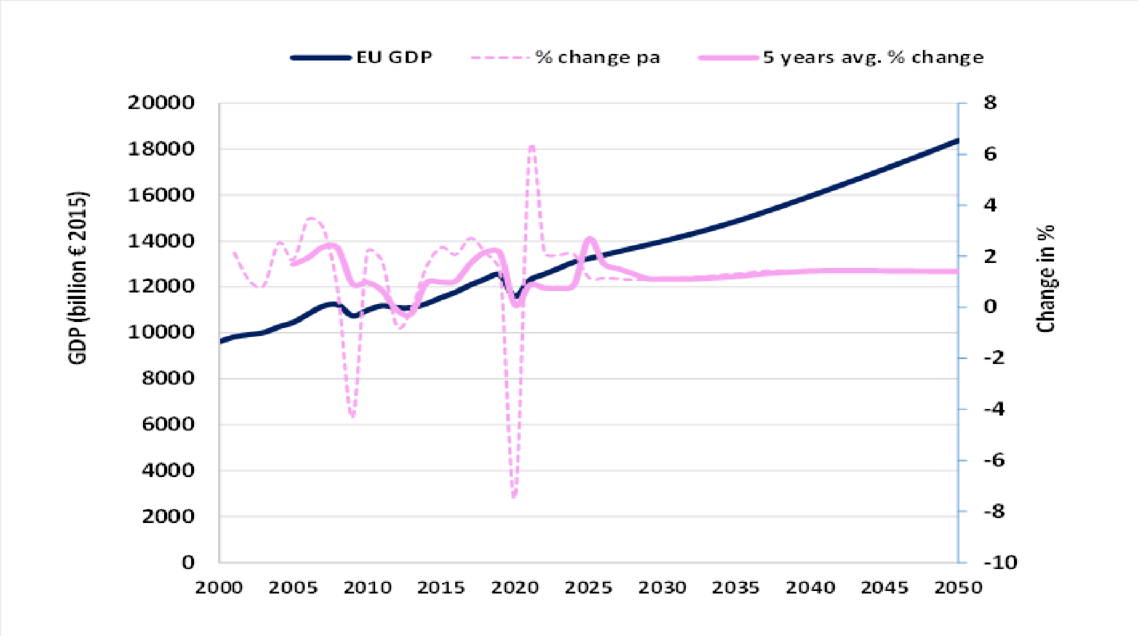


Figure 3: GDP projection for the EU, Source: European Commission 2021

The cost development of technologies relevant for the buildings sector is provided exogenously, namely for heating and cooling equipment, electric appliances, and the renovation of buildings' envelope. In the modelling framework, the decisions of consumers related to the purchase and use of appliances, technical building system equipment and heating technologies largely depend on the relative total costs of the competing options and energy forms. The total costs are driven by the evolution of technology purchase costs, the prices of energy products, the technology efficiency, and the potential carbon emission costs. In the Reference scenarios, the technical and economic characteristics of technologies and appliances related to the buildings sector change over time driven by economies of scale and learning-by-doing effects. In the EU Use Case, the techno-economic assumptions incorporated in the modelling framework have been revised following recent literature research. The figure below presents the future development of the purchasing costs for heat pump technologies in the EU.

Assumptions on the renovation costs for building envelopes depend on the building type, the depth of such renovation and the climate zone. In the modelling framework of the EU Use Case, we consider the investment costs for buildings' renovation which are the energy related expenditures needed for an energy renovation of a building envelope – without considering renovations performed for other purposes (structure, decoration etc.).

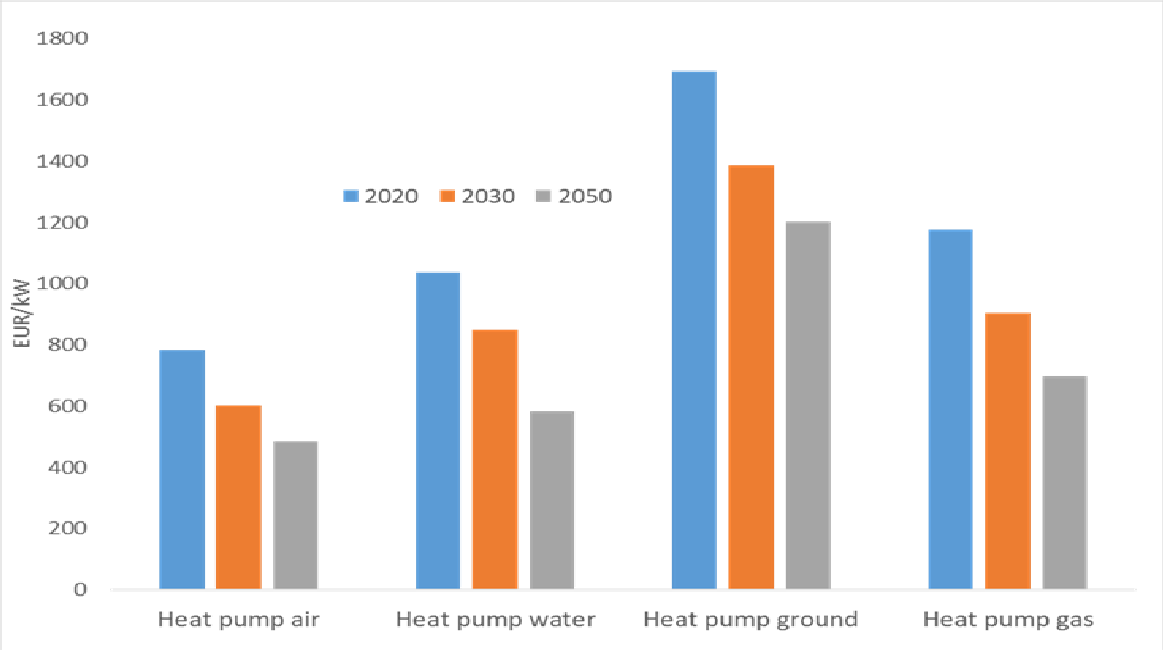


Figure 4:Purchasing costs for heat pump technologies.

The decision making of individual agents in the buildings sector is also influenced by the assumed valued of private discount rates. This is especially the case for a household, or a small enterprise deciding to purchase and install a low-carbon heating system or renovate a building shell, as the balance between upfront investment costs vs long-term operating and maintenance costs is a decisive factor in their decision. Agents' economic decisions are commonly based on the concept of cost of capital. Depending on the sector, this is either the weighted average cost of capital (for larger firms) or a subjective discount rate (for individuals or smaller firms). In both cases, the rate used to discount future costs and revenues involves a risk premium which reflects various risk factors and the cost of lending from banks. In the buildings sector, the discount rate for households also reflects risk averseness as consumers tend to prefer technologies with low upfront investment costs (and relatively higher operating costs). The discount rates vary across sectors, income classes and types of investment. In the European Use Case, we use discount rates of up to 14% for the decision making for buildings renovation of household with higher discount rates for low-income classes that commonly face large funding challenges.

In the PRIMES modelling framework employed in the EU Use Case, electricity and fuel prices are calculated in such way that allows recuperating all costs, including both capital and operating expenditures, but also costs related to renewables support polies (e.g., feed-in-tariffs), costs for the transmission and distribution grids, charging infrastructure for EVs and investment costs including stranded investments, back-up, and reserve costs as well as profit margin. Electricity prices are differentiated by sector reflecting differential load profiles, generation, and grid costs. The average electricity price of households is projected to modestly increase until 2030, due to the increasing price of gas and carbon taxes that impact the costs of fossil-fuel-based electricity producers and the higher grid costs due to infrastructure development to support grid expansion to facilitate expansion of variable RES and new interconnections. Fossil fuel products (e.g., natural gas, diesel oil, LPG) see increasing prices until 2030 and 2050 driven mostly by increasing international import prices in the absence of strong global climate action assumed in Reference scenario. The recent short-term increases in energy prices, especially for gas, electricity, and oil, as a result of the energy crisis are not included in the Reference scenario but will be fully considered in the policy scenarios of the EU Use Case described below.

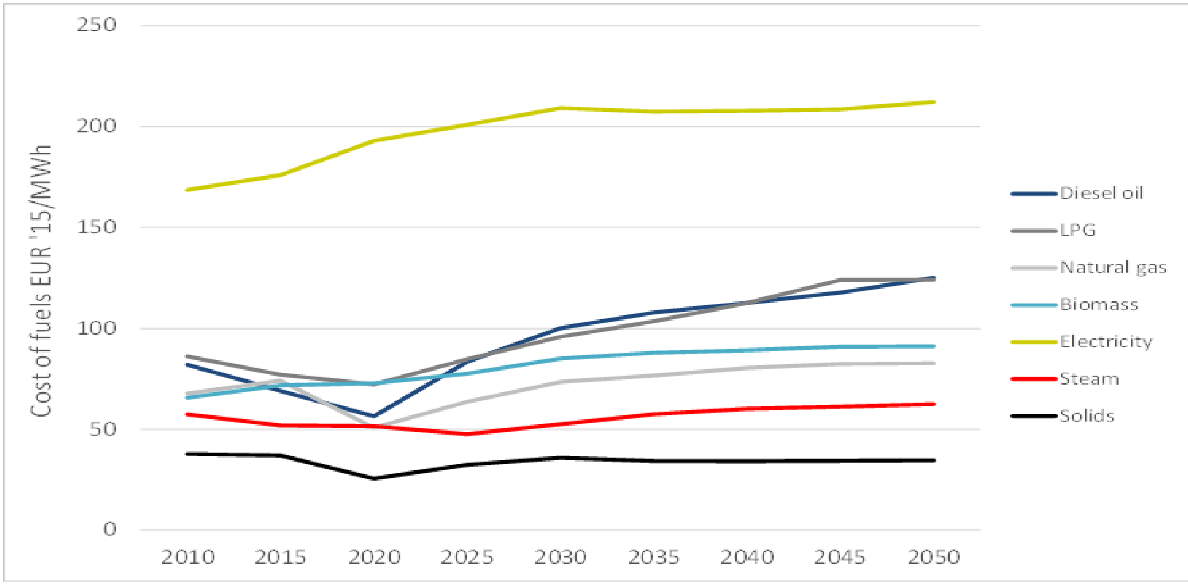


Figure 5:Average end user price for fuels in the residential sector, Source: European Commission 2021

The Reference Scenario builds on a series of already adopted energy and climate policies at EU and Member State level, assuming that their implementation intensifies until 2030 in line with the current legislative provisions. After 2030, the implementation of these policies continues but no additional measures apply in the period between 2030 and 2050. The most important EU policies include the directives and regulations included in the "Clean Energy for All Europeans" package, the revised EU ETS Directive, the Energy Efficiency and the Renewable Energy directive and major transport policies, including CO2 standards for vehicles, the Directive on alternative fuels infrastructure, the Clean Vehicles Directive, etc.

With regards to energy efficiency, the EU Use Case includes relevant European and national policies, including the Energy Labelling regulation, the Ecodesign directive, the revised Energy Efficiency Directive (EED) and the revised Energy Performance of Buildings Directive (EPBD). The Reference scenario of the EU Use case incorporates the level of ambition of the national contributions as set out in the National Energy and Climate Plans (NECPs). Eco-design standards are considered for the entire spectrum of technologies, particularly to define the standards and the transition from "ordinary" to "advanced" or "best available" technologies. The EED energy savings obligations in the buildings sector are implemented in the PRIMES-BuiMo in the form of energy efficiency values, acting as a virtual subsidy that makes energy saving investment more profitable for decision-makers, and inducing accelerated building renovation efforts, energy audits, deployment of energy management systems, consumer advice for best practice in energy efficiency, targeted energy efficiency education, significant voluntary agreements, etc. In the PRIMES BuiMo model, building codes are explicitly introduced reflecting the relevant regulations for new buildings as well as for major renovation of existing buildings, in line with the EPBD.

5.3.2. Internal variables

The Reference scenario of the EU Use case provides projections for the EU27 Member States and is based on the current modelling set-up, before the modelling enhancements to be realised in WHY and the soft linkage with the WHY Toolkit. The Reference Scenario is a projection on the future developments of the EU economy, energy system, transport and emissions based on current policies and market trends that acts as a benchmark to compare future policy measures and initiatives and their energy and economic impacts by 2030 and 2050. The scenario includes the key adopted and currently implemented EU and national policies, as discussed above. The major policies include: 1) A core target of at least 40% reduction in domestic greenhouse gas (GHG) emissions in 2030 compared to 1990 levels, 2) The share of renewable energy in total gross energy consumption should be at least 32% in 2030 (in line with the EU Renewable Energy Directive), 3) Increased energy efficiency improvements to at least 32.5% in 2030 (in line with the EED provisions) making use of the tools foreseen in the Governance Regulation. The scenario reflects the outcomes of adopted EU and national policies but assumes no intensification of current policies or development of new policies fostering the uptake of renewable energy, energy efficiency and clean fuels beyond 2030.

In the Reference scenario, energy demand is projected to decouple from income growth after 2020 triggered by accelerated efficiency improvements due to the implementation of the Energy Efficiency Directive, national renovation strategies and policies included in NECPs. These policies have an impact after 2030 as well, causing further decline in the energy demand in buildings, but at a slower pace in the absence of additional policies. Space heating requirements are projected to decline due to energy efficiency improvements, renovation strategies, and the gradual uptake of more efficient space heating equipment. The shares of water heating and cooking uses in useful demand are projected to remain rather stable, while cooling requirements increase driven by higher temperatures and climate extremes (due to climate change) and the increase in household income, which lead to higher penetration of cooling equipment. The stock of electric appliances is projected to constantly increase driven by income growth in EU countries, while the growth is particularly high for Information and communication technologies due to increased digitization. However, technology advancements will continue resulting in further efficiency improvements.

The fuel mix used in residential buildings shows a large shift driven by the reduced shares of gas, coal and oil products, from 48% in 2020 to only 30% in 2050. The reduced contribution of fossil fuels is replaced by the increased electrification of households' energy consumption which is projected to increase from 25% in 2020 to 35% in 2050, driven by the increased use of appliances and the uptake of heat pumps, facilitated by technological progress and efficiency measures (European Commission 2021). Heat pumps are prioritized in cases where deep renovation is pursued, or where buildings are highly insulated. Renewable shares increase modestly by 2050, mainly due to support measures for solar thermal and biomass boilers and air pollution policies.

Historically, demolition and construction rates are very low in the EU, implying that achieving large energy savings highly depends on the renovation strategies for existing buildings. It is expected that the implementation of the EED and EPBD regulations will increase the depth and rate of renovation relative to current levels. The EU-wide renovation rates have been on average below 0.8% per year, but the first stream of energy efficiency policies increased this rate, and current policies are expected to boost it further to about 1%-1.2% per year by 2030.

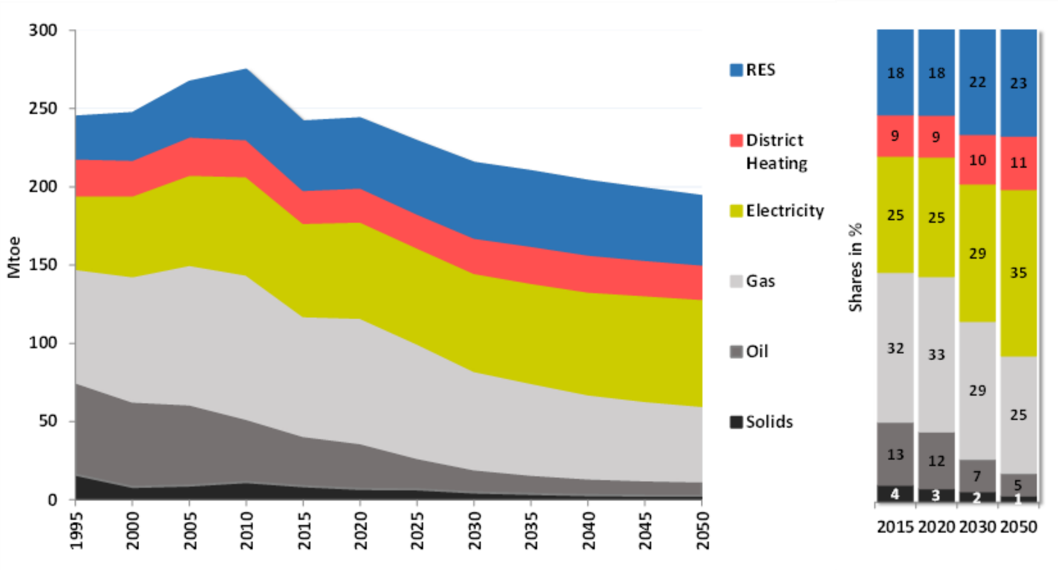


Figure 6:Residential energy demand by fuel, Source: European Commission 2021

5.4. Description of scenario design

In the last decades, the EU is actively implementing ambitious climate policies, aiming to mitigate climate change by reducing its domestic GHG emissions and fossil fuel consumption, while boosting economic growth and protecting societal and environmental sustainability. The EU climate policy framework is based on four main pillars, including: ambitious emission reduction targets for 2030 and 2050, promotion of energy efficiency improvements in all sectors, enhanced ambition for uptake of renewable energy, and carbon pricing through the EU Emission Trading System (ETS). The targets for emission reduction, energy efficiency and renewable energy are strengthened even more in recent years, especially though the Fit for 55 package, setting more ambitious climate goals. These targets and strategies are accompanied by specific policy options and instruments, which are commonly included in EU and national legislation in the form of directives (e.g., EU ETS or Energy Efficiency Directive-EED). Of special relevance to the residential sector is the amended in 2018 EED and its recent (July 2021) proposed update where buildings and the heating and cooling sector are recognized as the sectors with the highest potential for energy savings. In addition, the EC Regulation 2019/2021 laying down eco-design requirements is important to the white, grey, and black appliances used in households.

In order to co-design a set of policy relevant scenarios on the potential transformation of the EU buildings sector, we contacted a diverse group of stakeholders including policy makers, business associations, research institutes, consumer organizations and more. A dedicated workshop was organized to collect feedback from the various stakeholders focusing on policy interventions and technology options to drive the transformation of the buildings sector towards climate neutrality. The aim of the discussion was to prioritize the most important policy interventions and transition options relevant for reducing emissions from the EU's built environment. The process and insight from the stakeholder workshop are documented in detail in WHY Deliverable D1.3. Here we focus on how these insights can be translated into alternative policy scenarios for the EU Use Case.

The discussions held in the stakeholder workshop illustrated that the two most important options to drive the EU buildings' transformation are energy efficiency (including renovation of buildings and potential behavioural changes) and electrification of end uses, mostly through the increased uptake of heat pumps and the phase-out of combustion appliances. The stakeholders provided insights on policy measures and interventions to accelerate the rate and deepness of renovations including regulatory, economic, financial, innovation, educational and informative measures related to buildings' energy performance, electrification, and socio-economic issues (e.g., energy poverty). They include the Energy Performance of Buildings Directive (EPBD) and the Energy Plus building standards, complemented by mandatory efficiency standards, targeting renovations for energy poor households, and training schemes for renovation professionals. The stakeholders also addressed the industry knowledge gap, financing schemes, consumer awareness and one-stop-shops, and the split incentives between tenants and owners. Interventions like subsidies or other financial incentives can be used to reduce the low-carbon technology costs and design ambitious building codes standards. The figures below present the actions and interventions proposed by stakeholders to improve the performance of buildings and accelerate electrification.

Building on these insights, the policy interventions were prioritized based on their effectiveness and implementation barriers, related e.g., to social acceptance, technology availability and potential ramp-up, governance, policy, and institutional barriers. The analysis showed that the adoption of a carbon pricing scheme for buildings and the provision of targeted subsidies can accelerate the transition of the buildings sector. On the other hand, stakeholders disagreed about tax breaks since these were viewed as less effective and more difficult to implement than many other interventions. In addition to economic-based instruments, the experts mentioned that information resources will play a complementary role, as information campaigns are very effective for reducing energy consumption, but due to the implementation barriers, they need to be paired with other policy instruments. Regarding electrification, stakeholders mentioned economic, regulatory, and information-based measures, but focused on subsidization to reduce electricity prices, address the tax imbalance between electricity and fossil fuels in several EU countries and minimize the distributional effects of the clean energy transition. The regulatory interventions focused on banning combustion appliances and encouraging standards and market design. The information interventions concentrated around public information campaigns and encouraging training and communication regarding new technologies, like heat pumps, and new flexibility solutions, like demand response. Overall, stakeholders suggested that economic interventions (e.g., subsidies, carbon pricing) should be combined with information-based and educational interventions towards an effective policy package to empower citizens to gain buy-in to the energy transition demonstrating the need for Energy System Models (ESMs) to improve the representation of these aspects, which is the focus of the WHY project.

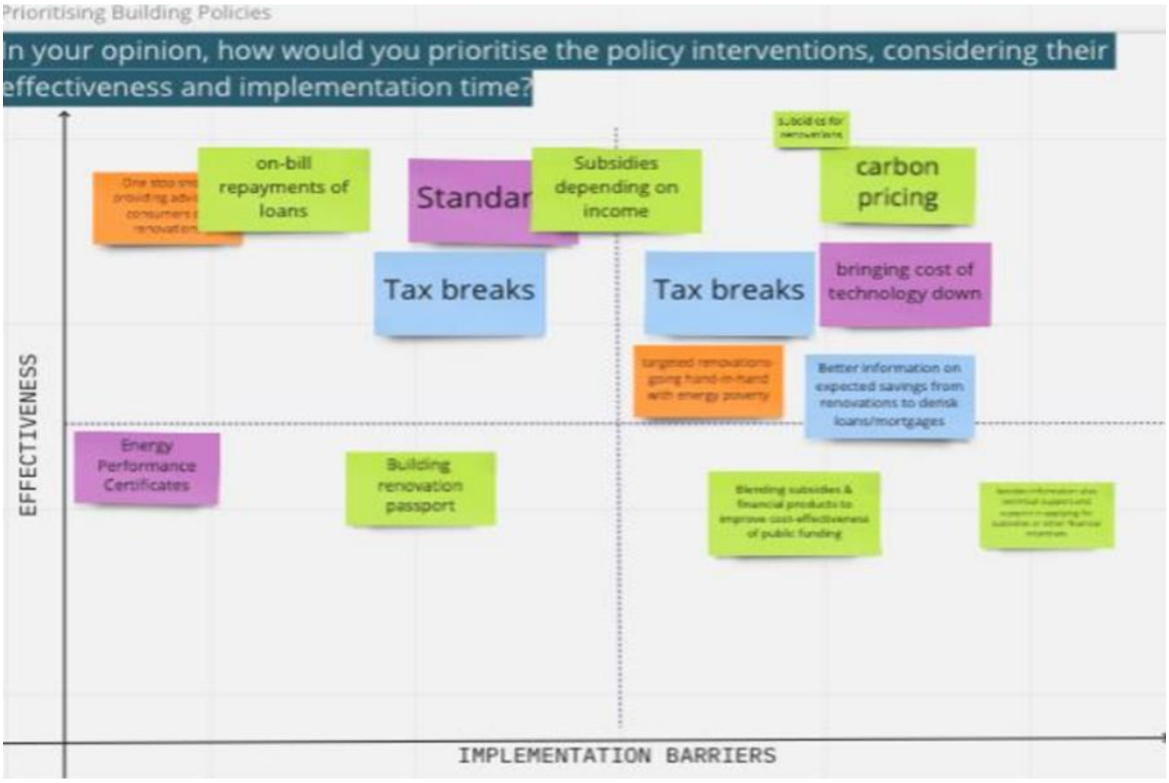


Figure 7:Prioritisation of policy interventions for the performance of Buildings

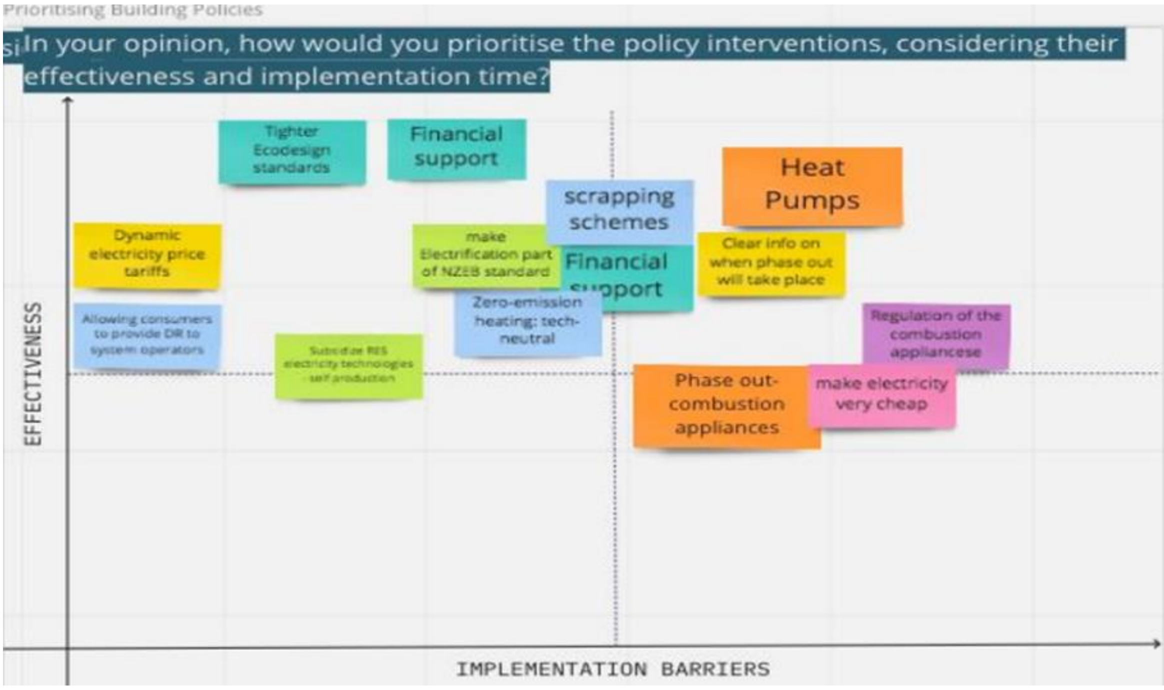


Figure 8:Prioritisation of policy interventions for Electrification of buildings

5.5. Identification of the key policy interventions to be explored in the EU Use Case

The discussions at the workshop with the invited stakeholders provided valuable insights for the definition and development of the European Use Case with energy and climate experts and policy makers developing an improved understanding and prioritising the energy policy aspects to be considered in the European Use Case. There are numerous political issues to be included in the energy demand modelling and prioritizing them is a challenging task, where also the modelling capabilities should be considered. Through the stakeholder workshop and our research expertise, we identified the most relevant regulatory, economic, and information-based interventions to be assessed in the EU Use Case. Policy instruments such as subsidies or other financial incentives (e.g., low-cost renovation loans) should be examined together with the enforcement of stringent building codes and energy performance certificates as well as measures to raise citizen awareness through informational campaigns and improved technical support.

Regarding electrification, the focus is on the potential uptake of heat pumps to electrify heating demand, while the tax imbalance between electricity and fossil fuels in several EU counties should also be addressed. On top of that, regulatory interventions for the gradual phase out of combustion appliances, uptake of heat pumps and the further encouragement of efficiency standards will be assessed. The complementary nature of information-based policy instruments will be added to the interventions studied, while the transition impacts on the most vulnerable population groups will also be considered, through targeted policy instruments.

The first set of scenarios to be analysed in the EU Use Case are presented in Section 5.5 below. These scenarios are used to validate the behaviour of the model under exogenously imposed assumptions, including changes in carbon prices or energy prices (Harmsen et al 2021) or changes in policy settings towards enabling ambitious decarbonisation of the European building stock (including a combination of carbon pricing with strong regulatory, institutional and informational measures). The detailed description of these "diagnostic" scenarios and some model-based results using PRIMES-Buimo can be found in Section 5.5. These scenarios will be enriched to cover additional policy instruments (both economic and regulatory but also informational based) and dimensions and will be presented in detail in the next WHY Deliverable D5.2 using also the new advanced modelling capabilities with the soft-linking of PRIMES-Buimo with the WHY Toolkit.

5.6. Validation methods

The PRIMES-Buildings Model (PRIMES-BuiMo) covers in detail the residential and services sectors for each EU country separately, segmenting the buildings into many categories, to account for the different energy efficiency potentials, consumer behaviors, and the implications for costs and energy savings. The main strengths of PRIMES-BuiMo that will be explored in WHY project are:

- the high-resolution segmentation of consumers into many classes considering the key factors influencing the decisions of individuals, including income, geographic, and other dimensions, as well as the classification of building types by age, the number of families, and other criteria.
- the (explicit or implicit) representation of the market and non-market barriers hampering energy efficiency investment, through specific parameters; market barriers are related to "true" costs (that are actually paid by consumers), and issues related to the access to capital resources, whereas non-market barriers refer to elements that do not have a direct payable or "true" cost and are often termed as "perceived costs [1]".
- the rich representation of policies to remove the various market and non-market barriers and facilitate energy efficiency investment. PRIMES-BuiMo can simulate a wide variety of policies and measures for the buildings sector, ranging from financial incentives (subsidies for building retrofits, loans) to institutional incentives that act as facilitators of investment, and even hard regulatory instruments (minimum efficiency standards, building codes)

To explore the features of PRIMES-BuiMo and assess the behaviour of the model under changing exogenous assumptions, we have designed six scenarios within the EU use case, the modelling results of which will be presented below. The scenarios have been designed in such a way to not only explore the possibilities of the PRIMES-BuiMo, but also to showcase how the data from the WHY toolkit is valuable to further develop and enhance PRIMES-BuiMo. In the current deliverable we present a first set of modelling results for the six diagnostic scenarios with the current model version. (i.e., before the integration of the data from the WHY toolkit through the energy model plug-ins (Task 4.4)). There will be a second round of modelling results for the same scenarios after the concrete integration of the WHY Toolkit- these results will be presented in detail in D5.2. The soft-linkage of PRIMES-BuiMo with the WHY toolkit means that specific parameters of PRIMES-BuiMo that represent behavioral aspects (e.g., "perceived" costs) will be revised based on new WHY data, so as to reflect actual behaviors of consumers more realistically. After the revision of these modelling parameters, the modeling framework will re-run for the same set of scenarios and possibly additional ones, and the results will be compared with the current scenarios to demonstrate the improved model capabilities after the integration with the WHY Toolkit.

The scenarios assessed within the EU Use case will lead to an improved understanding of system-level implications of enhanced energy efficiency and electrification in EU buildings in the context of ambitious EU climate targets by mid-century. The main outcomes of this scenario exercise are a set of medium and long-term projections of key energy-economy-emissions indicators that describe the future development of the EU buildings sector under alternative scenarios. These indicators include (among others): final energy consumption, energy mix in the EU buildings sector, CO2 emissions, uptake of low-carbon technologies (e.g., heat pumps), renovation rates, energy and carbon prices, investment requirements and total system costs.

Two set of diagnostic scenarios are presented within the EU use case. The scenarios are designed to explore two policy contexts: i) an "existing framework" context (i.e., a low energy efficiency ambition reflecting the Reference scenario assumptions) mirroring the NECPs and already adopted policies in a stylized manner and ii) a "Decarbonisation" context meeting upscaled targets in 2030, including the -55% GHG emission target and specific, more ambitious targets for energy efficiency and renewable; also leading to climate neutrality in the EU by 2050.

The "existing framework" context incorporates all policies and measures included in the national plans, including the NECPs and Long-Term Renovation Strategies. It is assumed that the Member States (MS) achieve their national climate targets for 2030, mainly their national energy efficiency and renewable targets. The combined implementation of the national targets would lead to primary energy savings in 2030 relatively in line with the EED energy efficiency target of 32.5% compared to the respective year of PRIMES 2007 baseline projection. The "Decarbonisation" scenario reflects a policy context that includes more ambitious market- and regulatory-based measures aiming at achieving the 55% GHG emission reduction target for 2030 and leading to climate neutrality in 2050. It assumes a high increase in the ambition of energy efficiency and renewable energy policies. The "Decarbonisation" context is in line with the "Fit For 55" policy package and aims at reducing domestic EY GHG emissions by at least 55% by 2030 relative to 1990 levels, while reaching

40% renewable energy share in gross final energy consumption in 2030 and achieving an overall reduction of 36-39% for final and primary energy consumption by 2030.

The scenarios include a large set of specific current and future policies (e.g., policies to promote the renovations of buildings, obligations for renewable fuels in Heating & Cooling, support for the electrification of heating, etc.). The decarbonisation context includes also assumptions that a variety of regulatory and non-regulatory policies facilitate the transition and the achievement of the upscaled targets supporting the uptake of new clean technologies and the corresponding investment undertaking. The enabling conditions also bring cost benefits by pulling technology along the learning curves.

In each one of the policy contexts ("existing framework" and "Decarbonisation") three diagnostic scenarios are designed and developed within the EU use case:

1) In this set of scenarios, it is assumed that only specific current and future policies will enhance energy efficiency and electrification in EU buildings. In addition, in the decarbonisation context the scenarios incorporate institutional and informational measures to remove the non-market barriers to investment in deep refurbishment of the building envelope and uptake of heat pumps. The measures tackle technical uncertainty, lack of information, inability to access funding, and other institutional issues. Such measures may include education and information campaigns, adaptation of building regulations, certification, third party financing systems, the obligation of energy companies to assist energy saving investment, and others. We consider that the institutional and informational measures constitute conditions enabling consumers using reasonable discount rates in the investment decisions in energy efficiency while minimising hidden and perceived costs. Thus, the enabling conditions can accelerate investment in deep refurbishment above the "existing framework" trends.
2) It is assumed that there is an extension of carbon pricing in non-ETS sectors (i.e., buildings sector) that acts as an explicit policy instrument and complements the bottom-up renewables and energy efficiency policies, as well as the enabling conditions of the first scenarios. The carbon price is defined exogenously and increases linearly by USD 15 per year, reaching USD 300 in 2040, and USD 450 in 2050. (Figure 9)
3) To reflect the current energy crisis and the drastic reduction of Russian gas imports to the EU, international energy prices increase drastically in 2025 and to a smaller extent in 2030 and onwards. The high energy prices act on top of the scenario assumptions described above, namely the enabling conditions as well as on the carbon pricing in non-ETS sectors. (Figure 10)

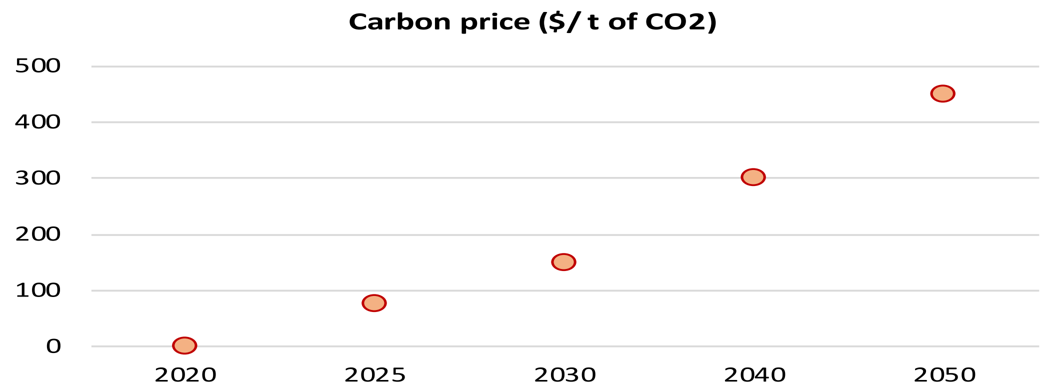


Figure 9: Exogenous carbon prices applied in the buildings sector.

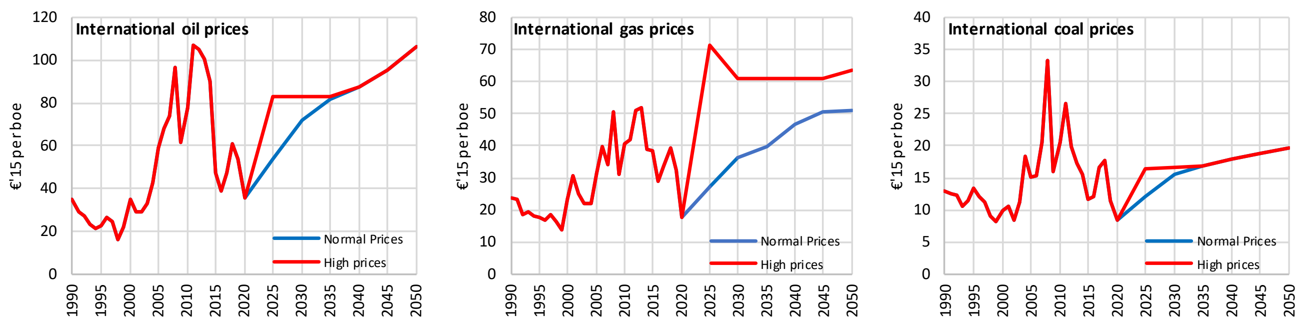


Figure 10:International oil, gas and coal prices projections in different scenarios

By combining the two policy contexts (termed as "Base" and "Decarb") with the above cases, we design six diagnostic scenarios as follows:

- Base: "existing framework" scenario mirroring the latest NECPs and Reference scenario "default" assumptions
- Base_CP: "existing framework" scenario mirroring the latest NECPs with extension of EU ETS scope to include the buildings sector with a carbon price increasing linearly to USD 300 in 2040, and USD 450 in 2050
- Base_HP_CP: "existing framework" scenario with extension of EU ETS scope to include the buildings sector and increased international energy prices to reflect the energy crisis.
- Decarb: "decarbonisation" scenario reflecting regulatory and institutional measures aiming at achieving the EU's 55% GHG emission reduction target by 2030 and climate neutrality by 2050, being in line with the "Fit For 55" policy package.
- Decarb_CP: "decarbonisation" scenario, being in line with the "Fit For 55" policy package with extension of EU ETS scope to include the buildings sector with a carbon price increasing linearly to USD 300 in 2040, and USD 450 in 2050

- Decarb_HP_CP: “decarbonisation” scenario, being in line with the “Fit For 55” policy package with extension of EU ETS scope to include the buildings sector and increased international energy prices to reflect the current energy crisis.

5.7. Scenario results and discussion

In this section, the results of the series of diagnostic scenarios are presented focusing on a set of medium and long-term projections of key energy-economy-emissions indicators of the EU buildings sector under each scenario.

Figure 11 shows final energy projections for the EU residential sector. In all “baseline” scenarios final energy demand is consistently higher than in the “decarbonization” scenarios throughout the projection period. Differences between scenarios are higher in 2050 due to the climate neutrality ambition of the decarbonization scenarios and the system inertia to changed energy and carbon prices in the first years of the simulation due to stock turnover dynamics. The carbon prices variants lead to a further decrease of final energy consumption compared to the respective “simple” variants. The increased energy prices also decline final energy consumption. The effects of high energy and carbon prices are larger in the “decarbonization” context compared to the “baseline”, as high energy (and carbon) prices alone are not sufficient to induce deep energy savings in the “Baseline” context, as the market and non-market barriers to energy efficiency do not allow for extensive energy efficiency investments. The regulatory and institutional measures of the decarbonisation scenarios that remove the market and non-market barriers enable accelerated uptake of energy efficiency investments for all consumer classes and building types that are necessary when energy prices increase (either alone or due to the inclusion of carbon taxes).

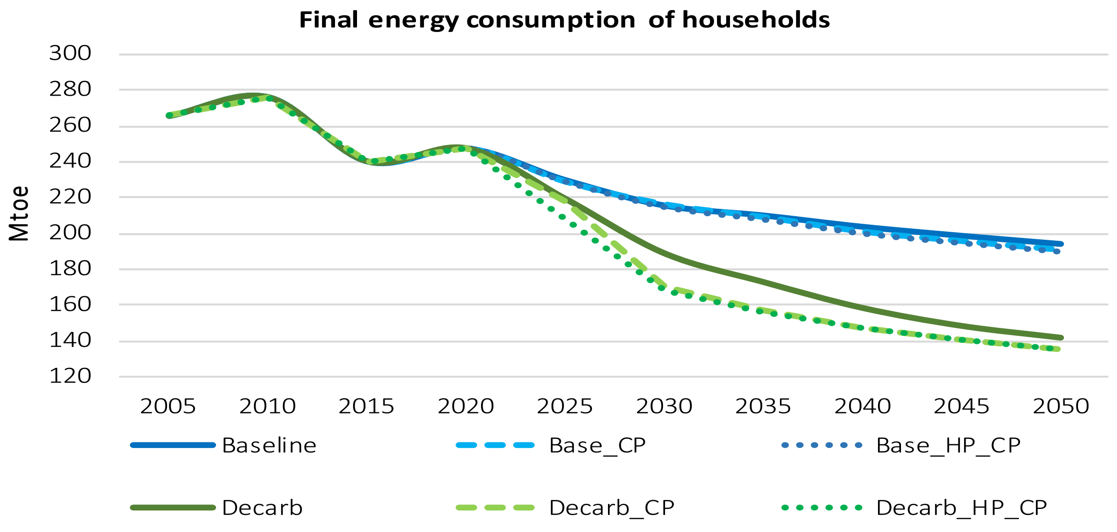


Figure 11:Final energy consumption outlook

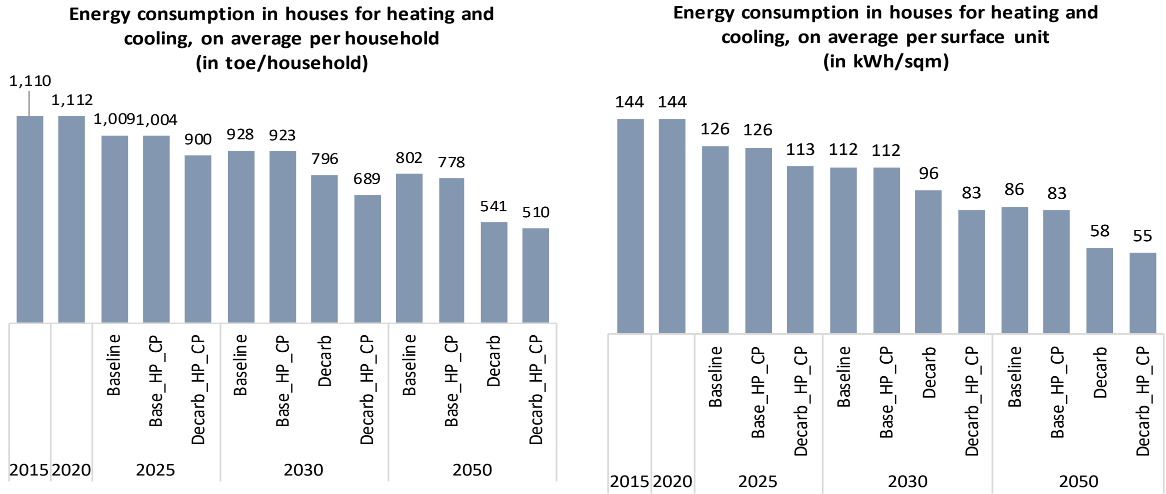


Figure 12:Energy efficiency indicator in households (thermal uses) - Energy consumption in houses for heating and cooling, on average per household (in toe/household)

Energy efficiency progress in the different scenarios can also be presented by comparing the average energy consumption per household or per surface unit (Figure 12). The combined effects of higher rate and deepness of renovation, more ambitious building codes and the adoption of advanced heating equipment, including heat pumps, would lead to a considerable reduction in average energy consumption per household. The ambitious energy efficiency policies in the decarbonization context decrease the average energy consumption of households by about 50% in 2050 compared to 2015 levels.

Figure 13 presents the model-based results for energy-related CO2 emissions from EU buildings in the series of diagnostic scenarios examined. In all variants of the decarbonisation scenarios energy-related CO2 emissions become zero in 2050, being in-line with the climate neutrality objective. The extension of the EU ETS scope to the buildings sector, as well as the assumption of higher energy prices decreases emissions further in both “decarbonization” and “baseline” context relative to the “default” variants because of changes in the fuel-mix for heat uses and the replacement of heating equipment with more efficient and low-carbon technologies.

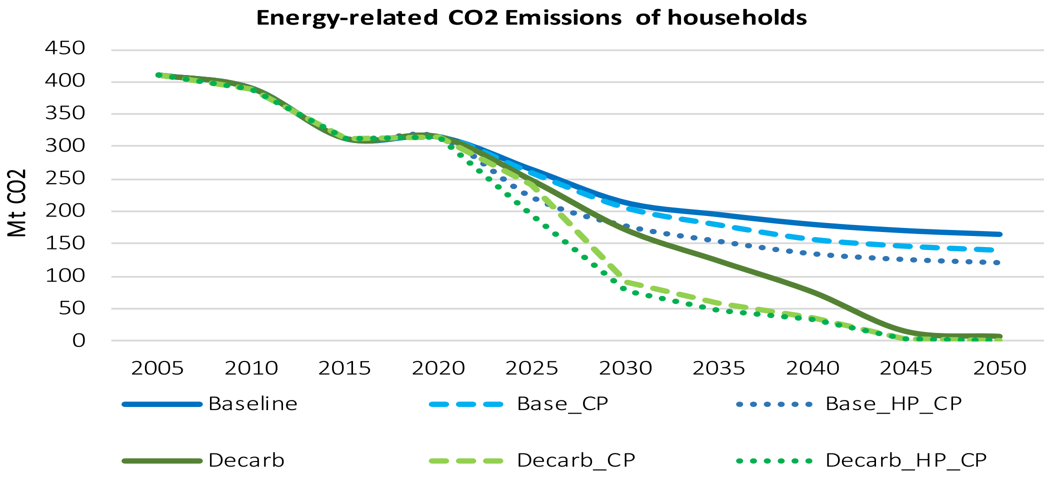
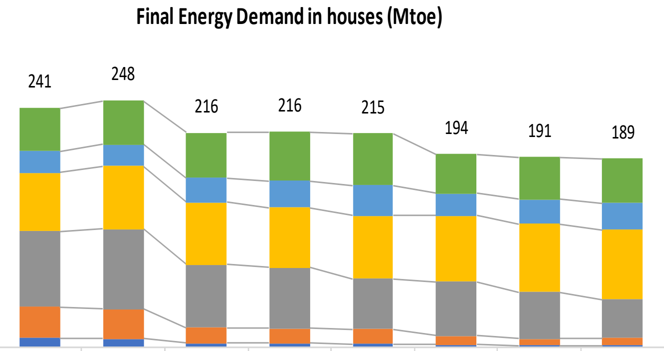


Figure 13:Energy-related CO2 emissions of households' outlook

The fuel mix used in the buildings sector is influenced by the different scenario settings. Even in the "Baseline" projections (Figure 14) there is a trend towards increasing electrification of energy demand, with the share of electricity in fuel mix increasing particularly in the longer term, as the capital costs of heat pumps decrease over time. On the other hand, there is a reduction in the share of fossil fuels (gas, coal, oil) over time in all diagnostic scenarios. The decrease is even larger in the variants assuming high carbon and energy prices compared to the "default" variants.



	2015	2020	2030 Baseline	2030 Base_CP	2030 Base_HP_CP	2050 Baseline	2050 Base_CP	2050 Base_HP_CP
Renewables	44	44	45	49	52	40	42	44
Heat	21	22	25	27	31	23	25	27
Electricity	59	63	63	61	63	67	68	70
Gas	76	81	63	61	50	54	47	39
Liquids	32	29	16	15	15	9	7	7
Solids	9	8	4	3	3	2	2	2
Total	241	248	216	216	215	194	191	189

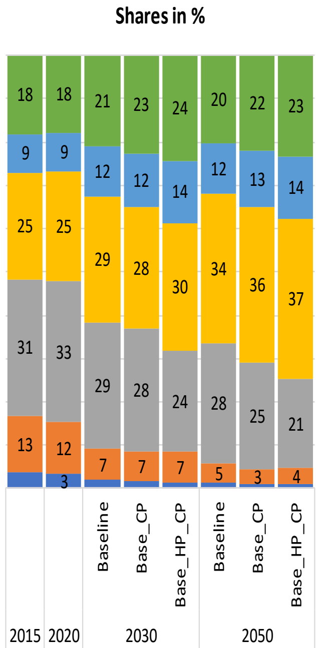
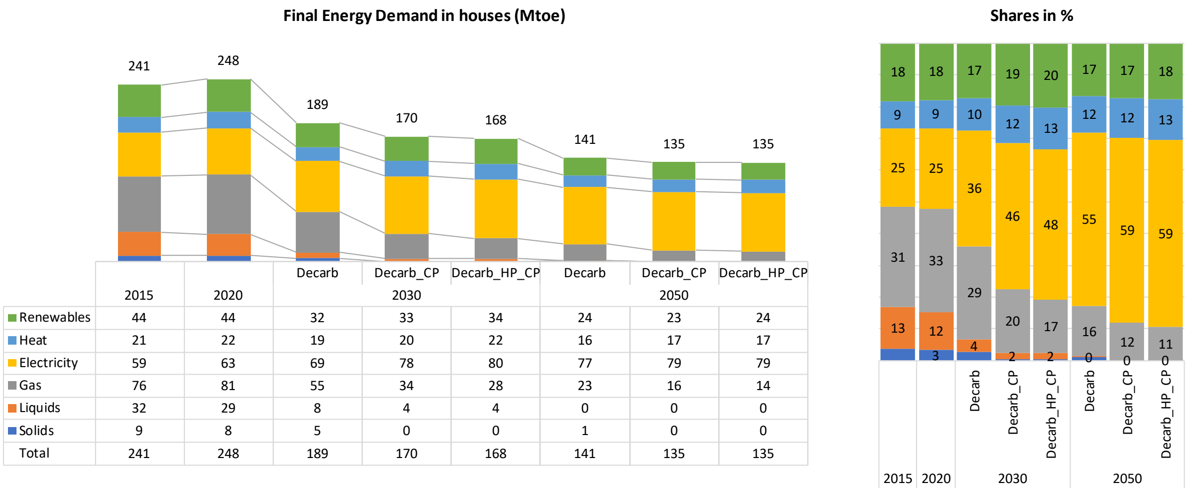


Figure 14:Fuel mix in the residential sector in the "existing framework" context scenarios

In the decarbonisation scenarios (Figure 15), electrification of heating in EU buildings is a dominant trend already in the short term: electricity shares almost doubles by 2030 compared to 2020 in all decarbonisation variants, because of the increasing penetration of heat pumps. The accelerated uptake of heat pumps is driven by both policies promoting the use of RES in heating and policies promoting the use of efficient equipment in heat uses. In the long-term electricity represents more than half of total energy consumption in all decarbonisation scenarios and reaches about 60% in the scenarios with high carbon and energy prices. In these scenarios, the remaining 40% of buildings energy demand is covered by renewable energy (mostly biomass and solar heaters) and decarbonized gases, including green hydrogen and clean synthetic gases.



	2015	2020	2030 Decarb	2030 Decarb_CP	2030 Decarb_HP_CP	2050 Decarb	2050 Decarb_CP	2050 Decarb_HP_CP
Renewables	44	44	32	33	34	24	23	24
Heat	21	22	19	20	22	16	17	17
Electricity	59	63	69	78	80	77	79	79
Gas	76	81	55	34	28	23	16	14
Liquids	32	29	8	4	4	0	0	0
Solids	9	8	5	0	0	1	0	0
Total	241	248	189	170	168	141	135	135

Figure 15:: Fuel mix in the residential sector in the "decarbonisation" context

The following figures show the projected average renovation rate of building envelope and equipment replacement rates. In the modelling framework used, deep energy renovation induces acceleration of replacement of heating equipment. Other policies, including eco-design standards and labelling, also induce acceleration of capital turnover in the heating systems of buildings. As a result, the "decarbonization" scenarios show a significant increase in the rate of replacement of heating equipment compared to the baseline ones. In particular, the renovation rate is projected to reach more than 2% of the housing stock per year over 2020-2050 in the decarbonization scenarios. The energy renovation rate, also shown in Figure 16, is a sum of the renovation rate of the building envelope and the rate of replacement of heating equipment.

Carbon prices and increased energy prices drive both the renovation of the building envelope and the replacement of heating equipment upwards. However, the impacts of increased energy and carbon prices on the renovation of the building envelope are less pronounced, as the uptake of such investments is mostly facilitated by regulatory and institutional measures. Such measures are included in the "decarbonization" context scenarios to remove the market and non-market barriers related to renovation investments. Increased energy and carbon prices would induce an acceleration of the replacement of heating equipment relative to the "default" variants, especially in the decarbonisation context, where concrete climate policies combined with the enabling conditions remove the barriers related to investments in efficient heating equipment.

Figure 16:Projection of renovation rates in houses

The depth of building envelope renovation intervention in houses is measured by the percentage of energy savings enabled by the renovation compared to the previous status of the building envelope (Figure 17). The decarbonisation scenarios assume that the energy efficiency policy drivers focus both on the depth and the rate of renovation and induce a significant increase in both of them, compared to the baseline. The effects of carbon prices and/or increased energy prices are relatively limited in both the "decarbonization" and "baseline" contexts; but on the expected direction (i.e., energy savings from renovation increase in the carbon price/energy prices variants relative to the "default" scenarios).

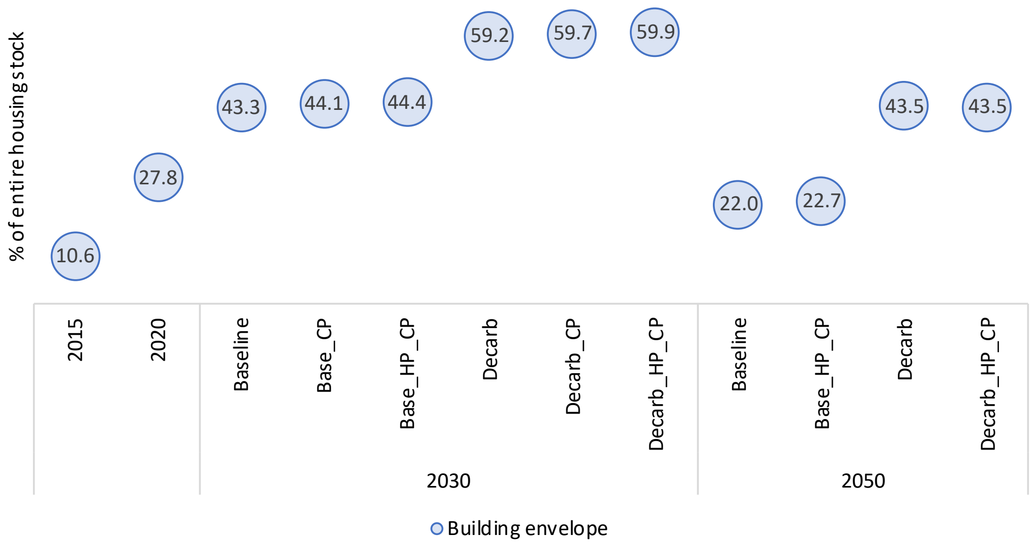
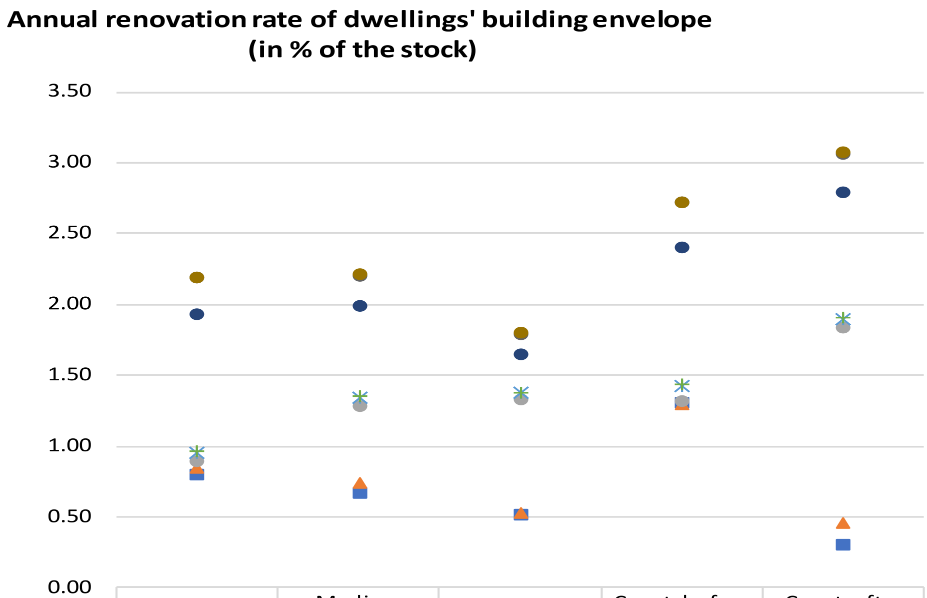


Figure 17:Energy Savings from Renovation of houses - % of space-heating on average (deepness of renovation)

The regulatory and institutional measures of the decarbonisation scenarios would increase the renovation rates for all consumer classes and years of construction of the buildings (Figure 18). However, the increase is projected to be higher for medium and high-income consumers compared to low-income ones, that have poor access to capital which implies high discount rates influencing renovation decisions negatively, compared to conditions of sufficient funding availability. Carbon prices and high energy prices increase renovation rates further (but to smaller extent) relative to the “default” variants for all consumer classes.



	Low income	Medium income	High income	Const. before 1975	Const. after 1975
<2015	0.80	0.67	0.51	1.30	0.30
2016-2020	0.84	0.74	0.52	1.30	0.46
2026-2030 Baseline	0.89	1.28	1.33	1.31	1.83
2026-2030 Base_CP	0.95	1.34	1.37	1.42	1.89
2026-2030 Base_HP_CP	0.96	1.35	1.38	1.43	1.90
2026-2030 Decarb	1.93	1.99	1.64	2.40	2.79
2026-2030 Decarb_CP	2.19	2.20	1.79	2.72	3.06
2026-2030 Decarb_HP_CP	2.19	2.21	1.80	2.72	3.07

Figure 18:Annual renovation rate of housing building envelope per income class and building age

The total annual system costs for households (Figure 19), include the annualized capital costs related to the renovation of the building envelope and the replacement of the energy equipment, as well as the fuel purchases for households. The higher rates of renovation and replacement of the heating equipment in the "decarbonization" scenarios explain the higher total annual costs for households relative to the "baseline" context. On the other hand, the costs for energy product purchases decrease in the "decarbonization" variants, but the additional investments more than counterbalance the reduced expenses to purchases fuels and consequently total energy costs are higher in the "decarbonization" context scenarios. The carbon prices and/or increased energy prices variants increase the respective total annual system costs of households, as they increase the costs for energy purchases. The differences of these variants relative to the "default" cases are similar in the two contexts ("decarbonization" and "baseline"), as the curves representing the total annual system costs in the variants are moved upwards in the same rate in both contexts.

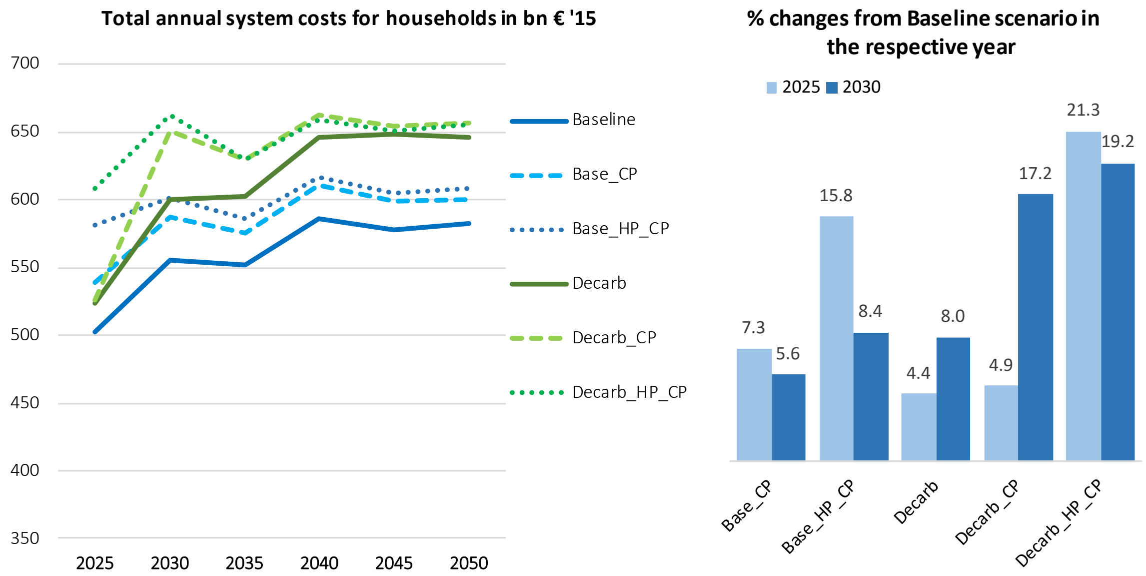
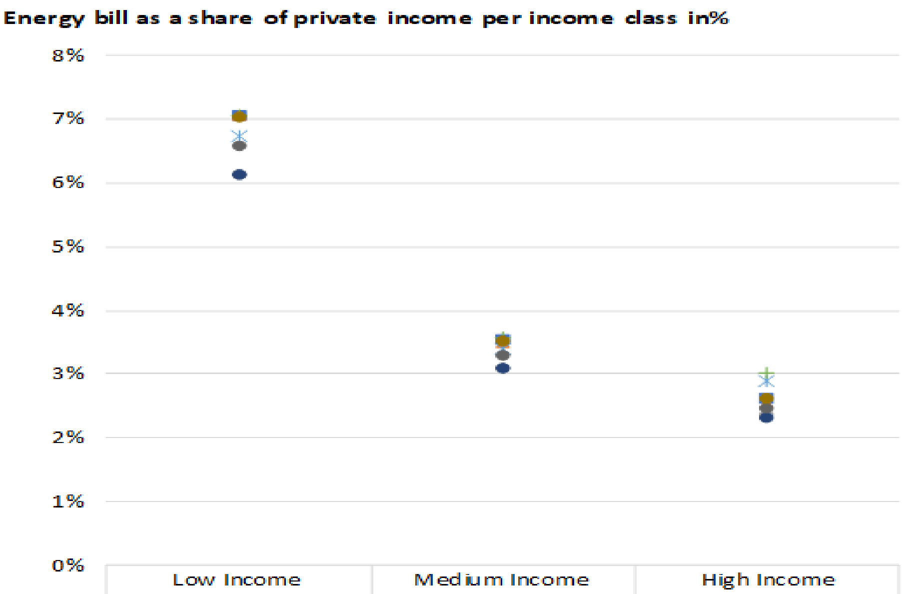


Figure 19:Total annual system costs for households

An indicator to measure the social differences across income classes is the ratio of energy purchasing costs as a percentage of household income (Figure 20). The energy efficiency policies enable an increase in renovation rates and improve the affordability of energy expenses by reducing energy consumption significantly, particularly for low and medium-income consumers. The differences across income classes in terms of energy bills per unit of income are lower in the "decarbonization" variants compared to the respective "baseline" variant. In the recent past, low-income consumers had to spend almost 3 times larger part of their income for purchasing energy products, compared to high-income consumers. In the "decarbonization" scenarios, the relative difference between low and high-income classes is reduced. As it is expected, all income classes will need to pay a higher part of their income for energy purchases in the variants assuming higher energy and carbon prices relative to the "default" scenarios in both "baseline" and "decarbonization" contexts, as these elements increase the end-user price of all fuels.



	Low Income	Medium Income	High Income
2015	7.06%	3.53%	2.60%
2020	7.04%	3.49%	2.54%
2030 Baseline	6.11%	3.08%	2.36%
2030 Base_CP	6.72%	3.39%	2.88%
2030 Base_HP_CP	7.04%	3.56%	3.02%
2030 Decarb	6.11%	3.08%	2.31%
2030 Decarb_CP	6.58%	3.29%	2.46%
2030 Decarb_HP_CP	7.02%	3.52%	2.62%

Figure 20:Energy bill as a share of private income per income class by scenario in 2030

5.8. Expected Results

The development and implementation of the EU Use Case will lead to an improved understanding of system-level implications of enhanced energy efficiency and electrification in EU buildings in the context of achieving climate neutrality by mid-century. It also enables an enhanced novel assessment of the alternative policy interventions to drive the implementation of the Fit for 55 policy package and pave the way towards a carbon neutral economy by mid-century. The main outcomes of the Use Case will be a set of projections up to 2050 of key energy-economy-emissions indicators in EU countries focusing on the buildings sector, driven by the alternative policy scenarios co-designed with stakeholders. These indicators include (among others): final energy consumption by building type and use, energy mix in buildings, CO2 energy-related emissions, uptake of low-carbon technologies, carbon prices, investment requirements, and energy system costs.

The European Use case will provide new insights into the factors influencing the energy-related choices of individuals in the residential sector and how these factors can be consistently integrated in large-scale models. The impacts of different energy policy interventions and incentive systems to reduce energy consumption and unleash the flexibility potentials in the residential sector will also be explored. The potential for the future uptake of low and zero-carbon solutions in the residential sector will be assessed in detail together with the system effects and broader socio-economic implications of their wide uptake in the context of transition towards climate neutrality by mid-century.

The model-based analysis will provide several KPIs related to the Sustainability Assessment, including: 1) development of emission trajectories in the EU buildings sector by 2050; 2) energy efficiency improvement in EU households; 3) Uptake of electrification and low-carbon, renewable fuels in European buildings by mid-century; 4) Development of building renovation strategies by building type in EU countries; 5) Development of energy system costs and electricity prices for households in the EU; 6) Energy affordability and energy expenditures by income class

The assessment of the transformation of the EU buildings sector will provide useful insight for several Sustainable Development Goals (SDGs). In particular, the EU use case results will be assessed in the context of SDG 7 “Affordable Energy and Clean Energy”. The EU Use Case will quantify future developments for several key themes related to SDG 7, including the uptake of renewable energy, energy efficiency improvements, and energy affordability. Several other SDGs, including SDG13 (Climate action), SDG 9 (Industry, Innovation, and Infrastructure), SDG 3 (Good Health and Well-Being), and SDG 10 (Reduced inequalities) are also linked with the EU Use Case.

6. The global use case

The global use case investigates the impact of ambitious climate policies and energy efficiency targets on the global energy mix and in particular in the future development of the buildings sector. For this use case, two well-established integrated assessment models (IAMs), TIAM-ECN and PROMETHEUS, are employed and linked with the WHY toolkit aiming to improve their simulation properties in the representation of decarbonization of the buildings sector. Scenario design and the selection of input data and output indicators are based on stakeholders’ consultation, extensive literature research and internal expertise of the two modelling teams.

6.1. Objective and Scope of the Use Case

Climate change is a phenomenon that affects the world. While its effects are local – and should be tackled by national and subnational policies – its scope and scale can only be grasped from a global perspective. As such, international cooperation should be the foundation on which to base local and national policies. This use case aims at explicitly bringing the global dimension into the WHY project, and showcasing how global energy and climate modelling scenario studies can profit from the tools developed in the project. Using PROMETHEUS and TIAM-ECN models, we make a connection with well-known long-term IAM-based scenario analyses at the global level by many high-level bodies and scientific orgnisations, such as the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA).

Specifically, the Global Use Case has two main objectives. First, we aim at investigating how the novel insights provided by the WHY toolkit can inform, shape and improve the IAM analysis. We will achieve this goal by creating a link between the WHY toolkit and our two IAMs – PROMETHEUS and TIAM-ECN –, running the models according to a set of diagnostic scenarios, and analyzing the outcome by means of a series of indicators. Both the diagnostic scenarios and the output indicators are specifically designed for this purpose, based on the partners' extensive expertise in this type of cross-model analysis. By showcasing and documenting how the WHY toolkit can be used in the context of global energy and climate modelling (and more in general with large-scale models) we provide a useful example for other modelers (especially those working with TIMES-based models, similar to TIAM-ECN). Second, we intend to contribute to the scientific literature on global energy scenario studies, by analyzing the effects of enhanced energy efficiency in the demand sectors on the global energy mix (as well as that of major economic regions), in the context of stringent decarbonization policies towards achieving the Paris Agreement goals. We already made a start in this direction by assessing the implications of pushing energy efficiency versus employing other means to reduce emissions, such as promoting renewable energy sources or deploying Carbon Capture, Storage and Utilization (CCSU) solutions in our peer-reviewed study (Dalla Longa et al., 2021).

6.2. Stakeholder input

A stakeholder consultation process with international experts on global energy scenarios and climate policies has been conducted in the spring of 2022, by means of written questionnaires and online interviews. This process was complemented with an internal evaluation of the responses received. The main policy dimensions identified through this process for the global case study can be summarized as:

- Global climate policy
- Carbon pricing
- Subsidization of clean heating and cooling technologies
- Obligations to meet energy efficiency standards in buildings
- Energy financing for retrofits in the building sector
- Clean cooking promotion in developing countries
- Sustainable Development Goals (SDGs0, especially those that focus on improved energy access and reduction of poverty.

6.3. External and Internal Variables

The internal and external variables that will form the basis of our scenario analysis were also discussed during the expert consultation process. The main variables to be considered are:

- Long-term GDP and population growth (including possible macro-economic effects triggered by the COVID19 pandemic)
- Targets for limiting global temperature increase
- Energy efficiency improvement objectives in the demand sectors
- Targets for fuel mix in the buildings or transport sector
- Electrification rate in residential energy consumption
- Availability and cost of electricity storage
- Share of decarbonized district heating/cooling networks
- Penetration of hydrogen and other synthetic fuels
- Targets on increasing energy access and limiting energy poverty.
- Energy costs and prices by type of consumer
- Investment by consumers to reduce emissions from buildings

The first three variables are the most impactful for an IAM analysis at the global level and will be placed at the heart of the scenario design. Economic and population growth are the main drivers that determine energy demand levels in an IAM. In this study we will start from the well-accepted projections of the Shared Socio-economic Pathways (SSPs) and account for the expected short-term economic effects of the COVID19 pandemics. Climate control targets in line with the Paris Agreement foresee limiting global temperature increase to 'well below 2°C' while the 1.5°C target is also heavily discussed, which requires the transition to net zero energy systems by mid-century. We will follow this practice in the global use case scenarios. Regarding energy efficiency improvements, the analysis will contrast the model outcomes of business-as-usual scenarios with those of scenarios in which a strong 'energy efficiency push' is applied, either globally or only in a selection of regions or sectors.

6.4. Scenarios

We designed several scenarios following the policy dimensions identified through the stakeholder consultation process. Among these, we prioritized those that are more directly linked with the European energy policy discourse (i.e. we do not look specifically at clean cooking and energy access, which relate mostly to developing economies). In Dalla Longa et al. (2021) we first explored the effect of enhanced energy efficiency under stringent global climate targets, and we refer the reader to our publication for additional details (in the appendix of the current deliverable). Here we focus on a series of "diagnostic" scenarios that we recently developed with the aim of testing the interaction of our IAMs with the WHY toolkit and evaluate the model behaviour under changing exogenous assumptions for some key drivers (e.g. carbon prices, technology costs, global energy prices). This has become a standard practice in IAM-based studies exploring transformational pathways (Harmsen et al 2021, Kriegler et al 2015).

The diagnostic scenarios run between 2020 and 2050 and have a global geographic scope. Table 2 summarizes the main features of each scenario. The BASE scenario corresponds to an implementation of current (approved and already implemented) national policies; it establishes a baseline to which the other scenarios can be compared to. In CP300-Lin and CP70-GR5 scenarios, we explore the effects of enforcing a global carbon price (uniform across regions and sectors) that grows linearly, respectively exponentially, from 2025 onwards. The growth rates of carbon price modelled in these two scenarios have been chosen to be in line with several IAM studies that explore carbon price trajectories compatible with a 2°C Paris Agreement target. In the 'LCHP' and 'Highprice' variants of the BASE and CP300 scenarios we investigate, respectively, the consequences of a steep decline in the cost of heat pumps (which are the most important option to electrify heating in buildings), and the implications of a 50% increase in international energy prices (i.e. of the orders observed recently in Europe).

Table 2: Global diagnostic scenarios.

Scenario name	Description
BASE	National Policies Implemented – the actual 2020 values are recreated by the models.
CP300-Lin	Impose exogenous carbon price globally linearly increasing • For t < 2025: Fix scenario to DIAG- NPI* • For t in [2025, 2100]: Tax(t) = 75 USD + 15 USD * (t-2025); (USD 300 reached in 2040, 450 in 2050)
CP70-GR5	Impose exogenous carbon price exponentially increasing • For t < 2025: Fix scenario to DIAG-NPI* • For t in [2025, 2100]: Tax(t) = 70 USD * 1.05(t-2040) (USD 70 reached in 2040)
BASE-LCHP	Like Base but Cost of heat pumps declines below BASE levels by 10% in 2025, 25% in 2030 and 50% from 2040 onwards
CP300-LCHP	Like CP300-Lin , but Cost of heat pumps declines below CP300 levels by 10% in 2025, 25% in 2030 and 50% from 2040 onwards
BASE-Highprice	Like Base, but Global energy prices increase by 50% from BASE levels in 2025, and 30% from 2030 onwards
CP300-Highprice	Like CP300-Lin, but Global energy prices increase by 50% from CP300 levels in 2025, and 30% from 2030 onwards

6.5. Validation

In this section we present some key results from the global diagnostic scenarios, without the interaction with the WHY toolkit. Once the latter has been finalized and tested in WP4, we will soft-link it with PROMETHEUS and TIAM-ECN models, rerun these scenarios and compare the outcomes of the two batches of modelling scenario runs in order to demonstrate the advancements realized in the global energy system and Integrated Assessment models as part of the WHY project.

6.5.1. Energy system development

This section presents projections for the global energy system, obtained with PROMETHEUS and TIAM-ECN under the assumptions of each of the diagnostic scenarios. In the odd-numbered figures, each panel corresponds to a specific combination of scenario and model, as indicated in the title above the panel (PROM for PROMETHEUS and TIAM for TIAM-ECN). In the even-numbered figures we zoom in on the 2050 situation, in order to more readily compare the two model projections in the various scenarios.

Figure 21 presents global CO2 emissions projections from energy supply and the three main demand sectors, i.e. transportation, buildings (residential and commercial) and industry. The BASE scenario variants display similar trends, with global emissions steadily increasing up to nearly 40 GtCO2 in 2050. In comparison with PROMETHEUS, TIAM-ECN projects a lower overall level of emissions from energy supply and an increasingly higher contribution from industry. The CP300 scenario variants also show similar trends in both models, with emissions decreasing strongly to around 10 GtCO2/yr by the middle of the century. For this subset of scenarios, the differences between models are more pronounced than in BASE: industry completely decarbonizes in TIAM-ECN but not in PROMETHEUS, while the opposite happens in energy supply and in buildings. Finally, in the CP70-GR5 scenario both models project a decreasing CO2 contribution from energy supply driven by the increased deployment of renewable energy in electricity generation; for the demand sectors TIAM-ECN projects a slight overall increase in CO2 emissions, while these are roughly constant in PROMETHEUS.

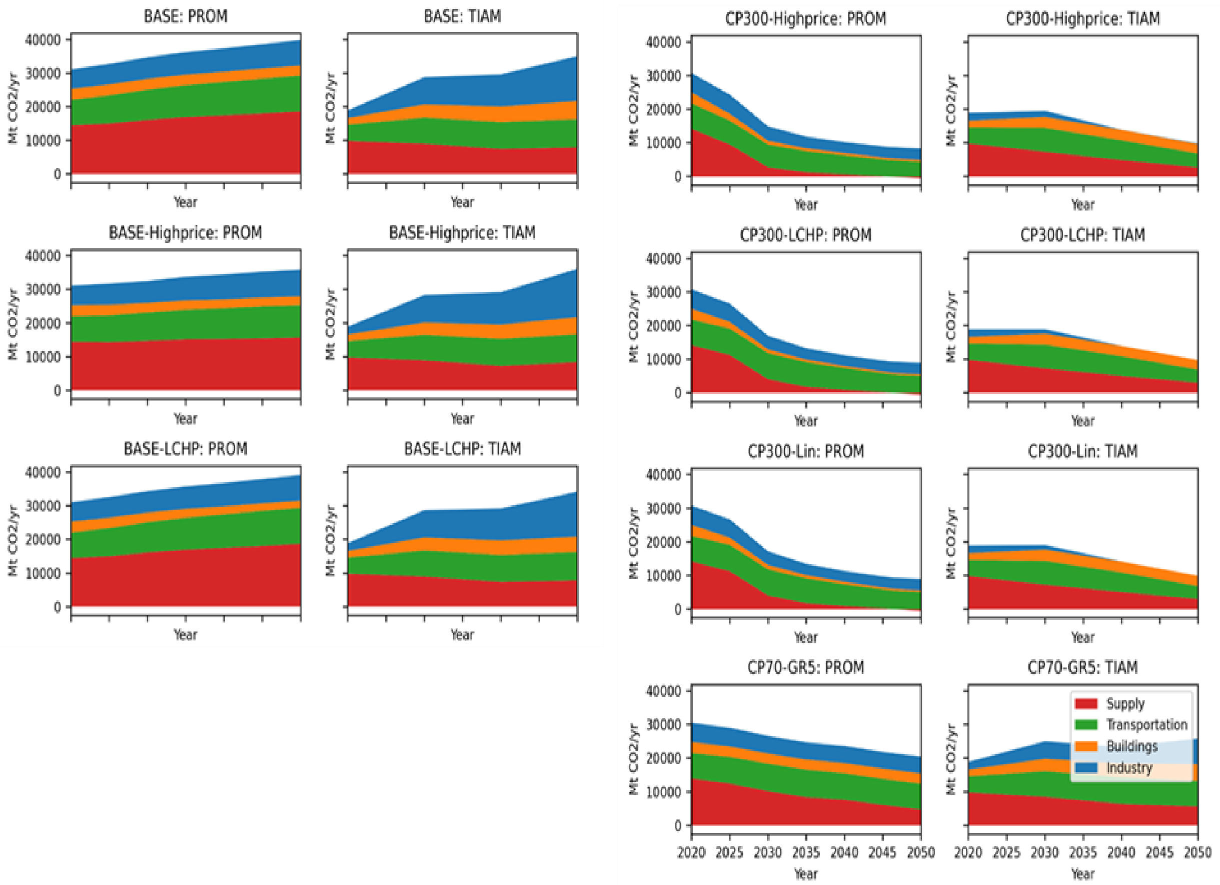


Figure 21:Global emissions projections per sector in the two global IAMs

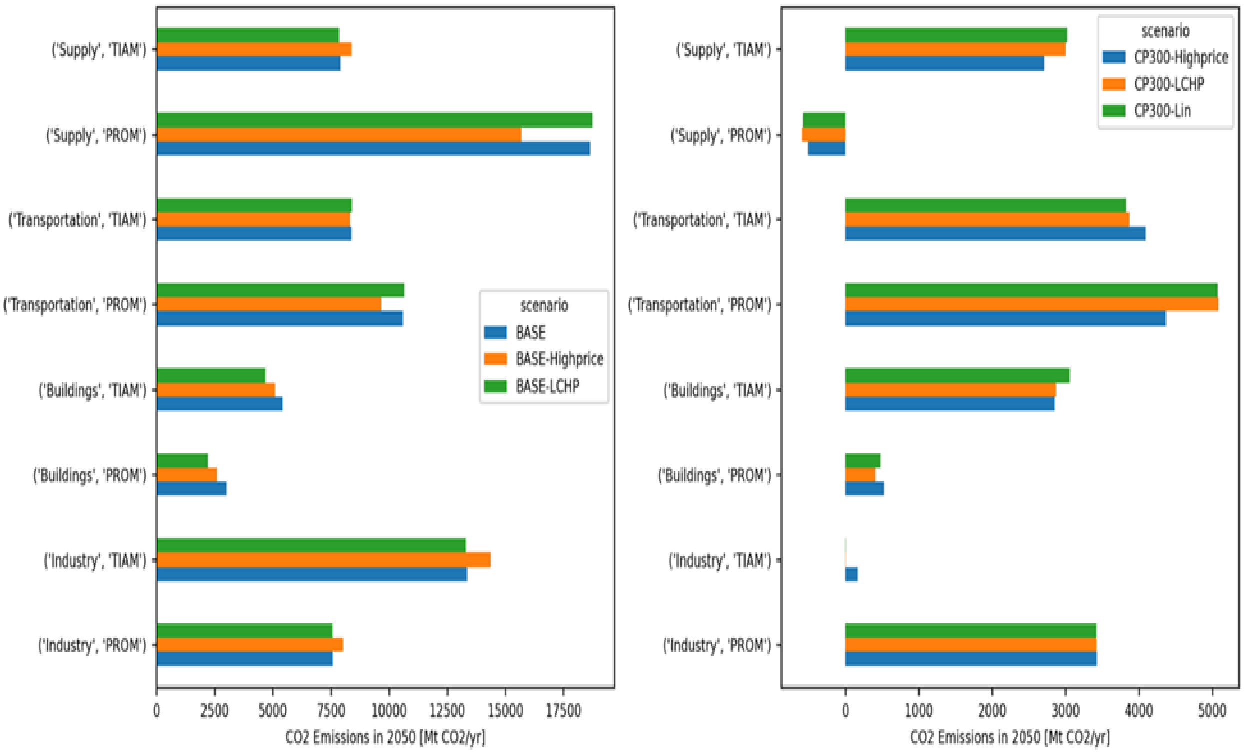


Figure 22:CO2 emissions in 2050 in the BASE (left) and CP300 (right) scenarios.

Figure 22 highlights the 2050 CO2 emission levels in the various sectors from both models, in the BASE and CP300 scenario variants. In the BASE case, for both models, the Highprice variant displays the largest variations. In the TIAM-ECN projection, higher energy prices induce higher emissions from energy supply, while the opposite is true for PROMETHEUS where higher energy prices drive a reduction in energy consumption and supply and in associated CO2 emissions. In the other sectors the trends across variants are the same in the two models, and of similar magnitude, with the exception of transportation where TIAM-ECN projects a much smaller emission reduction than PROMETHEUS in the Highprice variant. The CP300 case displays more diversity than BASE across scenario variants and models. CO2 emissions from energy supply remain always positive in TIAM-ECN, while a small negative contribution from energy supply is consistently projected by PROMETHEUS in all variants driven by the uptake of Biomass with Carbon Capture and Storage (BECCS). In the transport sector, under the assumption of higher energy prices, TIAM-ECN and PROMETHEUS project higher, respectively lower, emissions than in the other variants. Finally, the two models display opposite trends in projecting emissions from buildings and industry. Emissions from residential and commercial buildings decrease to about 500 MTCO2/yr in 2050 according to PROMETHEUS due to increased electrification of heating uses, while in the TIAM-ECN projection they remain at a level of about 3 GtCO2/yr. The opposite trend is observed for industry, which is essentially fully decarbonized in all CP300 variants according to TIAM-ECN but stays at levels of about 3.5 GtCO2/yr in the PROMETHEUS projections, as it is considered a hard-to-decarbonise sector with carbon pricing alone cannot deliver deep emissions reductions.

Figure 23 presents projections for the power sector mix. Each model displays a fairly consistent behavior in the BASE scenario variants, while several differences between the two models can be noticed. In the TIAM-ECN projections non-biomass renewables (i.e. wind and solar technologies) dominate electricity production from 2030 onwards. PROMETHEUS is more conservative in this respect and shows an energy mix that is still predominantly fossil-based until the middle of the century. The situation is very different in the CP300 variants. While single-model projections are again fairly similar between variants, in this case PROMETHEUS almost completely phases out fossil-based generation in favor of biomass, solar and wind technologies. TIAM-ECN projects only a minor role for bio-based technologies in the power sector, and an essentially constant contribution from fossil fuels throughout the modelling horizon. In the PROMETHEUS projection for the CP70-GR5 scenario, electricity generation grows steadily at a rate comparable to that of the BASE variants, but the share of non-biomass renewables in the mix increases much more significantly, driven by the increased carbon pricing. For this scenario TIAM-ECN project trends that are comparable to those observed in the CP300 variants.

Figure 24 zooms in on the 2050 power sector mix in the BASE and CP300 variants. For the BASE variants, as observed also in the analysis of CO2 emissions, the Highprice assumptions induce the largest variations in both models. In most cases the magnitude of these variations is different between the two models. The 2050 contributions from the various technology categories are also quite different in the two model projections, with the exception of nuclear and biomass-based processes which display (in the BASE and LCHP variants) similar values. In the CP300 variants, the 2050 model-based projections are more in harmony, displaying consistent trends across scenario variants and roughly aligned contributions from the various technology categories.

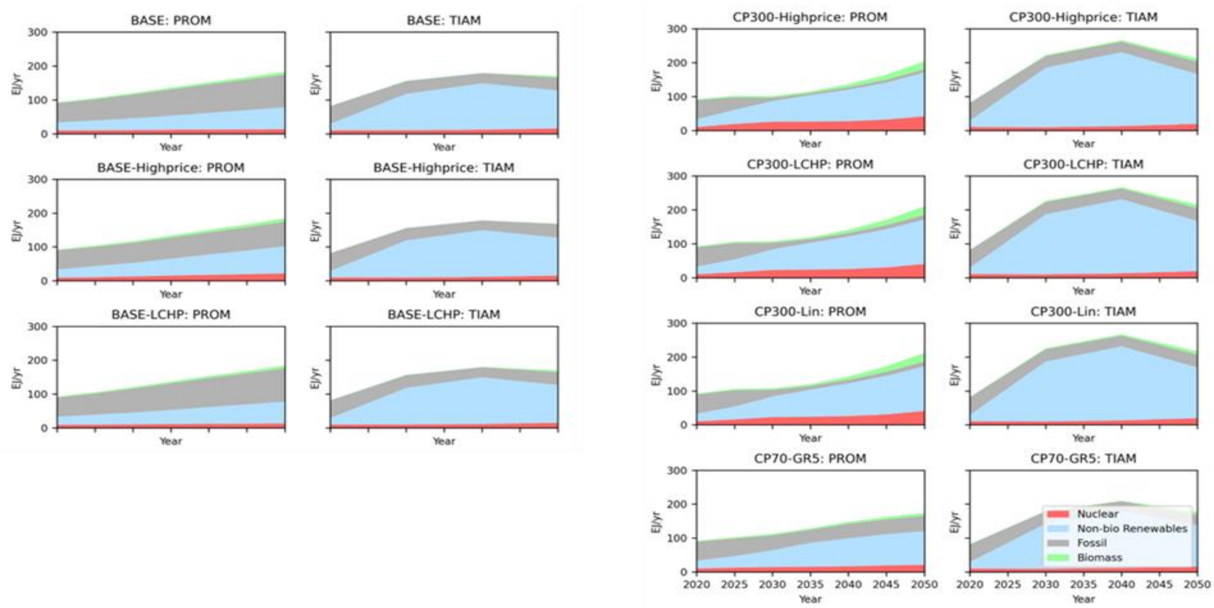


Figure 23:Global electricity supply mix per generation source

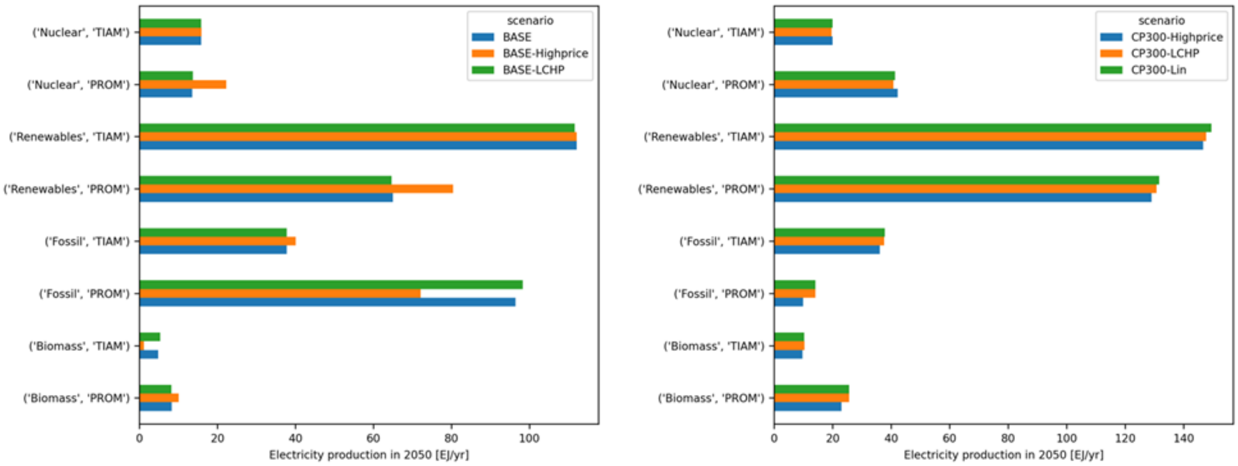


Figure 24:Electricity in 2050 in the BASE (left) and CP300 (right) scenarios.

In Figure 25 we show model-based projections for the energy mix in residential and commercial buildings. The two models project similar trends and contributions from the various energy carriers in all BASE variants. One clear difference between the two models is that in TIAM-ECN the electrification of buildings is boosted already between 2020 and 2025 and then proceeds at a relatively low rate, while for PROMETHEUS it grows at a roughly constant rate throughout the modelling horizon. Another substantial difference is that in TIAM-ECN the use of solid fuels in buildings is almost phased out by the middle of the century, while it remains roughly constant in the PROMETHEUS projections mostly due to continuous use of biomass solids. The CP300 variants display essentially the same trends as the BASE variants in the TIAM-ECN projections, indicating that this model does not allow many options for decarbonizing the buildings sector. On the contrary, the CP300 variants projections from PROMETHEUS differ greatly from their BASE counterparts. PROMETHEUS projects a steady decrease in energy used in buildings until 2035 – corresponding to improvements in energy efficiency and increased renovation of buildings– with the use of gaseous and liquid fuels being essentially phased out. After 2035 energy use is dominated by (green) electricity based on increasing electrification trend until the middle of the century. The CP70-GR5 case is for both models very similar to the BASE variants.

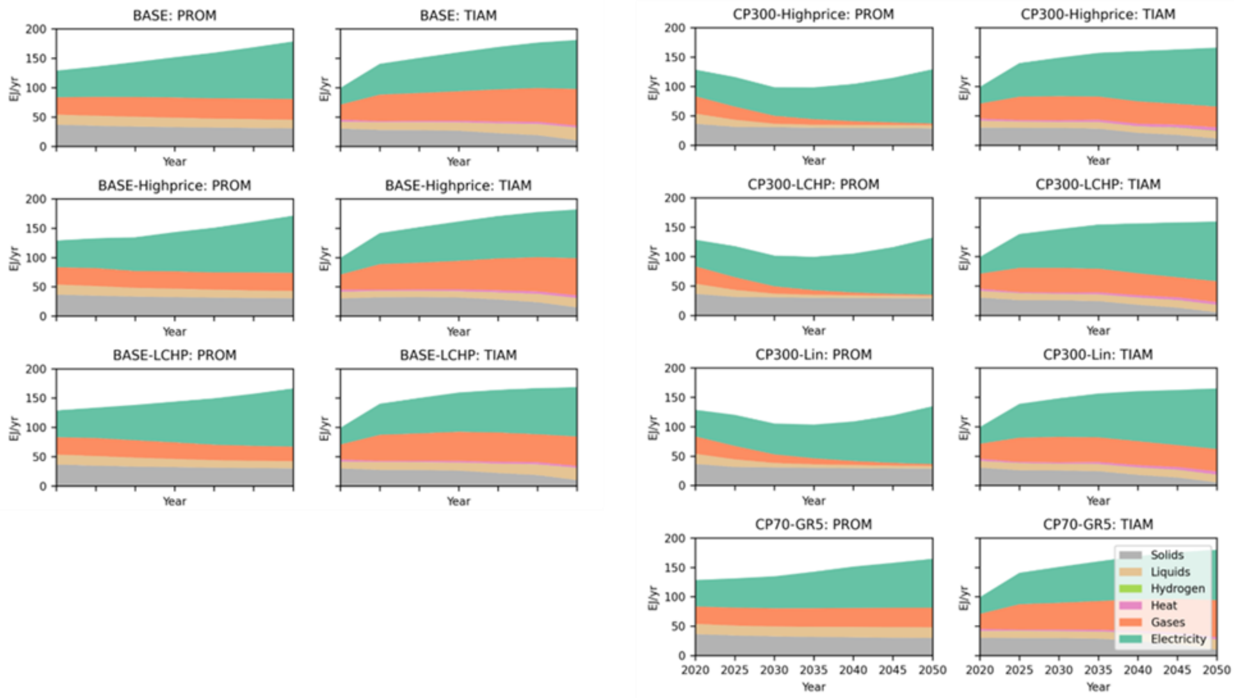


Figure 25:Global energy use in buildings (residential and commercial) by energy carrier.

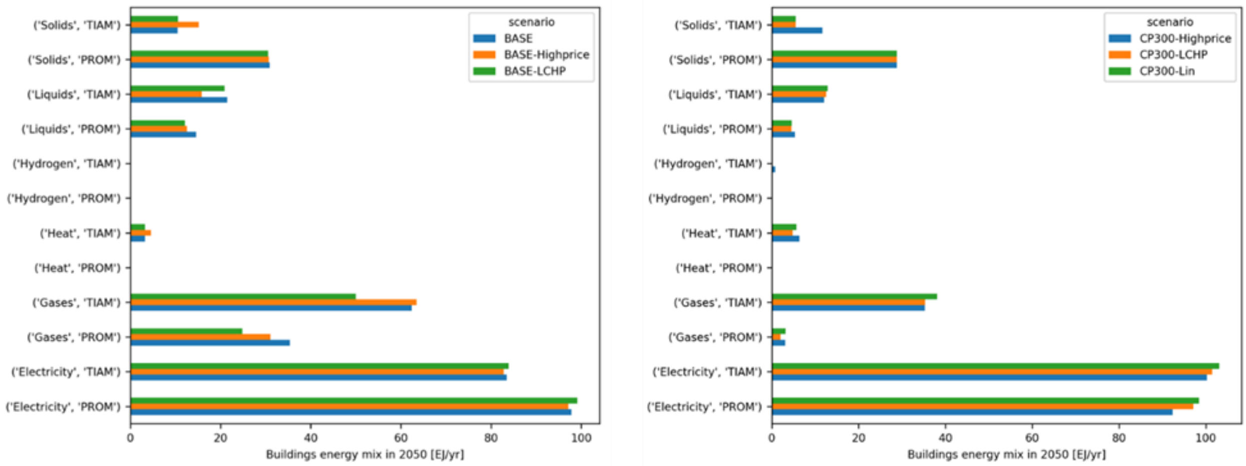


Figure 26:Energy mix in buildings in 2050 for the BASE (left) and CP300 (right) scenarios.

Figure 26 analyzes the 2050 situation for the BASE and CP300 variants. The most prominent features are the near phase out of natural gas in the CP300 variants for PROMETHEUS, the small role of hydrogen in the CP300-Highprice scenario for TIAM-ECN, and the contribution from district heat in all scenarios that is explicitly accounted for in TIAM-ECN while being absent in the PROMETHEUS projections. In addition, both models show increasing electrification of energy used in buildings in the variants assuming lower costs for heat pumps, while increased energy prices reduce total energy consumption for buildings.

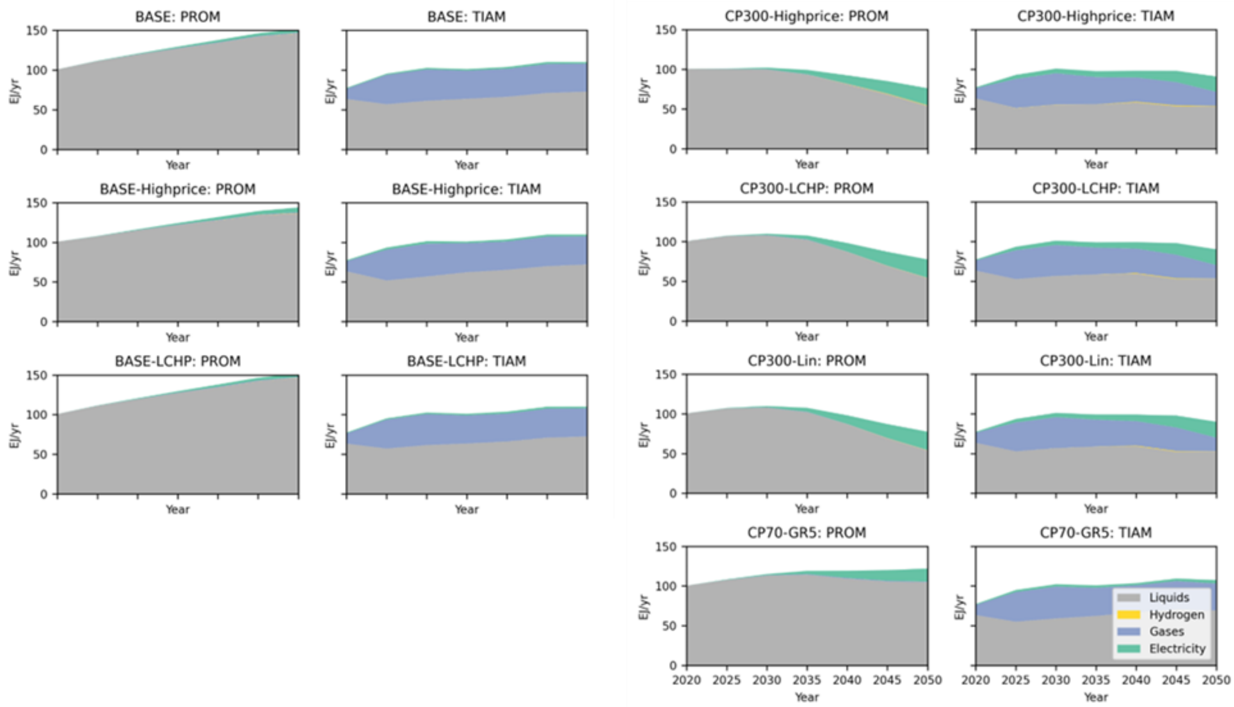


Figure 27:Global energy use in transportation by fuel.

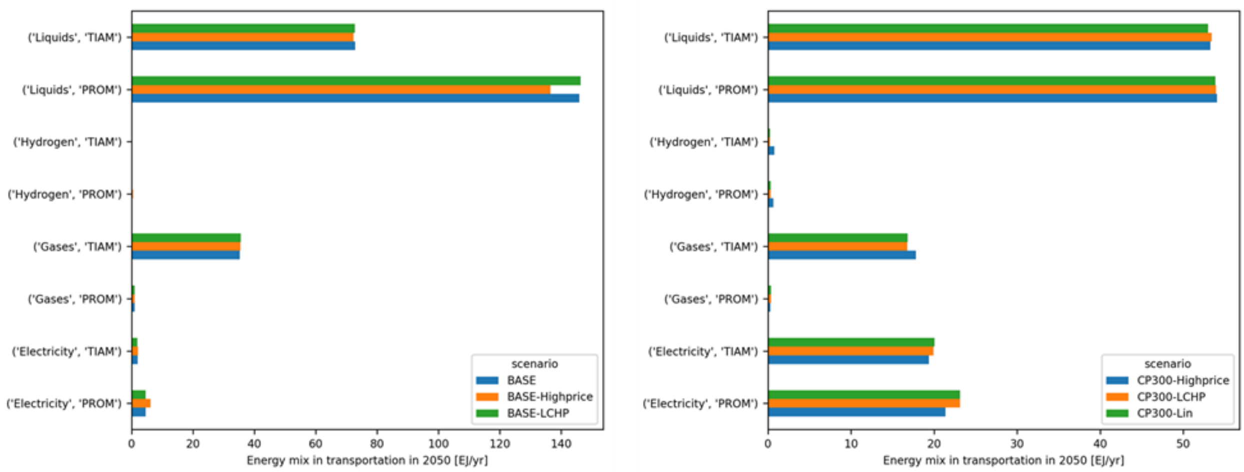


Figure 28:Energy mix in transportation in 2050 for the BASE (left) and the CP300 (right) scenarios.

Figure 27 presents the model-based projections for the transport sector mix. In all scenarios and for both models, liquid fuels are projected to remain the main energy carrier in use until the middle of the century. TIAM-ECN projects a substantial role for gas-based transportation, while this is essentially negligible in PROMETHEUS. Both models project a slight downward trend in total transport energy use in the CP300 scenarios relative to BASE variants, with electricity steadily gaining a growing share over the other energy carriers. Looking at the final 2050 contributions in Figure 28 we see that the model projections are consistent across scenarios, the main differences being: liquid fuels consumption in transport in the BASE variants is higher for PROMETHEUS than for TIAM-ECN; the share of gaseous fuels in the mix is nearly zero in all projections with PROMETHEUS, while these fuels can play a substantial role according to TIAM-ECN.

Figure 29 shows projections for the industry sector. The trends across BASE scenario variants are similar for each model. An overall growth of industrial energy consumption is projected by both models driven by increased industrial activity; in the case of PROMETHEUS a steady increase is observed for all carriers (with industrial energy consumption dominated by electricity and gases), while for TIAM-ECN the growth is more scattered throughout the time horizon and is mainly due to solid fuels. In the CP300 variants, PROMETHEUS projects first an overall decrease of energy consumption in industry (increasing energy efficiency) and then an increase mainly driven by gas and electricity, while liquid and solid fuels are nearly phased out by 2050. The trends in the CP300 scenarios are different in TIAM-ECN: electricity – the dominant fuel until 2040 – is largely replaced by gases, hydrogen and solid fuels in the last decade of the century. The reason behind this trend (especially the increase in solids) is not clear and should be further investigated.

In Figure 30 we examine the various energy carrier contributions to the industry mix in 2050. In the BASE variants the models display a consistent picture, with similar final contributions from the different carriers and comparable trends across variants. In the CP300 variants, TIAM-ECN projects a much larger role for solids, liquids, hydrogen and heat than PROMETHEUS (which considers the increased electrification as the major option to decarbonise industries). The trend is reversed for gases and electricity, i.e. for these carriers TIAM-ECN projects a lower contribution than PROMETHEUS.

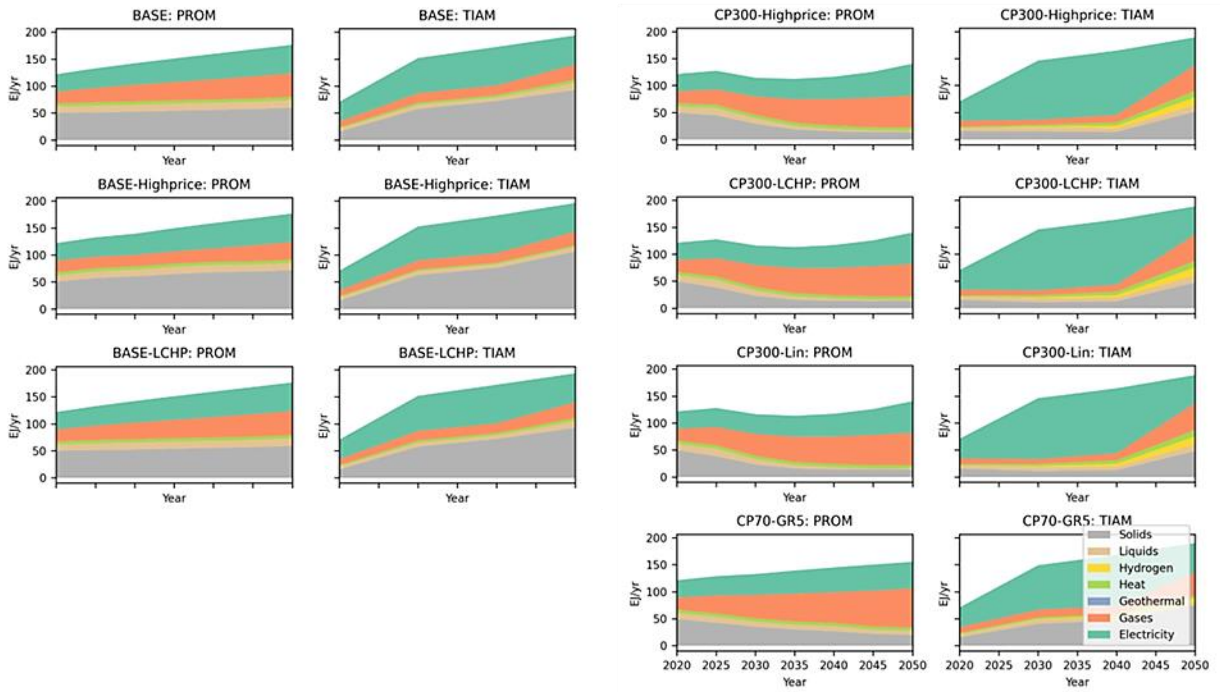


Figure 29:Global energy use in industry by fuel.

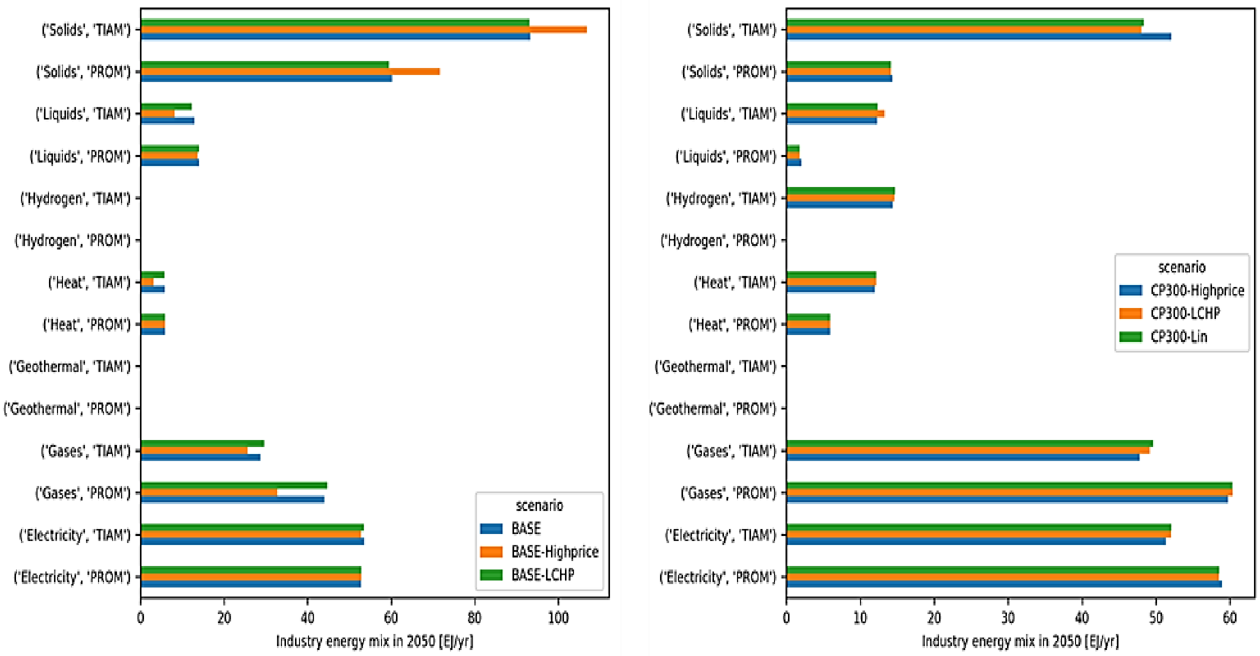


Figure 30:Energy mix in industry in 2050 for the BASE (left) and CP300 (right) scenarios.

6.5.2. Diagnostic indicators

In addition to analyzing the development of the global energy system mix, we also employ a series of diagnostic indicators that help us to characterize the sensitivity of our two IAMs to the various scenario assumptions. These indicators follow the analysis of Harmsen et al. (2021).

In Figure 31 we present projections of the Relative Abatement Index (RAI) in the various scenarios. The RAI expresses the relative CO2 emission reduction in a specific scenario with respect to BASE. The index is calculated according to the following formula:

$$RAI(y) = \frac{CO_2\,(BASE, y) - CO_2(SCEN, y)}{CO_2(BASE, y)}$$

Where *y* is the projection year, and *SCEN* indicates the specific scenario under consideration.

In the BASE scenario variants, the overall emission reductions are limited (slightly larger in the high energy price case in PROMETHEUS). In all CP300 scenarios the RAI increases over time, due to the increasing stringency of the mitigation effort and the increasing carbon price. The trends shown in the CP300 variants reveal that both models display relatively similar responses to carbon price, with PROMETHEUS being consistently more sensitive to this parameter than TIAM-ECN.

Figures 32 and 33 show projections for, respectively, Carbon Intensity (CI) and Energy Intensity (EI). The former expresses the total emissions per unit of final energy used in the system, while the latter measures final energy per unit of gross domestic product (GDP). In a decarbonizing world one expects to observe steadily decreasing CI trends, as more low and zero-carbon technologies are being used to provide energy services replacing options based on fossil fuels. Similarly, with increasing energy efficiency trends one expects to see a decoupling of energy use and GDP growth resulting in a downward EI trajectory. The models display roughly constant CI in the BASE scenario variants and decreasing CI trajectories in the CP300 scenarios – consistently with the fact that the latter scenario family corresponds to large decarbonization efforts. The impact of the LHPC and Highprices scenario assumptions is limited in all scenarios, indicating that the models are more sensitive to decarbonization constraints than heat pump costs and energy prices. Energy intensity displays a rather consistent downward trend in all scenarios for TIAM-ECN. In the PROMETHEUS projection the EI decrease is more pronounced in the CP300 variants than in the BASE ones, indicating that for this model high carbon prices induce significant energy efficiency improvements in all demand sectors.

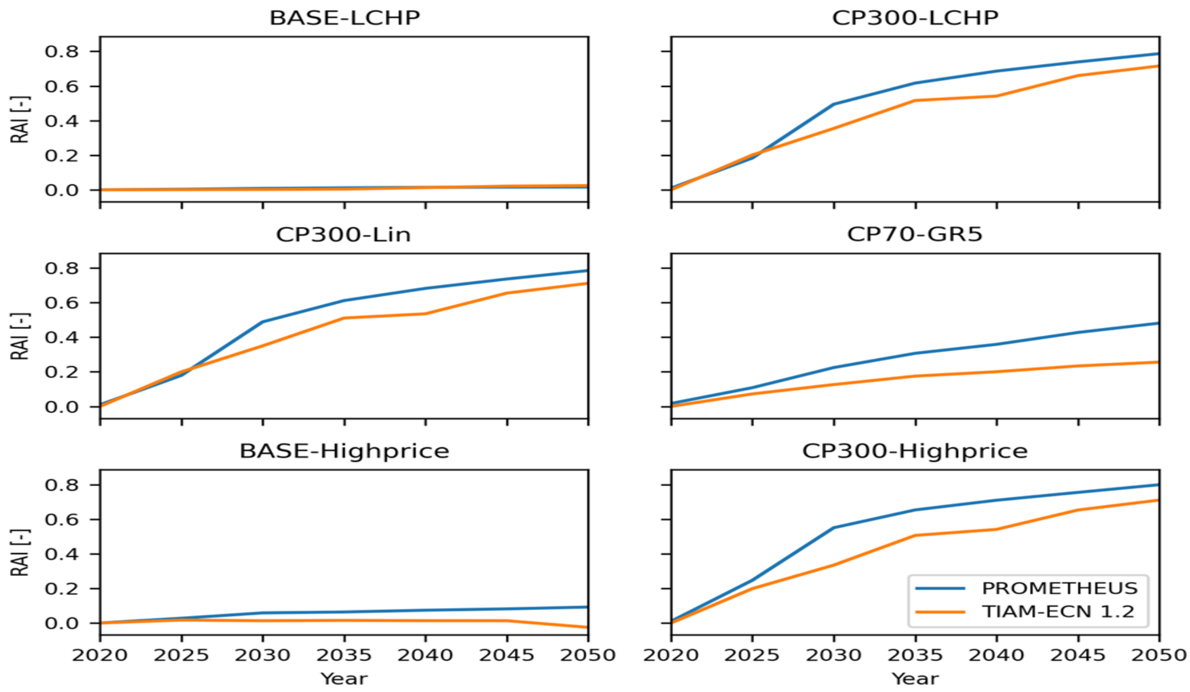


Figure 31:Relative abatement index.

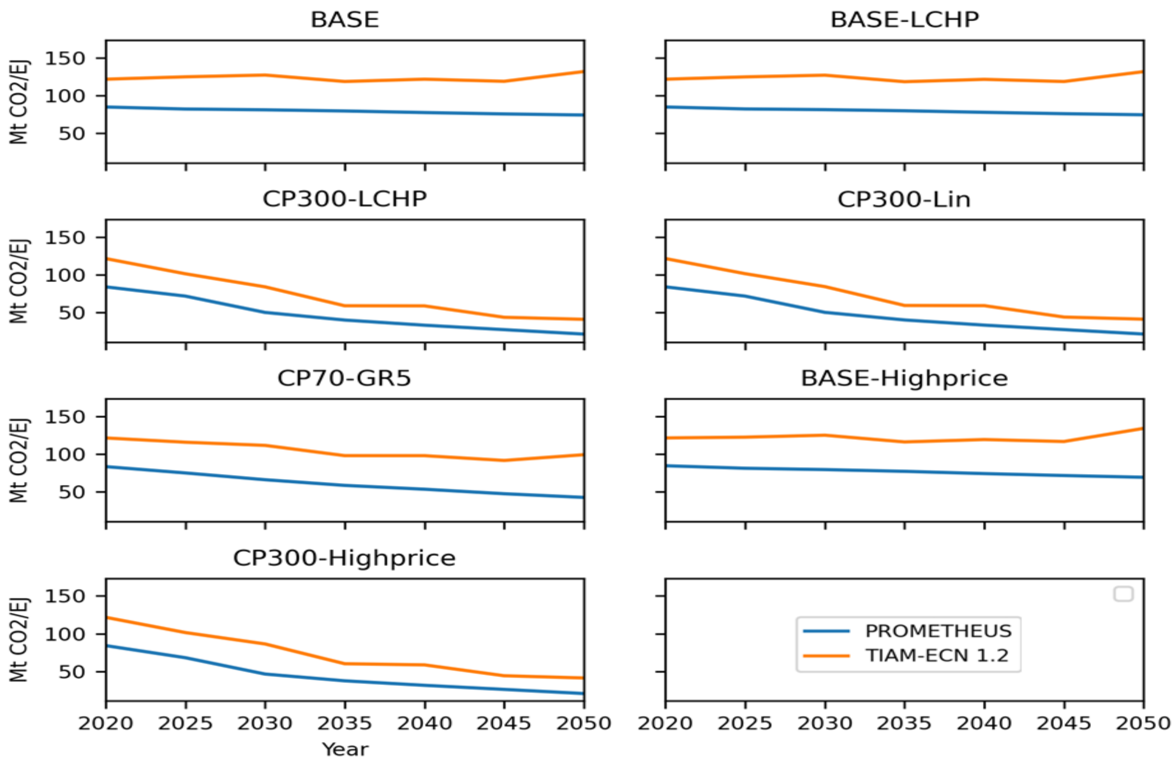


Figure 32:Carbon intensity.

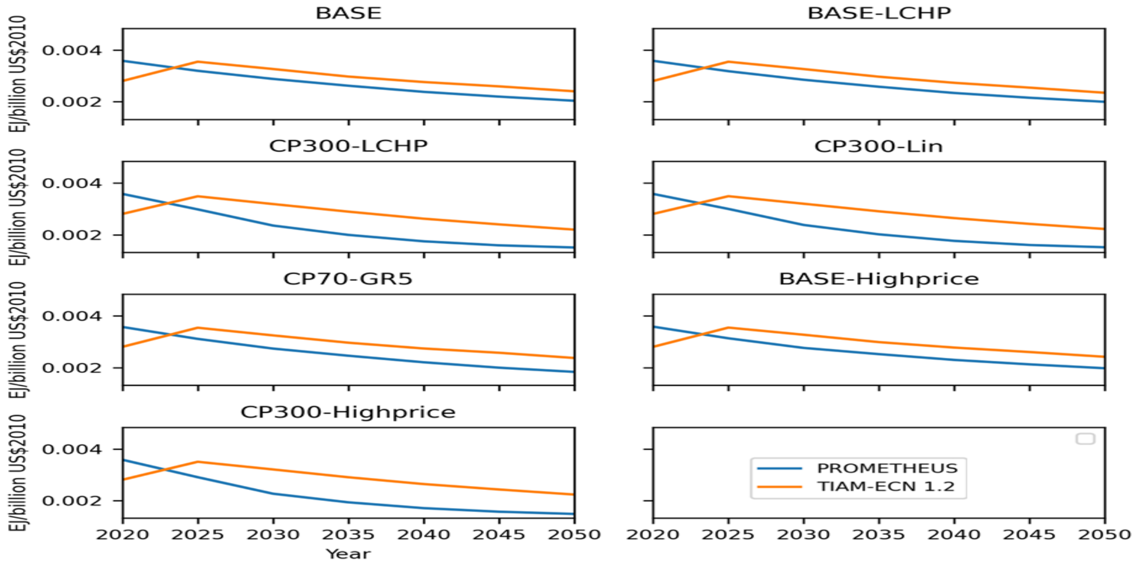


Figure 33:energy intensity.

In figures 32 and 33 we report the relative reduction in, respectively, carbon and energy intensity with respect to BASE in the climate control scenarios. The overall trends for CI are very similar in the two models, with PROMETHEUS being slightly more sensitive to carbon price than TIAM-ECN. This difference becomes larger for EI, with PROMETHEUS reaching Energy Intensity reductions that are more than three times larger than those in TIAM-ECN.

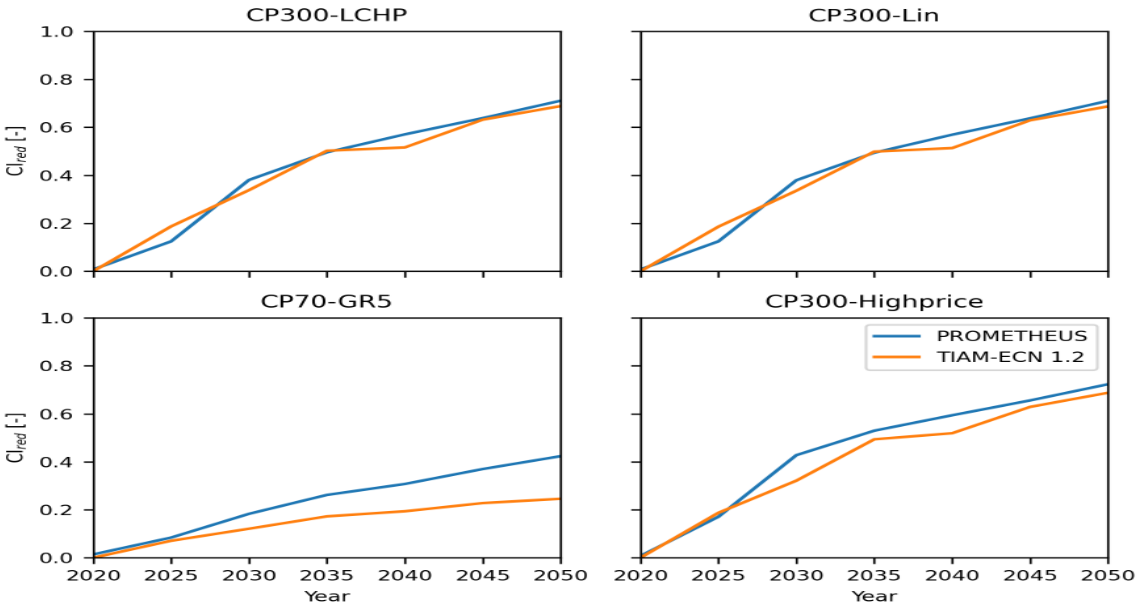


Figure 34:Carbon intensity reduction in carbon pricing scenarios.

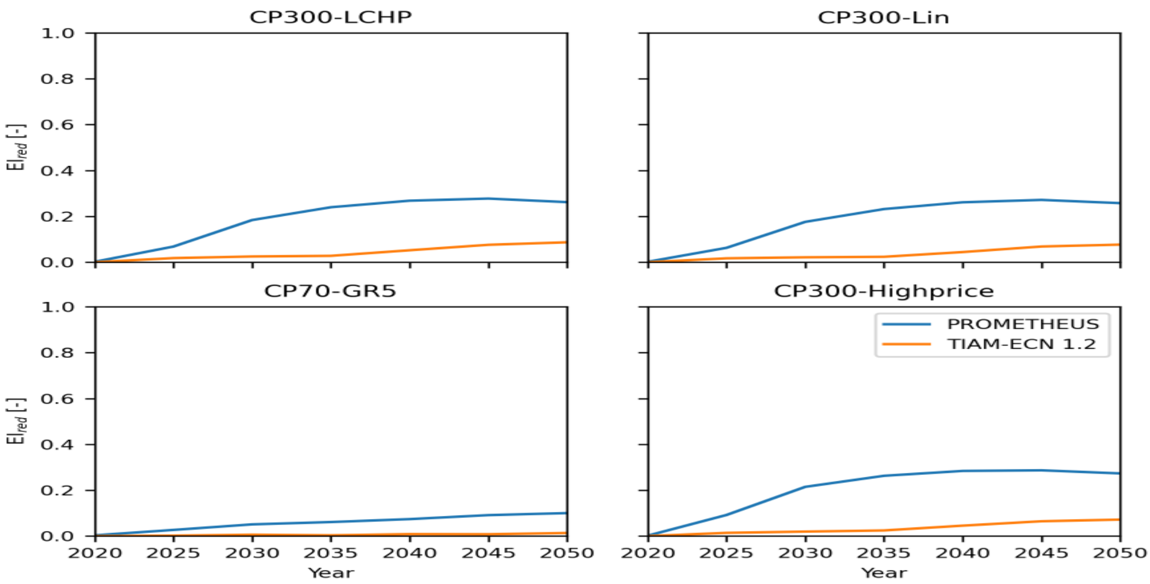


Figure 35:Energy intensity reduction in carbon pricing scenarios.

Finally, we estimate the Emission Reduction Type (ERT) index. This is calculated for each year *y* and scenario *SCEN* as:

$$ERT(SCEN, y) = \frac{CI_{red}(SCEN, y)}{CI_{red}(SCEN, y) + EI_{red}(SCEN, y)}$$

Where CI_{red} and EI_{red} are, respectively, the CI and EI reduction indexes reported in figures 14 and 15. An ERT close to 1 indicates that the CO_2 abatement in the respective scenario is mainly obtained by reducing emissions on the supply side. Conversely, ERT values close to 0 reveal that decarbonization is achieved primarily via energy efficiency enhancements on the demand side. Based on this, the ERT can be interpreted as the share of RAI attributed to energy supply (resp. demand) side measures. This is shown in Figure 36, for the four carbon price scenarios and for each model individually. While the overall trends are – for each model – very similar across scenarios, Figure 36 shows that decarbonization in TIAM-ECN is predominantly achieved through supply-side changes (more than 90% of the emissions reduction effort), while in PROMETHEUS demand-side changes (e.g. efficiency improvements) also provide a substantial contribution (ranging from 20% to 40%).

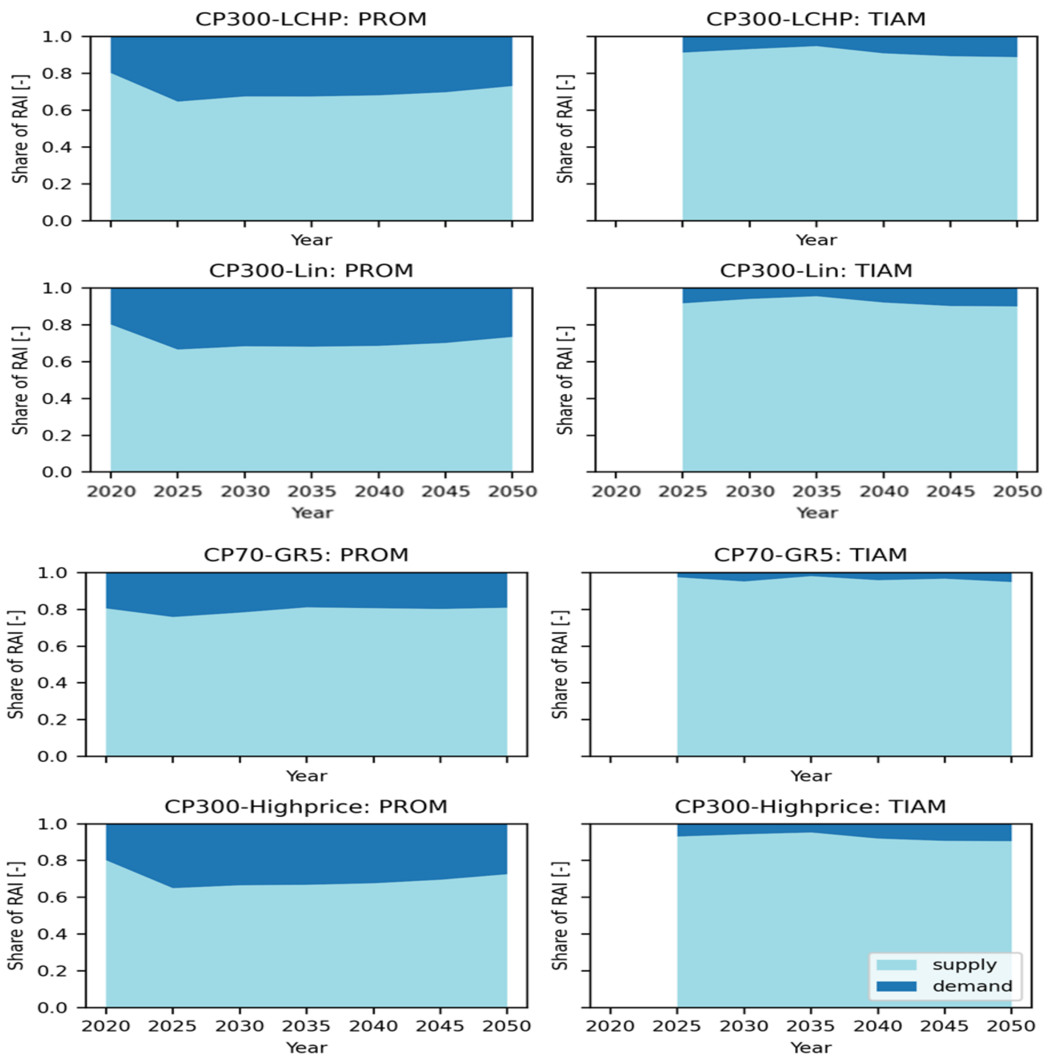


Figure 36:Supply and demand shares of RAI according to the Emission Reduction Type index.

6.5.3. System-level effects of increased energy efficiency in global low-carbon scenarios: A model comparison

The development of energy demand determines the size of future energy supply and the corresponding investment costs, and thus directly influences the assessment of climate change mitigation challenges. Large increases in energy consumption may put an additional burden to the energy supply sector to further reduce emissions (Grubler et al., 2018). Accordingly, most global mitigation scenarios tend to focus on supply-side options (Rogelj et al., 2018) and commonly require the large-scale uptake of negative emission technologies, such as those based on carbon capture and storage (CCS) in combination with bio-based fuels. These technologies, however, face large uncertainty and critical limitations related to e.g. their high costs, the availability of suitable sites for CO_2 storage and land for growing bio-energy crops, and sustainability of upscaling their deployment (Fuss et al., 2018; Nemet et al., 2018). On the other hand, there exist a high potential for reducing energy consumption in end-use sectors, without adversely affecting the comfort of living for the population, by deploying enhanced energy efficiency solutions, technologies, and practices. Pursuing such efficiency options on the demand-side provides a complementary avenue to achieving Paris goals that may reduce the necessity to invest heavily in expensive and uncertain clean technologies on the supply side, while also reducing the pressure on exploitation of energy resources to provide human needs like housing and mobility (Grubler et al., 2018). The importance of energy efficiency for reducing emissions is widely recognized: 143 out of 189 Parties explicitly mention energy efficiency in their Nationally Determined Contribution (NDC) plans (IEA 2016). However, while many options and technologies to increase energy efficiency are readily available in all sectors, current deployment levels are below those required to meet the Paris Agreement goals. Annual investments in energy efficiency amount to 290 billion US$ (IEA 2020b), while a pathway to achieve net zero emissions by 2050 requires annual efficiency-related investment of 1.3 trillion US$ by 2030 (IEA 2021).

Most analyses of the role of energy efficiency in climate mitigation scenarios are currently based on bottom-up detailed assessments with large technological granularity (e.g. Hummel et al., 2021; Fleiter et al., 2018; Swan et al., 2009). However, these often lack the connection with the global climate target narrative and cannot capture system-level effects, including changes in energy prices, supply and/or consumer behavior. Therefore, there is a need to expand Integrated Assessment Models (IAMs) to appropriately represent the technical and behavioral details related to energy efficiency (Brugger et al., 2021; Grubler et al., 2018; Fotiou et al., 2019), while capturing system level effects (e.g. demand-supply interactions, sectoral shifts and spillovers, carbon price and system costs) in a holistic, comprehensive and consistent energy-environment-economy framework. In this way, potential linkages, synergies and trade-offs between ambitious climate targets and energy efficiency policies can be systematically assessed.

In this study we investigate a set of scenarios to meet the Paris goals using two well-established IAMs: PROMETHEUS and TIAM-ECN. Both models are based on a detailed bottom-up description of the energy system, a specific regional disaggregation and an estimated development of future sectoral energy demand driven by exogenous projections of economic and population growth. At the same time, the inner workings of the two models are different, since each model is characterized by a set of unique design choices and assumptions (e.g. the parametric description of processes and technologies, the way in which interactions between sectors are represented). Because of this diversity one can expect that the models will respond differently to changes in input parameters and policy settings. The use of two models increases the robustness of the analysis and allows the derivation of policy-relevant recommendations for a cost-efficient and socially acceptable transition to a decarbonized economy.

This study aims at exploring the effects of a strong push in energy efficiency on the global energy system under stringent climate policies. For this purpose, we design five scenarios combining assumptions regarding (i) climate change mitigation targets, (ii) energy efficiency improvements, and (iii) carbon price developments. These scenarios are then implemented in PROMETHEUS and TIAM-ECN modelling frameworks. Table 3 presents a summary of the key assumptions used in each scenario.

The first scenario, REF, is based on the continuation of existing energy and climate policies, in consistency with Roelfsema et al. (2020). The energy system develops in line with current trends, including already legislated climate policies until 2030 and further cost improvements in low-carbon technologies. Beyond that, we impose no binding climate change mitigation targets and no technology or sector-specific increases in energy efficiency. Slightly higher overall energy efficiency levels are still achieved endogenously throughout the modeling horizon since energy intensity of GDP is assumed to keep improving at rates close to historical values in each region. The 2DC scenario assumes a cost-optimal trajectory compatible with a well-below 2°C increase in global warming, in line with the Paris goal. Global CO_2 emissions from fossil fuels and industrial operations in the 2016-2050 period are exogenously limited to a budget of 850 Gt CO_2 (in line with Mc Collum et al 2018). No efficiency improvements are assumed beyond those induced by carbon pricing (and those assumed in REF based on continuation of historic trends). The 2DC_eff scenario is a variant of 2DC in which we impose an increase in energy efficiency in the most widespread technology classes across all demand sectors, accompanied by an increase in the corresponding capital costs for a technology category, derived from Fotiou et al. (2019) and the 2020 EU Reference scenario report (EC, 2021a). 2DC_eff aims at illustrating the possible effects of a consumers' shift towards purchasing the most energy efficient technologies in the market that could be induced by ambitious measures targeting the gradual phase-out of low-efficiency energy appliances in favor of high-efficiency technology standards, the implementation of energy labelling directives, increased renovation rates (e.g. induced by subsidies), and the application of stringent energy efficiency standards. In TAX_eff the assumptions on increased energy efficiency are maintained, while the global carbon price is imposed exogenously to the same level as in the 2DC scenario. The 1.5DC scenario assumes a more stringent 2016-2050 global carbon budget of 600 Gt CO_2, resulting in a maximum temperature increase of 1.5°C by 2100 (Rogelj et al 2018), by implementing a universal carbon pricing scheme in all regions and sectors.

Table 3: Model scenarios.

Scenario	Climate Targets	Energy Efficiency	Carbon Price
REF	No additional targets beyond current 2030 climate policies	Endogenous	Endogenous
2DC	Global 2016-2050 carbon budget of 850 Gt CO_2 (compatible with below 2°C)	Endogenous	Endogenous
2DC_eff	Global 2016-2050 carbon budget of 850 Gt CO_2 (compatible with below 2°C)	Exogenously increased in all sectors to levels higher than in 2DC	Endogenous
TAX_eff	No additional targets beyond current 2030 climate policies	Exogenously increased in all sectors to levels higher than in 2DC	Exogenous, based on 2DC scenario
1.5DC	Global 2016-2050 carbon budget of 600 Gt CO_2 (compatible with a 1.5°C)	Endogenous	Endogenous

Figure 37 shows the projections for energy-related CO_2 emissions (top panel) and carbon price (bottom panel) obtained with PROMETHEUS and TIAM-ECN. In the REF scenario both models project a limited increase of global CO_2 emissions by 2050, despite the robust growth of global economic activity, indicating a relative decoupling of emissions from GDP growth. This decoupling is triggered by the adoption of low-carbon technologies (e.g. PV panels, wind turbines, electric vehicles) and high-efficiency processes, induced by their respective future cost reductions. In the 2DC and 2DC_eff scenarios, ambitious climate policies are applied resulting in large reductions of global emissions (of about 80% below REF levels in 2050). The emission cap triggers an endogenous increase in carbon price which applies uniformly to all regions and economic sectors to achieve emission reductions when and where it is most cost-efficient, thus ensuring that the global climate goal is achieved with the lowest possible costs globally. The required carbon price is lower in the increased efficiency scenario showing that the implementation of ambitious efficiency policies, standards and regulation may reduce the need for high carbon pricing to achieve the same mitigation target. In PROMETHEUS, the required carbon price appears to be more sensitive to the implementation of higher efficiency standards than in TIAM-ECN, as the former includes a more detailed description of energy end use technologies and related efficiency measures, while TIAM-ECN has a higher granularity in representing energy supply. This is especially evident in 2050 as the carbon price in 2DC_eff is less than half of that in 2DC for PROMETHEUS, whereas for TIAM-ECN the reduction is only 10%.

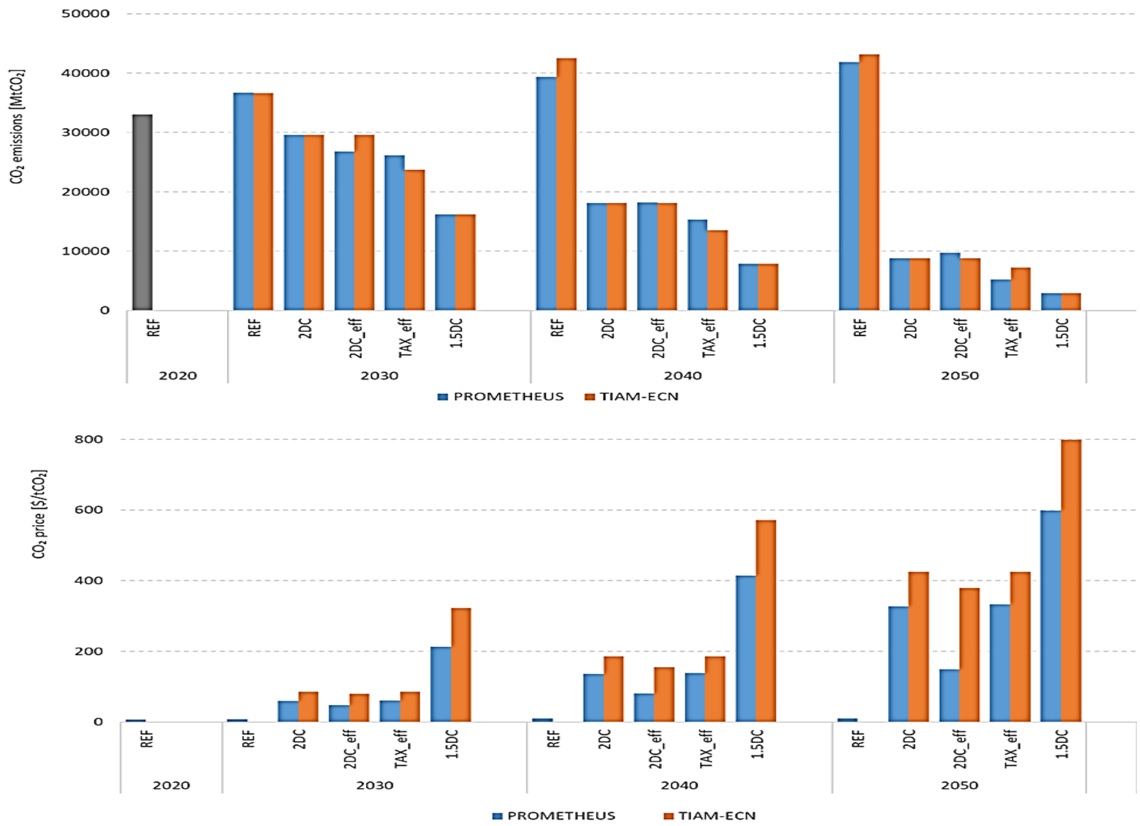


Figure 37:CO2 emissions (top panel) and carbon price (bottom panel).

In the REF scenario energy consumption from buildings grows steadily at similar rates for both models, because of our assumptions on population and GDP growth, increasing urbanization and rising income and living standards in developing economies (Figure 38). The application of emission and efficiency constraints in the low-carbon scenarios causes a reduction of energy consumptions in buildings - triggered by an increased rate and depth of renovation, a more rational use of energy and the uptake of more efficient fuels and equipment - and the emergence of electricity and hydrogen for heating. PROMETHEUS projects larger energy savings than TIAM-ECN, with final energy consumption declining by about 20%-33% from REF levels in 2050. While the use of oil in buildings is completely phased out by 2050 in most low-carbon scenarios in the PROMETHEUS projections, TIAM-ECN maintains a small amount of oil consumption in all scenarios. This is mainly occurring in developing economies, such as several countries in Sub-Saharan Africa that lack the means to deploy the required infrastructure to support a full-scale switch to cleaner alternatives by mid-century (see e.g. van der Zwaan et al, 2018).

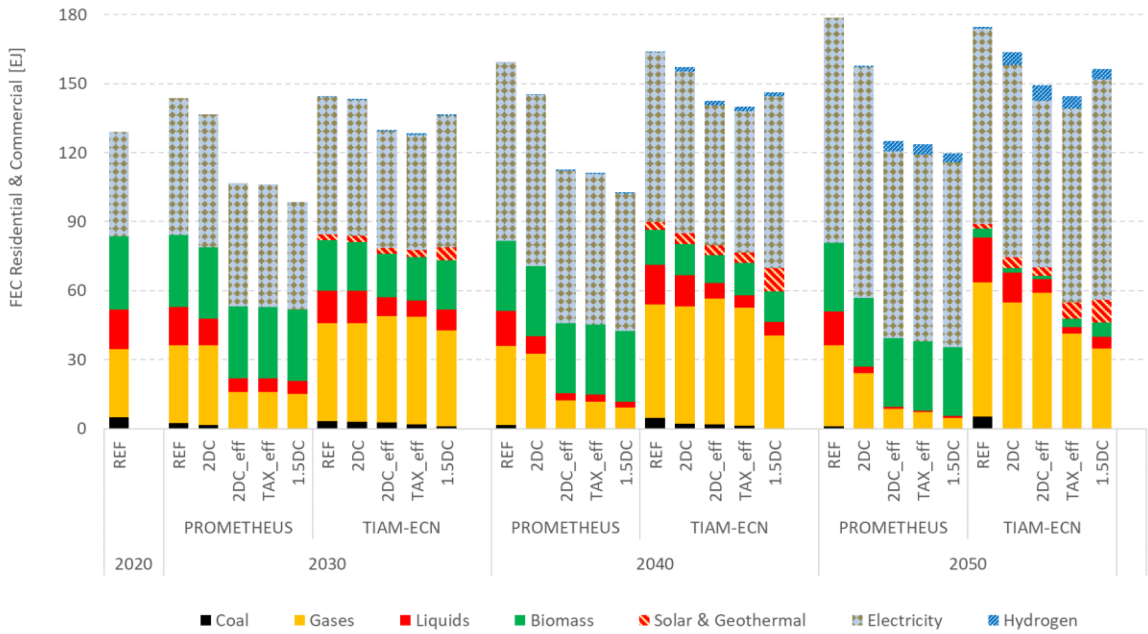


Figure 38:Final energy consumption in residential and commercial buildings.

Figure 39 shows the projections for CO2 removal in the various scenarios, mostly referring to the uptake of CCS technologies in the electricity generation, industry, and fuel production sectors. CCS processes are used in all low-carbon scenarios, in quantities that depend on the model used and the scenario-specific assumptions. In general PROMETHEUS is less optimistic than TIAM-ECN regarding the potential spread of CCS technologies, relying more heavily on energy efficiency improvements to achieve decarbonization. Maximum CO2 capture levels are reached in 2050 in the carbon cap scenarios: 5 GtCO2/yr in 2DC and 16 GtCO2/yr in 1.5DC for PROMETHEUS and TIAM-ECN, respectively. The efficiency push in the "_eff" scenarios cause a significant decrease in the need for CCS deployment with CO2 removal in 2050 being 90% and 13% lower than in 2DC for, respectively, PROMETHEUS and TIAM-ECN; thus the PROMETHEUS projection indicates that in the presence of strong energy efficiency measures, there is little need for CCS uptake, as carbon prices stay considerably lower than in 2DC.

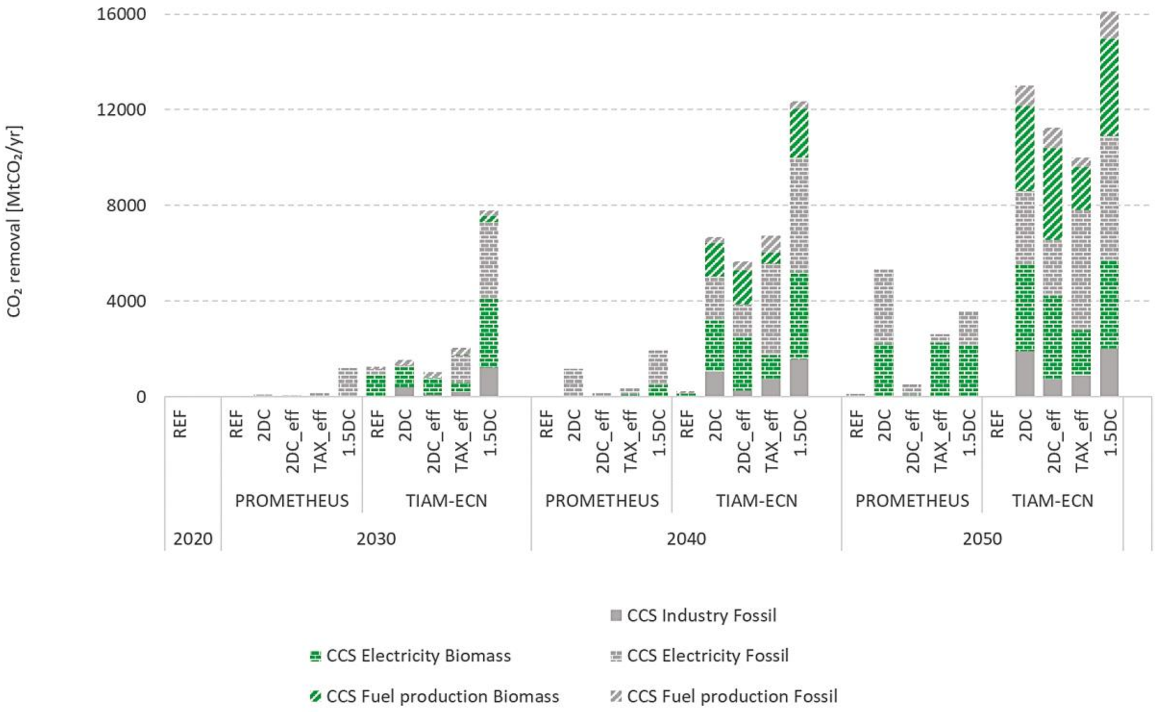


Figure 39:Uptake of CO2 removal technologies.

The model-based analysis identified several pillars to achieve global decarbonization targets. First, a large expansion of energy generation from renewable sources is projected especially prominent in the power generation sector, which in some cases becomes almost carbon-free by 2050. Second, the dependence of end-use energy services from fossil fuels can be lessened through increased electrification in the demand sectors, complemented by the deployment of advanced biofuels and hydrogen when electrification is neither technically feasible nor economically efficient. Third, energy demand savings through uptake of enhanced energy efficiency technologies or through improved thermal insulation of buildings proves to be a robust strategy to reduce CO_2 emissions across the economy. Fourth, the deployment of carbon removal technologies, such as CCS, is necessary to achieve decarbonization targets, but CCS requirements are considerably lower if ambitious energy efficiency policies are implemented, thus reducing society's reliance on a costly and risky technology, currently not used at scale.

Policies combining the promotion of high energy efficiency with a carbon cap can lead to lower carbon prices than those focusing solely on capping emissions. Utilizing energy efficiency policies together with a moderate carbon price could provide the required additional effort to move towards a “well below” 2°C future down to and possibly even below 1.5°C, without requiring very high CO_2 prices. Our analysis shows that the adoption of high efficiency standards can contribute to mitigating the environmental, economic, ethical and social risks that emerge from relying on currently immature carbon removal technologies, such as CCS (Van Vuuren et al 2018). The diffusion of high energy efficiency technologies also leads to lower supply-side investments and may bring important co-benefits, e.g. in terms of job creation (see e.g. IEA, 2020a), reduced air pollution and lower dependency on energy imports. Our analysis using two leading IAMs under a range of policy and technology assumptions confirms that scenarios driven by energy demand reductions provide a robust alternative to technology-driven scenarios, possibly entailing some significant economic, social, and environmental benefits (Creutzig et al., 2018; Grubler et al., 2018). The energy efficiency assumptions simulated here do not reduce living standards of consumers (Rao et al., 2017) and do not constrain the thermal comfort or the use of appliances (Levesque et al., 2019).

Our model comparison analysis shows that pushing enhanced energy efficiency can be an effective strategy to pursue ambitious emission reduction objectives and pave the way for the transformation required to meet the Paris goals. From a policy perspective, however, achieving efficiency acceleration remains a challenge. Large upfront investments are needed to expand the deployment of high-efficiency processes and the purchase of efficient equipment and technologies by consumers and scale up the implementation of renovation strategies in the residential and commercial sectors. Advancing the uptake of high efficiency end-use technologies, such as household appliances, may prove particularly difficult for low-income households, and policy makers are already concerned about this, as shown in the EU 'Fit for 55' policy package (EC, 2021b). Energy efficiency policies should be designed so as to target a just and inclusive energy transition, paying special attention to the social groups that are most at risk of energy poverty (see e.g. Dalla Longa et al., 2021b). Important policy measures in this regard are those explicitly addressing behavior and lifestyle changes that should complement traditional economic instruments, such as subsidies and low-cost loans, and enforcing regulation and building or technology standards.

7. Way forward and Conclusions

The WHY project aims to improve the energy demand modelling to forecast the domestic sector's energy consumption and improve the representation of energy consumption and energy efficiency in large-scale Energy System Models. The deliverable D5.1 focuses on the design and development of five distinct use cases capturing a wide diversity of contexts from the local to the city, European and global level. Through the actual application of the WHY Toolkit in diverse situations and use cases, we directly contribute to the Toolkit validation by comparing both the techno-economic decisions and policy recommendations made in the 5 Use Cases with and without the use of the Toolkit. The current report contains the description of implementation of the Use Cases on the WHY Toolkit, the data collected, the exogenous and endogenous factors influencing the use cases, the scenarios assessed, and the results of the test simulations carried out in the validation process.

The Positive Energy District Use Case in Maintal focuses on creating a positive energy district and optimizing it for energy consumption and provision. This Use Case is an example of a successful energy community in Germany. The aim of this Use Case is to create a decentralized and sustainable energy system by leveraging renewable energy sources and energy storage systems. The Energy Cooperative case analyses a specific type of energy community that operates as a cooperative business uses the WHY-Toolkit to simulate the behavioral change of residential consumers in response to modification of the electric tariff structure. Effective cooperation and planning are extremely important components in ensuring the success of energy community projects. This involves identifying and addressing the technical, economic, and regulatory challenges that energy communities' deals (grid connection, energy storage, market participation). The main objective of the Energy community use case is to show the way that new energy community-based business models can advance the energy communities and lead to climate neutral cities.

The aim of the European Use Case is to explore the impact of EU-wide energy and climate policies on achieving the EU's goals on climate change mitigation and energy efficiency. The Global Use Case investigates the implications of ambitious climate and energy efficiency policies on the future development of the global energy mix and the buildings sector. These two use cases are based on the soft-linkage of the WHY Toolkit with large-scale ESMs (like PRIMES, TIAM and Prometheus) to enhance their representation of the load profiles and consumer behaviour. The validation process was implemented based on the development of a set of diagnostic scenarios to evaluate the behaviour of the modelling suite under varying input assumptions (e.g. carbon prices, heat pump costs, global energy prices). The report also includes two peer-reviewed papers (Dalla Longa et al, 2022, Fragkos 2022) aiming to quantify the potential to reduce emissions through accelerated energy efficiency in end-use sectors and the synergies between energy efficiency and carbon taxation policies in the EU and major emitters globally using the two well established Integrated Assessment Models PROMETHEUS and TIAM-ECN.

Building upon the designed and developed Use Cases, stakeholder interactions for scenario design and using the innovative WHY Toolkit (and its linkages with large-scale ESMs through model plug-ins), the next tasks of WP5 will develop the new generation pathways of energy systems at local, city, national and EU levels capturing in detail the specifics of the 5 Use Cases and consumer heterogeneity. The subsequent reports D5.2 and D5.3 will assess the impacts of a broad range of policy measures (covering both market-oriented and non-market interventions) for all 5 Use Cases considering the specificities and heterogeneities of each Use Case. The policy scenarios will include an improved representation of existing and planned instruments as well as market and non-market policies that can influence energy decisions and consumer behavior in buildings and promote efficient energy use (i.e. energy taxation, supportive policies, measures to address barriers and market failures, subsidies for RES/EV, informational campaigns, DR schemes, access to finance, ambitious ecodesign, energy performance of buildings and energy labeling, technology standards) as well as broad climate policies like Emission Trading System pricing (when relevant). The model-based data and projections will be published in an open-access database (ensuring full compliance with the FAIR principles) to be reused by the stakeholders and the research community, while a policy brief including a Social Impact Assessment will be developed as part of the deliverable D5.3, aiming to provide policy-relevant recommendations.

REFERENCES

Fotiou, T.; de Vita, A.; Capros, P. Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonisation in the EU. *Energies* 2019, *12*, 2745. https://doi.org/10.3390/en12142745

Fotiou, T.; Capros, P.; Fragkos, P. Policy Modelling for Ambitious Energy Efficiency Investment in the EU Residential Buildings. *Energies* **2022**, *15*, 2233. https://doi.org/10.3390/en15062233

WHY Deliverable D1.3, D1.3 Use Case Definition: objectives, scope, variables, available at: https://www.why-h2020.eu/fileadmin/Inhalte/Dokumente/WHY_Deliverable__D1.3_1.0.pdf

COM(2020) 662 final on ‘A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives’ 2020 European Commission [Online]. Available at: https://eurlex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662 (Accessed: 22 May 2021)

Energy Performance of Buildings Directive 2010/31/EU (EPBD) 2019 European Commission [Online]. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficientbuildings/energy-performance-buildings-directive_en (Accessed: 22 May 2021)

Mathijs Harmsen *et al* 2021 *Environ. Res. Lett.* **16** 054046**DOI** 10.1088/1748-9326/abf964

WHY Workshop Summary Report Improving Demand-side Modelling to Inform Ambitious Climate Policies in the European Union, Available at: https://www.why-h2020.eu/fileadmin/Inhalte/Dokumente/WHY__The_EU_Use_Case_Workshop_Report.pdf

European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, De Vita, A., Capros, P., Paroussos, L., et al., EU reference scenario 2020 : energy, transport and GHG emissions : trends to 2050, Publications Office, 2021, https://data.europa.eu/doi/10.2833/35750

Francesco Dalla Longa et al. System-level Effects of Increased Energy Efficiency in Global Post-COVID Low-carbon Scenarios: a Model Comparison Computers & Industrial Engineering, 2021

Panagiotis Fragkos Analysing the Systemic Implications of Energy Efficiency and Circular Economy Strategies in the Decarbonisation Context, AIMS Energy, 2022

Andreas Andreou et al. Assessing Lifestyle Transformations and Their Systemic Effects in Energy-System and Integrated Assessment Models: A Review of Current Methods and Data MPDI, 2022

van den Berg, N.J. et al. (2019) ‘Improved modelling of lifestyle changes in Integrated Assessment Models: Cross-disciplinary insights from methodologies and theories’, Energy Strategy Reviews, 26, p. 100420. Available at: https://doi.org/10.1016/j.esr.2019.100420.

Brand, C., Anable, J. and Morton, C. (2019) ‘Lifestyle, efficiency and limits: modelling transport energy and emissions using a socio-technical approach’, Energy Efficiency, 12(1), pp. 187–207. Available at: https://doi.org/10.1007/s12053-018-9678-9.

Brand, C., Tran, M. and Anable, J. (2012) 'The UK transport carbon model: An integrated life cycle approach to explore low carbon futures', Energy Policy, 41, pp. 107–124. Available at: https://doi.org/10.1016/j.enpol.2010.08.019.

Creutzig, F. et al. (2016) 'Beyond Technology: Demand-Side Solutions for Climate Change Mitigation', Annual Review of Environment and Resources, 41(1), pp. 173–198. Available at: https://doi.org/10.1146/annurev-environ-110615-085428.

Creutzig, F. et al. (2018) 'Towards demand-side solutions for mitigating climate change', Nature Climate Change, 8(4), pp. 268–271. Available at: https://doi.org/10.1038/s41558-018-0121-1.

Dalla Longa, F. et al. (2022) 'System-level effects of increased energy efficiency in global low-carbon scenarios: A model comparison', Computers and Industrial Engineering, 167(May), p. 108029. Available at: https://doi.org/10.1016/j.cie.2022.108029.

EC (2018) IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM (2018) 773: A Clean Planet for all A European long-term strategic vision for a prosperous , modern , competitive and climate neutral economy. European Commission: Brussels, Belgium. Available at: https://ec.europa.eu/clima/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf.

Fragkos, P. (2022) 'Analysing the systemic implications of energy efficiency and circular economy strategies in the decarbonisation context', AIMS Energy, 10(2), pp. 191–218. Available at: https://doi.org/10.3934/energy.2022011.

Fragkos, P., Kouvaritakis, N. and Capros, P. (2015) 'Incorporating Uncertainty into World Energy Modelling: the PROMETHEUS Model', Environmental Modeling and Assessment, 20(5), pp. 549–569. Available at: https://doi.org/10.1007/s10666-015-9442-x.

Gaur, A. et al. (2022) 'Low energy demand scenario for feasible deep decarbonisation: Whole energy systems modelling for Ireland', Renewable and Sustainable Energy Transition, 2(August), p. 100024. Available at: https://doi.org/10.1016/j.rset.2022.100024.

Grubler, A. et al. (2018) 'A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies', Nature Energy, 3(6), pp. 515–527. Available at: https://doi.org/10.1038/s41560-018-0172-6.

IEA (2021a) Net Zero by 2050: A Roadmap for the Global Energy Sector, Net Zero by 2050. Paris, France: OECD Publishing. Available at: https://doi.org/10.1787/c8328405-en.

IEA (2021b) World Energy Outlook 2021. Paris, France: OECD Publishing. Available at: https://doi.org/10.1787/14fcb638-en.

IPCC (2014) Climate Change 2014 Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press. Available at: https://doi.org/10.1017/cbo9781107415416.

Ivanova, D. et al. (2020) 'Quantifying the potential for climate change mitigation of consumption options', Environmental Research Letters, 15(9), p. 093001. Available at: https://doi.org/10.1088/1748-9326/ab8589.

Keppo, I. et al. (2021) 'Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models', Environmental Research Letters, 16(5), p. 053006. Available at: https://doi.org/10.1088/1748-9326/abe5d8.

Levesque, A. et al. (2021) 'Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario', Environmental Research Letters, 16(5), p. 054071. Available at: https://doi.org/10.1088/1748-9326/abdf07.

Levesque, A., Pietzcker, R.C. and Luderer, G. (2019) 'Halving energy demand from buildings: The impact of low consumption practices', Technological Forecasting and Social Change, 146(March), pp. 253–266. Available at: https://doi.org/10.1016/j.techfore.2019.04.025.

McCollum, D.L. et al. (2017) 'Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices', Transportation Research Part D: Transport and Environment, 55, pp. 322–342. Available at: https://doi.org/10.1016/j.trd.2016.04.003.

McCollum, D.L. et al. (2018) 'Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles', Nature Energy, 3(8), pp. 664–673. Available at: https://doi.org/10.1038/s41560-018-0195-z.

Pettifor, H. et al. (2017) 'Modelling social influence and cultural variation in global low-carbon vehicle transitions', Global Environmental Change, 47, pp. 76–87. Available at: https://doi.org/10.1016/j.gloenvcha.2017.09.008.

Rogelj, J. et al. (2018) 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.', in Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf.

Trutnevyte, E. et al. (2019) 'Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step', One Earth, 1(4), pp. 423–433. Available at: https://doi.org/10.1016/j.oneear.2019.12.002.

van de Ven, D.J., González-Eguino, M. and Arto, I. (2018) 'The potential of behavioural change for climate change mitigation: a case study for the European Union', Mitigation and Adaptation Strategies for Global Change, 23(6), pp. 853–886. Available at: https://doi.org/10.1007/s11027-017-9763-y.

Van Vuuren, D.P. et al. (2018) 'Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies', Nature Climate Change, 8(5), pp. 391–397. Available at: https://doi.org/10.1038/s41558-018-0119-8.

Wilson, C. et al. (2019) 'The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation', Energy Efficiency, 12(2), pp. 423–440. Available at: https://doi.org/10.1007/s12053-018-9679-8.

Yeh, S. et al. (2016) 'A modeling comparison of deep greenhouse gas emissions reduction scenarios by 2030 in California', Energy Strategy Reviews, 13–14, pp. 169–180. Available at: https://doi.org/10.1016/j.esr.2016.10.001.

IEA (2020), *World Energy Outlook 2020*, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2020, License: CC BY 4.0

IEA (2018), *World Energy Outlook 2018*, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2018, License: CC BY 4.0

IEA (2021), *World Energy Outlook 2021*, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2021, License: CC BY 4.0

Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814 , Available online: https://eur-lex.europa.eu/eli/dir/2018/410/oj, Accessed on 30/12/2022

ANNEX 1: System-level Effects of Increased Energy Efficiency in Global Low-carbon Scenarios: a Model Comparison

The annex presents the already published paper in the peer-reviewed scientific journal "Computers and Industrial Engineering". The reference can be found here:

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Abstract

Supporting investments in energy efficiency is considered a robust strategy to achieve a successful transition to low-carbon energy systems in line with the Paris Agreement. Increased energy efficiency levels are expected to reduce the need for supply-side investments in controversial technologies, such as carbon dioxide capture and storage (CCS) and nuclear energy, and to induce a downward push on carbon prices, which may facilitate the political and societal acceptance of climate policies, without adversely affecting living comfort and sustainable development. In order to fully reap these potential benefits, economies need to design policy packages that balance emission reduction incentives on both the demand and the supply side. In this paper we carry out a model-comparison exercise, using two well-established global integrated assessment models, PROMETHEUS and TIAM-ECN, to quantitatively analyze the global system-level effects of increased energy efficiency in the context of ambitious post-COVID climate change mitigation scenarios. Our results confirm the expected benefits induced by higher energy efficiency levels, as in 2050 global carbon prices are found to decline by 10%-50% and CO_2 storage from CCS plants is 13%-90% lower relative to the "default" mitigation scenarios. Similarly, enhanced energy efficiency reduces the additional average yearly system costs needed globally in 2050 to achieve emission reductions in line with the Paris Agreement. These additional costs are estimated to be of the order of 2 trillion US$ – or 1% of global GDP – in a well-below-2°C scenario, and can be reduced by 6-30% with the adoption of higher energy efficiency standards. While the two models project broadly consistent future trends for the energy mix in the various scenarios, the effects may differ in magnitude due to intrinsic differences in how the models are set up and how sensitive they are to changes in energy efficiency and emission reduction targets.

Highlights

- We model the global effects of enhanced energy efficiency in well-below-2°C scenarios.
- We systematically compare the projections of two integrated assessment models.
- Increasing energy efficiency may lead to substantial long-term economic benefits.
- Carbon price and CCS use may decline by, respectively, 10-15% and 13-90%.
- The additional system costs needed to achieve climate targets may become 6-30% lower.

1. Introduction

The global energy system aims to provide useful energy and mobility services to various end users, including consumers and businesses. The development of energy demand determines the size of future energy supply and the corresponding investment costs, and thus directly influences the assessment of climate change mitigation challenges (Wilson et al., 2012). Large increases in energy consumption may put an additional burden to the energy supply sector to further reduce emissions (Grubler et al., 2018). Accordingly, most global mitigation scenarios tend to focus on supply-side options (IPCC, 2014; Rogelj et al., 2018) and commonly require the large-scale uptake of negative emission technologies, such as those based on carbon capture and storage (CCS) in combination with bio-based fuels. These technologies, however, face large uncertainty and critical limitations related to e.g. their high costs, the availability of suitable sites for CO_2 storage and land for growing bio-energy crops (which might in some cases compete with food production needs), and sustainability of upscaling their deployment (Fuss et al., 2018; Nemet et al., 2018). On the other hand, there exist a high potential for reducing energy consumption in end-use sectors, without adversely affecting the comfort of living for the population, by deploying enhanced energy efficiency solutions, technologies, and practices. Pursuing such enhanced efficiency options on the demand-side provides a complementary avenue to achieving climate change mitigation targets that may reduce the necessity to invest heavily in expensive and uncertain low-carbon technologies on the supply side, while also reducing the pressure on exploitation of primary energy resources – including renewable resources – to provide human needs like housing and mobility (Grubler et al., 2018).

In the Paris Agreement under United Nations Framework Convention on Climate Change (UNFCCC), governments agreed to a long-term target of keeping the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit temperature increase to 1.5°C (UNFCCC, 2015). This requires large and rapid changes in the energy system towards net-zero emissions by or slightly after 2050 (Van Soest et al., 2021). In this study, we explore the role of energy efficiency as a no-regret strategy for deep decarbonization at the global level in the post-COVID era, as it may provide multiple environmental and economic benefits. In the short-term, energy efficiency offers a low-hanging fruit to reduce emissions while providing a strong stimulus to domestic labor markets (e.g. in the construction business), as it typically creates more domestic jobs per million of expenditure relative to other types of energy investments (IEA, 2020a). In the medium term, energy efficiency reduces the need for supply-side investment and the costs of transformation, which may lead to an increase in the social acceptance of climate policies (Van Vuuren et al., 2018). Finally, in the long term, accelerated efficiency improvements lower the need for expensive and risky technologies like CCS and other Carbon Dioxide Removal (CDR) options. Therefore, energy efficiency provides a resilient, low-cost, and low-risk pathway towards the net-zero transition, while offering important co-benefits such as improved air quality and health (Rauner et al., 2020) and reduced energy trade bills for major economies like the EU, China, Japan, and India (Reuter et al., 2020).

Policy makers are increasingly recognizing the important role of energy efficiency in national low-emission strategies. For example, specific targets for energy efficiency are set by the EU for 2030 as part of the "Clean Energy for All Europeans" policy package, the revised Energy Efficiency Directive and the recent Fit for 55 package. Following this, several EU Member States have legislated policies targeting energy efficiency, while ambitious efficiency measures have been put in place in non-EU countries (e.g. Japan, Canada, USA) in the form of fuel efficiency standards, energy appliance labeling or implementation of stringent building standards. The importance of energy efficiency for reducing emissions is widely recognized: 143 out of 189 Parties explicitly mention energy efficiency in their Nationally Determined Contribution (NDC) plans (IEA 2016). However, while many options and technologies to increase energy efficiency are readily available in all sectors, current deployment levels are below those required to meet the Paris Agreement goals. At the time of writing, annual investments in energy efficiency amount to 290 billion US$ (IEA 2020b), while a pathway to achieve net zero emissions by 2050 is estimated to require annual efficiency-related investment of 1.3 trillion US$ by 2030 (IEA 2021).

Most analyses of the role of energy efficiency in climate mitigation scenarios are currently based on bottom-up detailed assessments with large technological granularity (e.g. Hummel et al., 2021; Fleiter et al., 2018; Swan et al., 2009). However, these often lack the connection with the global climate target narrative and cannot capture system-level effects, including changes in energy prices, supply and/or consumer behavior. Therefore, there is a need to expand Integrated Assessment Models (IAMs) to appropriately represent the technical and behavioral details related to energy efficiency (Brugger et al., 2021; Grubler et al., 2018; Fotiou et al., 2019), while capturing system level effects (e.g. demand-supply interactions, sectoral shifts and spillovers, carbon price and system costs) in a holistic, comprehensive and consistent energy-environment-economy framework. In this way, potential linkages, synergies and trade-offs between ambitious climate targets and energy efficiency policies can be systematically assessed.

In this study we investigate a set of scenarios to meet the Paris goals using two well-established IAMs: PROMETHEUS and TIAM-ECN. Both models rely on the same modelling paradigm: estimating the cost-optimal global energy mix based on a detailed bottom-up description of the energy system, a specific regional disaggregation and an estimated development of future sectoral energy demand driven by exogenous projections of economic and population growth. At the same time, the inner workings of the two models are different, since each model is characterized by a set of unique design choices and assumptions (e.g. the equations used to calculate the objective function, the parametric description of processes and technologies, the way in which interactions between sectors are represented). Because of this diversity one can expect that the models will respond differently to changes in input parameters and policy settings. We refer to this feature as the sensitivity of a model to a certain input. By systematically varying a set of key input parameters (related to climate targets and energy efficiency) to define our scenarios in each model, we can take advantage of the unique models' sensitivities to assess the robustness of the trends observed in the outcomes. We can thus derive policy-relevant recommendations for a cost-efficient and socially acceptable transition to a decarbonized economy, identify uncertainties in our results, and highlight aspects that should be investigated in more detail.

The paper is structured as follows: Section 2 describes the methods used in this work, including the IAMs used and the definition of scenarios based on alternative climate targets and assumptions for energy efficiency. In section 3, we present the main model outcomes in terms of decarbonization pathways, low-emission strategies shared by the different scenarios, and specific insights useful to inform the design of climate and energy efficiency policies. Finally, section 4 discusses the main findings and provides policy-relevant conclusions.

2. Methodology

In this paper – as is common-practice in most studies of this type (see e.g. Bertram et al., 2021; Riahi et al., 2021; IPCC, 2018; van der Zwaan et al., 2016) – the term 'model comparison' means that the outcomes of different models are compared, based on a set of common output variables, under consistent scenario assumptions. The main drivers of the models are harmonized (in our case population and GDP), along with the energy system representation (e.g. installed capacities, CO_2 emissions) in the start year of scenario simulations. Each model, however, retains its specific assumptions and granularity in terms of technology portfolio, sectoral representation and regional disaggregation. In this type of analysis 'model comparison' does not mean providing a detailed comparison of models in terms of their inputs, granularity, energy flows, technologies, etc. The 'comparison' is done exclusively on a limited series of selected output variables, which can be reported in a consistent manner for all models involved. The differences in terms of outcomes reflect thus both the differences in representation of the energy system, as well as the differences in the inner workings of each model. In this section we briefly introduce the main characteristics of PROMETHEUS and TIAM-ECN, and we provide the interested reader relevant literature references for more details on how the models are set up, and how they have been used in previous studies. We then describe our scenario framework.

2.1 Models

We use for our analysis two well-established IAMs: PROMETHEUS and TIAM-ECN. PROMETHEUS is a global energy system model capturing the complex interlinkages between energy demand and supply, technology development and deployment, energy prices and CO2 emissions at global and regional level (Fragkos and Kouvaritakis, 2018). The model simulates the development of the global energy system in different forward-looking scenarios until 2050 exploring alternative socio-economic, policy or technology pathways (Fragkos, 2021). It divides the world into 10 regions and has a distinct representation of major emitters, including the EU, China, the US, and India. The model includes the main end-use sectors, including transport (different modes), industries and buildings, while energy supply and transformation (e.g. power generation, refineries, resource extraction, hydrogen production) are modelled in a bottom-up way based on explicit technologies and processes. PROMETHEUS has been used to provide scenarios focusing on international fossil fuel prices (Capros et al, 2016), the impacts of specific mitigation options like CCS (Fragkos, 2021), Nationally Determined Contributions and low-emission strategies in major emitters (Fragkos and Kouvaritakis, 2018), energy system transformation to 1.5°C (Fragkos, 2020, Marcucci et al., 2019), assessment of the emission and energy system impacts of COVID-19 and recovery plans (Rochedo et al., 2021), and analysis of the role of comprehensive policy measures and portfolios to bridge the gap towards the Paris goals (Van Soest et al., 2021).

TIAM-ECN (IAMC, 2021) is an IAM, built upon the TIMES model generator, that operates at the global level. The TIMES framework and its global realization – TIAM – are well described in e.g. Loulou and Labriet (2008), Loulou (2008) and Syri et al. (2008), and we refer the interested reader to these publications for an overall description of their main characteristics and their mathematical formulation. Here we focus on the features that are specific to TIAM-ECN and particularly relevant for the present paper. As all TIMES-based models, TIAM-ECN is a bottom-up linear optimization model that finds the cost-optimal regional energy mix within scenarios defined through a set of exogenous constraints. TIAM-ECN possesses an input database consisting of several hundreds of processes both for energy production (supply side) and consumption (demand side). It encompasses energy conversion in the main economic sectors, i.e. resource extraction, fuel production, electricity generation, transportation, residential and commercial buildings, and industry. In its most recent implementation, TIAM-ECN divides the global energy system in 36 national or supra-national regions (Kober et al., 2016; van der Zwaan et al., 2018). TIAM-ECN has been used to create long-term scenario projections at global and regional level for specific sectors, such as transportation (Rösler et al., 2014) and electricity generation (Kober et al., 2016), for certain technology classes, such as CCS (Dalla Longa et al., 2020) and off-/mini-grid power production (Dalla Longa et al., 2021a), and for climate change (Kober et al., 2014) and technology diffusion (van der Zwaan et al., 2013; van der Zwaan et al., 2016).

In the context of this paper, assumptions for future development of the main socio-economic drivers – population and GDP growth – in PROMETHEUS and TIAM-ECN have been harmonized in order to provide a robust and consistent framework for model comparison. Projections for population and GDP growth are based on the second Shared Socioeconomic Pathway (SSP2) developed by the global integrated assessment modelling community (Fricko et al., 2017). The SSP2 GDP trajectory has been modified to better reflect the short-term impacts from COVID-19 and the expected developments in the post-COVID era (see the Appendix for an overview of our modified SSP2 trajectory at the global level). In order to obtain this modified GDP trajectory, we consulted several short-term GDP projections from official sources and international organizations, including DG ECFIN (Summer 2021), OECD Economic Outlook (November 2020), and World Bank Global Economic Prospect (June 2021). We settled for the projections derived from the OECD Economic Outlook (OECD, 2020), which entail for the year 2020 a global GDP that is 8% lower than pre-COVID forecasts (i.e. 4.5% below 2019 levels). The GDP projections further assume a V-shape growth recovery after 2021, assuming a strong and effective vaccination programme and no further major outbreaks after 2021 (see Dafnomilis et al., 2021, for a detailed analysis).

Both IAMs can be utilized to provide an improved understanding of the impacts that energy and environmental policies at national and global levels may have on the sectoral energy mix, CO_2 emissions, energy investment and costs at the global level. They can both simulate the effects of various policy instruments, including price signals (e.g. carbon prices, energy or carbon taxation, energy or technology subsidies), policies promoting the use of renewable energy and energy efficiency, technology standards and phase-out policies (Capros et al., 2016; Fragkos et al., 2018; Kober et al., 2016). The modelling frameworks are well equipped to quantify the medium- and long-term effects of ambitious energy efficiency policies in the context of the Paris Agreement goals.

2.2 Scenarios

This paper aims at exploring the effects of a strong push in energy efficiency across all sectors on the global energy system under stringent climate change control policies. For this purpose, we design five scenarios based on specific assumptions with regard to (i) climate change mitigation targets, (ii) energy efficiency improvements, and (iii) carbon price developments. These scenarios are then implemented in PROMETHEUS and TIAM-ECN. Table 1 presents a summary of the key assumptions used in each scenario.

Table 1: Model scenarios.

Scenario	Climate Targets	Energy Efficiency	Carbon Price
REF	No additional targets beyond current 2030 climate policies	Endogenous	Endogenous
2DC	Global 2016-2050 carbon budget of 850 Gt CO_2 (compatible with a below-2°C target)	Endogenous	Endogenous
2DC_eff	Global 2016-2050 carbon budget of 850 Gt CO_2 (compatible with a below-2°C target)	Exogenously increased in all sectors to levels higher than in 2DC	Endogenous
TAX_eff	No additional targets beyond current 2030 climate policies	Exogenously increased in all sectors to levels higher than in 2DC	Exogenous, based on 2DC scenario
1.5DC	Global 2016-2050 carbon budget of 600 Gt CO_2 (compatible with a below-1.5°C target)	Endogenous	Endogenous

The first scenario, REF, is based on the continuation of existing energy and climate policies, in consistency with Roelfsema et al. (2020). The energy system develops in line with current trends, including already legislated climate policies until 2030 and further cost improvements in low-carbon technologies. Beyond that, we impose no binding climate change mitigation targets and no technology or sector-specific increases in energy efficiency. Slightly higher overall energy efficiency levels are still achieved endogenously throughout the modeling horizon due to the fact that energy intensity of GDP is assumed to keep improving at rates close to historical values in each region. This scenario represents a projection of current system trends into the future and serves as a benchmark with which to compare the results of the remaining scenarios. By systematically varying some key model parameters, in the other scenarios we explore possible realizations of a low-carbon global energy system until 2050.

In the 2DC scenario we assume that the world will settle on a cost-optimal trajectory compatible with a well-below 2°C increase in global average temperature, in line with the Paris Agreement goal (COP-21, 2015). Global CO_2 emissions from fossil fuels and industrial operations in the 2016-2050 period are exogenously limited to a budget of 850 Gt CO_2 (in line with Mc Collum et al., 2018). Emission certificates can be traded through a universal carbon pricing mechanism across regions and sectors. The carbon price emerges endogenously in the models as the dual variable related to the maximum allowed CO_2 emissions by 2050, and it applies uniformly to all regions and sectors. No efficiency improvements are assumed beyond those induced by carbon pricing (and those already assumed in REF based on continuation of historic trends).

Table 2: Assumptions for the increased efficiency scenarios 2DC_eff and TAX_eff.

Sector	Technology category	Average efficiency increase	Average capital cost increase
Industry	All	10%	10%

Residential	All	20%	10%
Commercial	All	20%	10%
Transport	Electricity	15%	10%
	Biomass	10%	10%
	Gas	10%	10%
	Oil	10%	10%
	Hydrogen	20%	10%

The 2DC_eff scenario is a variant of 2DC in which we impose an increase in energy efficiency to be realized between 2020 and 2050 in the most widespread technology classes across all demand sectors. Higher efficiency is typically accompanied by an increase in the corresponding capital costs for a technology category, as discussed in e.g. Fotiou et al. (2019). Our assumptions, detailed in Table 2, are largely based on the 2020 EU Reference scenario report (EC, 2021a). 2DC_eff aims at illustrating the possible effects of a consumers' shift towards purchasing the most energy efficient technologies in the market. Such a shift could be induced by ambitious policy measures targeting, among others, the gradual phase-out of low-efficiency energy appliances in favor of high-efficiency technology standards, the implementation of energy labelling directives for residential and commercial buildings, the increase in renovation rates (e.g. induced by subsidies), and the application of stringent energy efficiency standards in industry and in the transport sector.

In TAX_eff we maintain the assumptions on increased energy efficiency reported in Table 2. In this scenario, however, global emission reductions are achieved by exogenously imposing a carbon price that is equal to that in the 2DC scenario, rather than by directly capping the release of CO_2 in the atmosphere. The scenario aims at simulating the effects of increasing efficiency standards and legislation in the context of ambitious carbon pricing towards 2°C in order to assess whether this policy combination can pave the way towards meeting the more ambitious 1.5°C Paris goal.

Our final scenario – 1.5DC – is analogous to 2DC, but we assume a more stringent 2016-2050 global carbon budget of 600 Gt CO_2, resulting in a maximum temperature increase of 1.5°C by the end of the century (IPCC SR1.5, Rogelj et al., 2018). This scenario is meant to explore the impacts that are triggered when all countries work together to limit the global temperature increase to levels below 1.5°C as per the more ambitious climate goal proposed in the Paris Agreement (COP-21, 2015), by implementing a universal carbon pricing scheme in all regions and sectors.

3. Modelling Results

In this section we present the main scenario-based outcomes of PROMETHEUS and TIAM-ECN over the period 2020-2050.

3.1 CO_2 emissions and carbon prices

Figure 1 shows the projections for energy-related CO_2 emissions (top panel) and carbon price (bottom panel) obtained with PROMETHEUS and TIAM-ECN. In the REF scenario both models project a limited increase of global CO_2 emissions over the 2020-2050 period, despite the robust growth of global economic activity (Fricko et al., 2017), indicating a relative decoupling of emissions from GDP growth. This decoupling is triggered endogenously by the adoption of low-carbon technologies (e.g. PV panels, wind turbines, electric vehicles) and high-efficiency processes, induced by their respective future cost reductions. The current climate policies and targets assumed in REF are realized in both models through a series of exogenous constraints on the minimum and maximum shares of, respectively, low-carbon and fossil fuel-based technologies in the energy mix at regional and sectoral level. PROMETHEUS also explicitly simulates the strengthening of the European Emission Trading System (resulting in the small increase in global average carbon price observed in REF in Figure 1), while for TIAM-ECN no carbon markets are assumed in REF – hence no carbon price is calculated by the model.

In the 2DC and 2DC_eff scenarios, ambitious climate policies to limit global carbon emissions are applied. Mid-century global CO_2 levels in the 2DC scenarios are 80% lower than in REF for both models. The emission cap imposed in these scenarios triggers an endogenous increase in carbon price which applies uniformly to all regions and economic sectors to achieve emission reductions when and where it is most cost-efficient, thus ensuring that the global climate goal is achieved with the lowest possible costs. By comparing the bars relative to 2DC and 2DC_eff in the bottom panel of Figure 1, one can notice that the required carbon price is, in both model projections, lower in the increased energy efficiency scenario, showing that the implementation of ambitious efficiency policies, standards and regulation may reduce the need for high carbon pricing to achieve the same mitigation target. This is expected to have a positive effect on the social acceptance of ambitious climate policies, as energy (or carbon) taxation has regressive distributional impacts, posing a disproportionately high cost burden to low-income households (Fragkos et al., 2021), and often raises social concerns (see e.g. Vona, 2019). In PROMETHEUS, the required carbon price appears to be more sensitive to the implementation of higher efficiency standards than in TIAM-ECN, as the former includes a more detailed description of energy end use technologies and related efficiency measures, while TIAM-ECN has a higher granularity in representing energy supply. This is especially evident in 2050 as the carbon price in 2DC_eff is less than half of that in 2DC for PROMETHEUS, whereas for TIAM-ECN the reduction is only 10%.

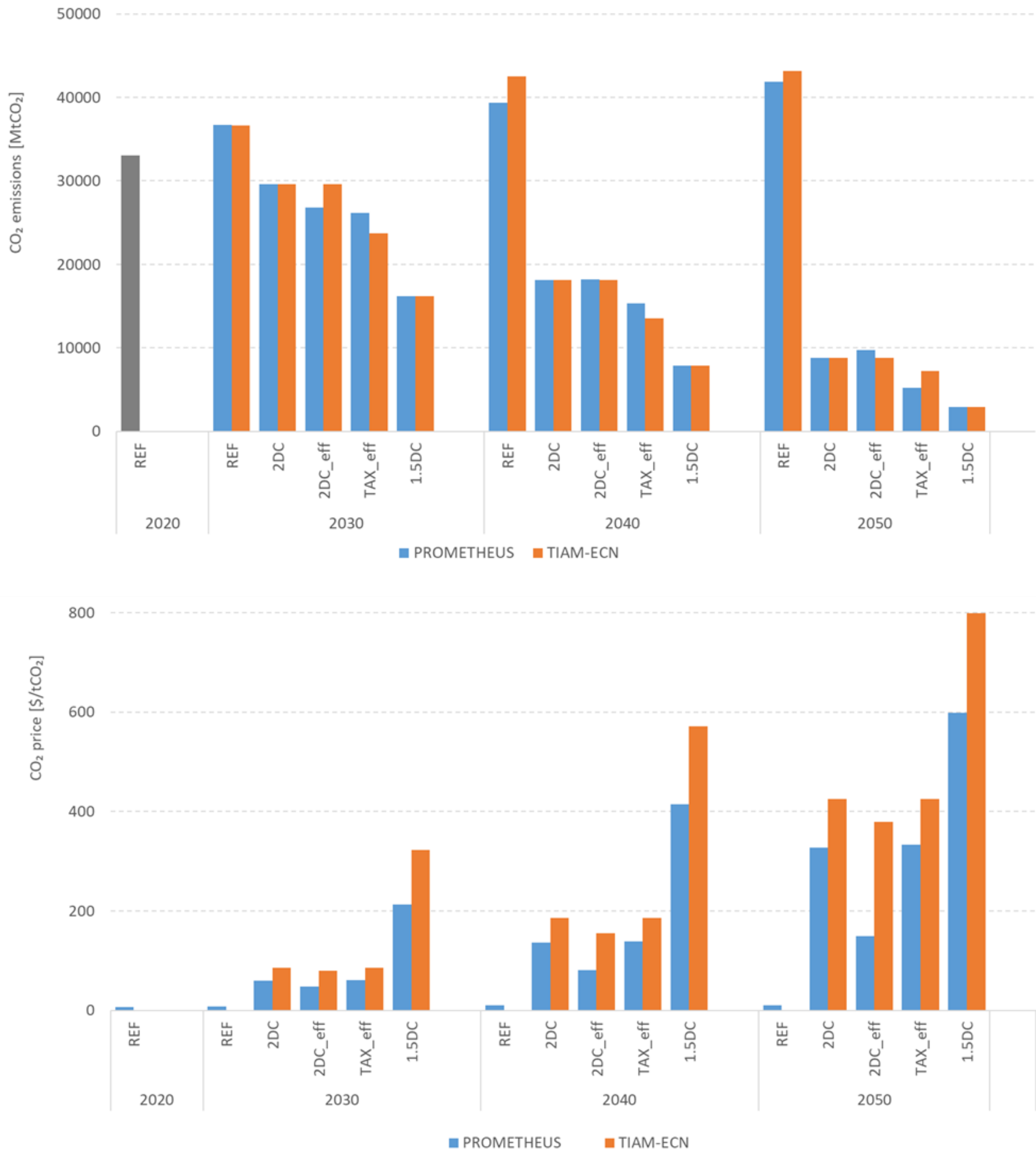

Figure 1: CO_2 emissions (top panel) and carbon price (bottom panel).

The TAX_eff scenario combines the carbon pricing of 2DC with the increased energy efficiency improvements of 2DC_eff, and thus achieves further reductions in global emissions relative to 2DC and 2DC_eff. These are projected to vary in 2050 from 83% to 86% below REF levels for, respectively, TIAM-ECN and PROMETHEUS. In comparison with the 2DC scenario, CO2 emissions in TAX_eff are 35% and 20% lower for, respectively, TIAM-ECN and PROMETHEUS. In TAX_eff the carbon price is imposed exogenously in order to trigger emission reductions without applying a CO_2 cap. This scenario illustrates that utilizing energy efficiency policies and standards could prove an effective way to bridge the effort gap between a “well below” 2°C scenario and a below 1.5°C one without requiring very high CO_2 prices until 2050. To further emphasize this point, in our final scenario, 1.5DC, we impose a constraint on global carbon budget compatible with a 1.5°C climate control target. In this scenario both models project that global CO2 emission levels in 2050 would be more than 90% lower than in REF – hence very close to reaching net zero by 2050 – but the corresponding carbon prices are nearly twice as high as in 2DC and TAX_eff.

Figure A2 in the Appendix complements the data presented in Figure 1 by providing a sector-level overview of emission reductions in the various scenarios.

3.2 Power sector

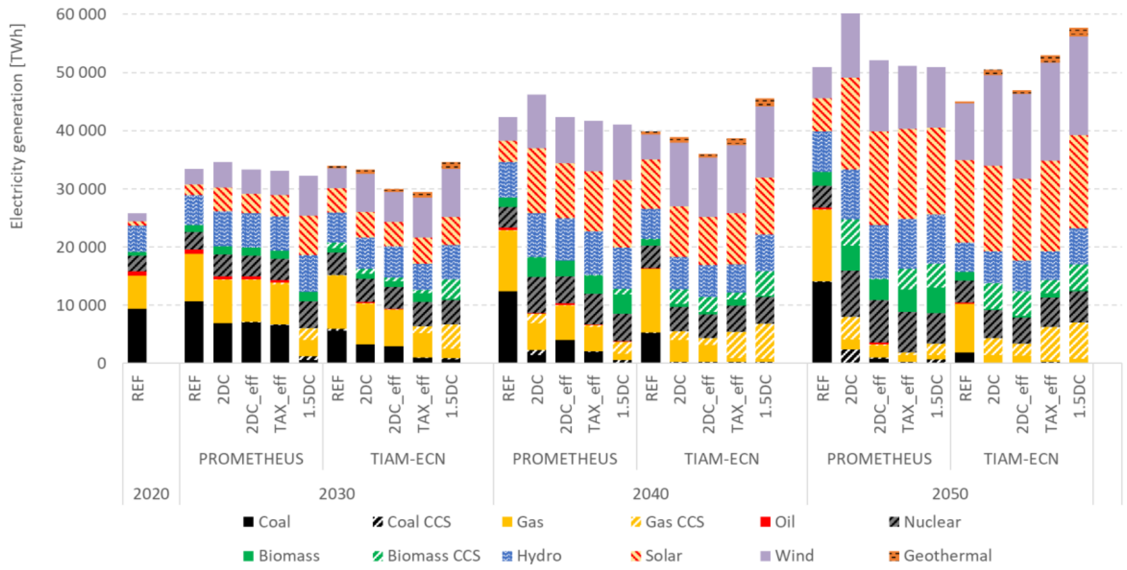

Figure 2: Global power generation mix.

In Figure 2 we present the global power generation mix. For all scenarios, both models project a steady increase in electricity production between 2020 and 2050 with an average annual growth between 2% and 3% (depending on model and scenario assumptions) triggered by growing living standards (due to rising incomes) combined with increasing electrification of energy services. The relative magnitude of the increase in electricity generation requirements and the projected technology mix differ in the two models, mainly as a result of different assumptions in technology cost developments, technology potentials, carbon price levels, and different sensitivity levels to changes in the parameters that define our scenarios. In REF, global electricity generation grows to 50000 TWh/yr by the middle of the century for PROMETHEUS, against the 45000 TWh/yr projected by TIAM-ECN. The main contributors to the electricity mix in the REF scenario in 2050 are solar, wind, hydro, natural gas and nuclear. In the REF scenario, due to the lack of ambitious climate policies, PROMETHEUS projects that coal-based generation maintains a share of 28% by 2050 (albeit reduced from 39% in 2015), while this source is almost completely phased out in TIAM-ECN due to the high uptake of renewable energy (especially solar and wind) at levels considerably higher than in PROMETHEUS. In both models, nuclear energy, hydro and biomass provide a small, but non-negligible, amount of electricity over the 2020-2050 period. In the 2DC scenario electricity generation increases with respect to REF by respectively 20% and 10% for PROMETHEUS and TIAM-ECN as electricity use expands in buildings, transport and industries to substitute for fossil fuels which are penalized by high carbon pricing. Both models project a larger renewable-electricity production than in REF, with the share of renewables in 2050 increasing from 40% (REF) to over 70% (2DC) and from nearly 70% (REF) to slightly more than 80%, respectively, in PROMETHEUS and TIAM-ECN. Both model projections also feature the adoption of carbon capture and storage (CCS) technologies combined with biomass and fossil fuels – while the utilization of the latter carriers without CCS is almost completely phased out – and an increase in the use of nuclear energy. TIAM-ECN also projects a small contribution from geothermal energy. In 2DC_eff, total electricity production in 2050 reverts back to slightly over the REF level for both models, as a result of the increased efficiency assumptions that induce an overall reduction of electricity requirements especially in buildings and industries. In the 2DC_eff PROMETHEUS projection, electricity production from CCS technologies is negligible, while for TIAM-ECN it is only slightly smaller than in 2DC. Overall 2050 electricity generation levels in TAX_eff and 1.5DC remain roughly the same as in 2DC_eff for PROMETHEUS, indicating that the policy measures simulated in these two scenarios trigger a degree of electrification and energy efficiency in the energy system that is of the same order of magnitude of that triggered in the 2DC_eff scenario. The situation is different in the TIAM-ECN projections. These show higher total electricity production, reaching 53000 and 58000 TWh/yr, respectively, in TAX_eff and 1.5DC. In both models, the power sector is almost completely decarbonized by mid-century in all ambitious mitigation scenarios. This decarbonization is triggered by high carbon pricing and the emergence of low-cost clean alternatives to fossil fuel-based generation, especially renewable energy and CCS technologies.

3.3 Demand sectors

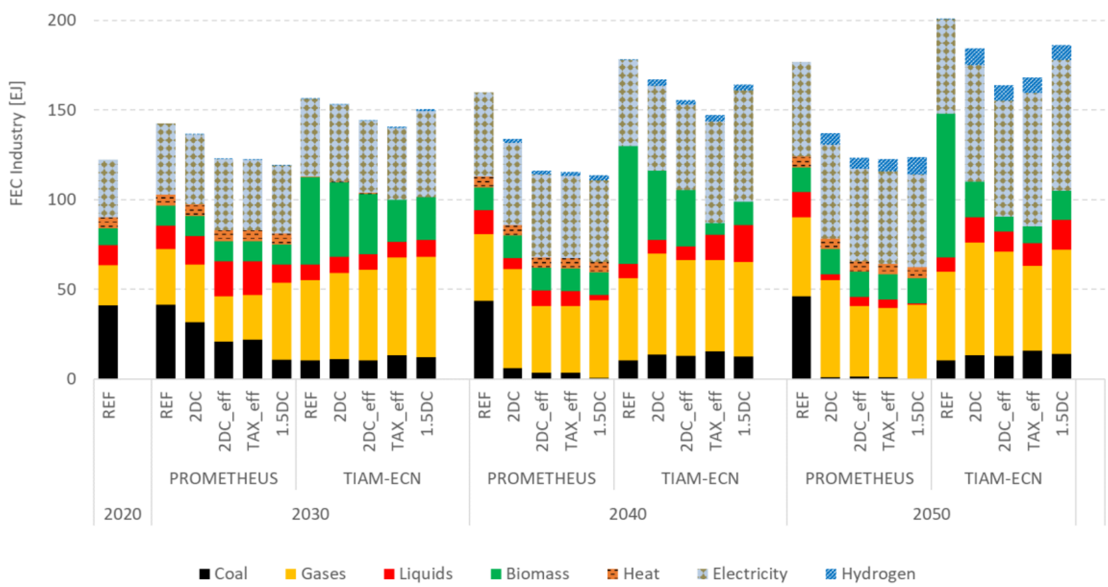

Figure 3: Final energy consumption by energy carrier in industry.

In figures 3 through 5 we analyze scenario projections of final energy consumption (FEC) in the three main demand sectors: industry, residential and commercial buildings, and transport. The REF projections in Figure 3 show that FEC in industry undergoes a steady increase reaching values of 175 and 200 EJ/yr for PROMETHEUS and TIAM-ECN, respectively, driven by increasing industrial activity (following socio-economic developments increasing the need for materials and industrial products) and the lack of ambitious climate policies. The main industrial fuels remain the same throughout the modeling horizon: natural gas, coal, oil, biomass and electricity, with a small contribution from heat. The PROMETHEUS projection shows in REF only small changes in the relative shares of industrial fuels in future decades (gas and electricity slightly increasing, coal and oil products slightly decreasing), while in TIAM-ECN coal is almost completely replaced by natural gas and biomass already from 2030.

The application of ambitious climate control policies causes a decrease of total industrial FEC in both models, as more efficient technologies start to be utilized and more efficient energy carriers (e.g. electricity) increasingly replace the inefficient use of coal and oil products. Both models thus identify accelerated energy efficiency improvements and fuel switching as the main instruments to achieve industrial decarbonization. In general, PROMETHEUS projects larger FEC reductions relative to REF (up to 31% in TAX_eff) than TIAM-ECN (up to 19% in 2DC_eff). While for PROMETHEUS the emission constraint and efficiency assumptions mainly induce a reduction in fossil fuel consumption, for TIAM-ECN the use of hydrogen also emerges as an important transformation pathway for industry, especially in hard-to-abate sectors like Iron and Steel. The application of CCS in biomass and fossil fuel-based industrial processes in the low-carbon scenarios is also projected in both models (not shown in Figure 3) as will be discussed later in this section.

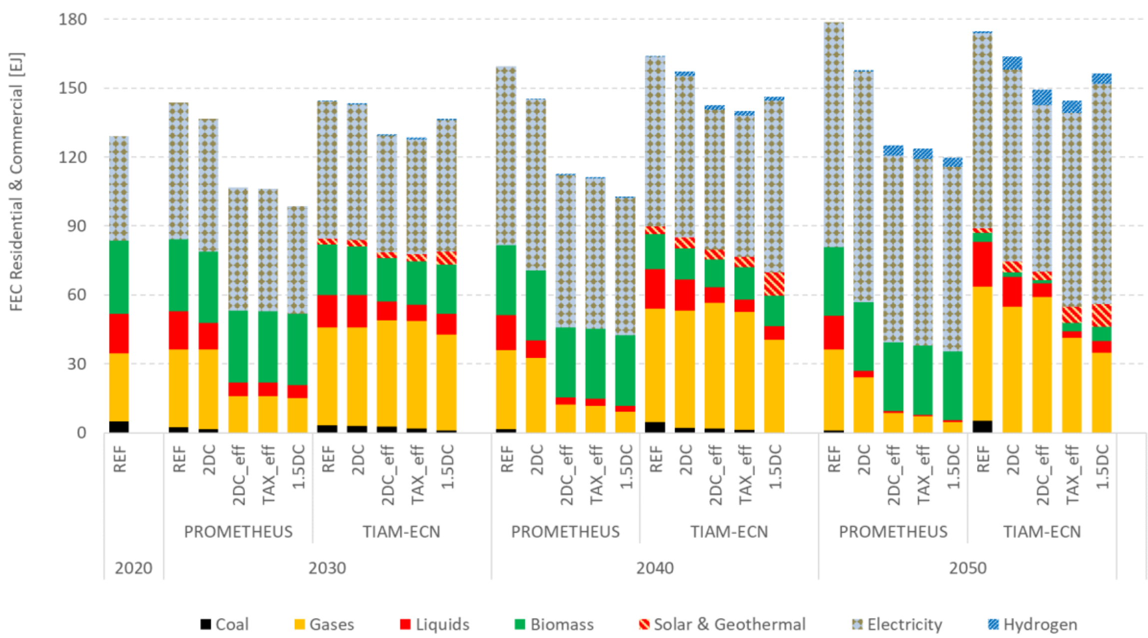

Figure 4: Final energy consumption in residential and commercial buildings.

In Figure 4 we present FEC projections for residential and commercial buildings. In the REF scenario energy consumption from buildings grows steadily at similar rates for both models, as a consequence of our assumptions on population and GDP growth, increasing urbanization and rising income and living standards in developing economies. The main difference between the two REF model projections in 2050 is that PROMETHEUS is more optimistic than TIAM-ECN with regard to the replacement of natural gas with technologies based on electricity and biomass. The application of emission and efficiency constraints in the low-carbon scenarios causes a reduction of total FEC in buildings - triggered by an increased rate and depth of renovation, a more rational use of energy and the uptake of more efficient fuels and equipment - and the emergence of electricity and hydrogen for heating, accompanied, in the TIAM-ECN case, by a growth of solar thermal and geothermal technologies. As for industry, also in the residential and commercial sectors PROMETHEUS projects larger FEC decreases than TIAM-ECN. Maximum FEC reductions with respect to REF levels in 2050 are projected at 33% and 17% for, respectively, PROMETHEUS (1.5DC) and TIAM-ECN (TAX_eff). Our analysis is in line with Levesque et al. (2019) who have shown that global energy demand from buildings can be reduced by up to 47% in a highly-efficient scenario compared to a scenario following current trends. In 2050 the emergence of hydrogen in the PROMETHEUS projection is only triggered by the application of high energy efficiency requirements (2DC_eff, TAX_eff) or by a very stringent emission cap (1.5DC), whereas TIAM-ECN projects that hydrogen also penetrates the residential and commercial sectors in 2DC. While the use of oil in buildings is completely phased out by 2050 in most low-carbon scenarios in the PROMETHEUS projections, TIAM-ECN maintains a small amount of oil consumption in all scenarios. This is mainly occurring in developing economies, such as several countries in Sub-Saharan Africa that lack the means to deploy the required infrastructure to support a full-scale switch to cleaner alternatives by mid-century (see e.g. van der Zwaan et al, 2018).

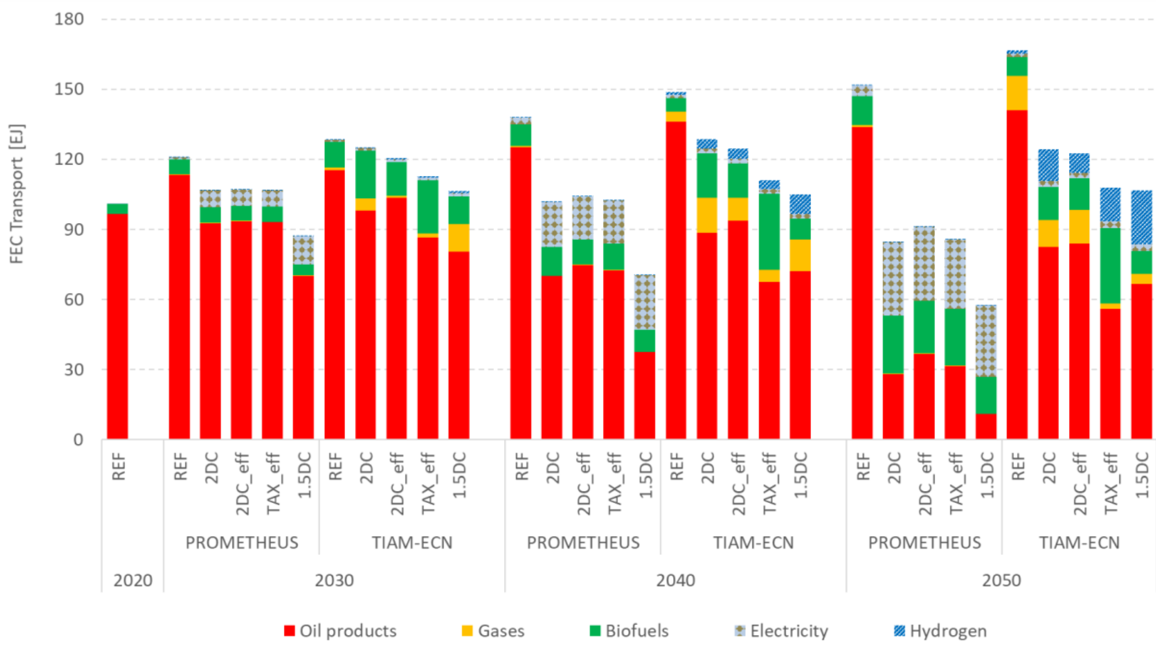

Figure 5: Final energy consumption mix in transport.

Figure 5 shows the model-based projections for final energy consumption in the transport sector. As in the other two demand sectors, the REF projection displays in both models a steady growth between 2020 and 2050, reaching 150 and 165 EJ/yr for PROMETHEUS and TIAM-ECN, respectively. This is triggered by the increasing living standards, rising GDP and the increasing motorization trends in developing regions, combined with the lack of policies to reduce emission footprint and facilitate the switch to transport modes requiring less energy (e.g. public transport, biking and walking). Oil products remain the dominant transport fuel in the REF projections, with biofuels, natural gas, electricity and (only for TIAM-ECN) hydrogen each gaining a small share in the transport energy mix, as conventional vehicles with internal combustion engines (ICEs) are projected to remain predominant in all transport modes. In the four low-carbon scenarios, total consumption shrinks as a result of switching to more efficient vehicles. Maximum reductions of, respectively, 60% and 35% are achieved in PROMETHEUS and TIAM-ECN in the 1.5DC scenario. The fuel mix is altered in different ways in the two models. In 2DC, 2DC_eff and TAX_eff, PROMETHEUS projects a total fuel consumption in the transport sector of around 90 EJ/yr by mid-century (close to current levels), fulfilled in nearly equal parts by oil products, biofuels and electricity. Energy use is further reduced to 60 EJ/yr in the 1.5DC scenario, mainly by phasing out most of the ICE and hybrid fleets combined with a rapid expansion of electric vehicles in passenger transport and hydrogen fuel cells especially in road freight transport, aviation and navigation. In the TIAM-ECN projections the decrease in total FEC with respect to REF is in general less pronounced than for PROMETHEUS: fuel consumption in 2050 is slightly above 120 EJ/yr for both 2DC and 2DC_eff, while a further decrease down to about 105 EJ/yr is triggered in TAX_eff and 1.5DC. The consumption of oil products is severely reduced in all low-carbon scenarios, and natural gas is almost completely phased out in TAX_eff and 1.5DC. Biofuels continue to provide a substantial contribution to the fuel mix, up to over 30 EJ/yr in TAX_eff. The share of electricity in the transport mix remains small (below 3%) in all scenarios, while hydrogen becomes a prominent transport fuel with shares up to 20% in the 1.5DC scenario. Electricity emerges as the main decarbonization fuel for transport in the PROMETHEUS mitigation scenarios, whereas this role is fulfilled by hydrogen in the TIAM-ECN projections. This difference is caused by diverging assumptions in the evolution of costs for batteries and fuel cells for, respectively, electric vehicles (BEV) and hydrogen ones (FCEV). While BEVs are currently more widespread than FECVs, since both their respective underlying storage technologies have experienced significant cost declines in recent years, a large uptake of hydrogen-based transportation might also materialize in the near future, alongside or in competition with the growth of the electric vehicles fleet (Rösler et al., 2014; Capros et al., 2019). For this reason, we find it valuable to present the outcomes of the two models without trying to further harmonize our cost assumptions, as they represent two different – but equally realistic and self-consistent – possible realizations of the future transport fuel mix under ambitious mitigation policies.

3.4 CO_2 removal

In Figure 6 we plot the projections for CO_2 removal in the various scenarios. The main mechanism for removing CO_2 from the atmosphere considered in this study is the deployment of CCS technologies in the electricity generation, industry and fuel production sectors, which is triggered by high carbon pricing. As Figure 6 shows, CCS processes are used in all low-carbon scenarios, in quantities that depend on the model used and the scenario-specific assumptions. In general PROMETHEUS is less optimistic than TIAM-ECN with regard to the potential spread of CCS technologies, relying instead more heavily on energy efficiency improvements to achieve decarbonization targets. The former model projects the utilization of CCS exclusively in the power sector, while the latter deploys it also in industry and fuel production. Maximum CO_2 capture levels are reached in 2050 in the carbon cap scenarios: 5 $GtCO_2$/yr in 2DC and 16 $GtCO_2$/yr in 1.5DC for PROMETHEUS and TIAM-ECN, respectively. The efficiency push in the "_eff" scenarios causes a significant decrease in the need for CCS deployment. While this reduction is consistently projected by both models, its magnitude varies across models and scenarios. In 2DC_eff, CO_2 removal in 2050 is 90% and 13% lower than in 2DC for, respectively, PROMETHEUS and TIAM-ECN; thus the PROMETHEUS projection indicates that in the presence of strong energy efficiency measures, there is little need for CCS uptake, as carbon prices stay considerably lower than in 2DC. In the same year, in TAX_eff, the relative reductions with respect to 2DC are 50% and 23% for PROMETHEUS and TIAM-ECN, respectively, showing that deep emission reductions can be achieved through accelerated uptake of renewable energy, low-emission vehicles and energy efficiency.

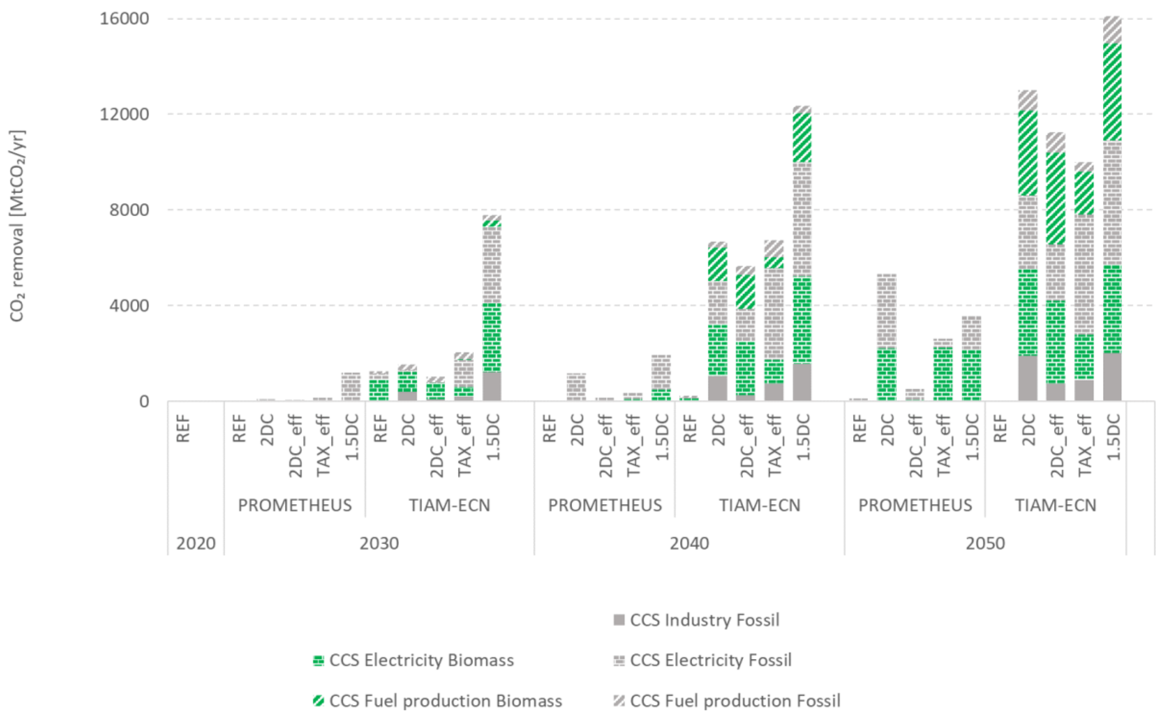

Figure 6: Uptake of CO_2 removal technologies.

3.5 Mitigation costs

Figure 7 presents additional energy system costs with respect to REF for all mitigation scenarios. Ambitious climate control targets in 2DC and 1.5DC drive system costs up by forcing additional investments in low-carbon technologies, clean vehicles and energy efficiency. As shown in (Fragkos, Kouvaritakis, 2018), energy system costs generally increase with the mitigation effort. For PROMETHEUS additional global energy system costs in 2050 for 2DC and 1.5DC are, respectively, 1.8 and 3.6 tln$/yr, while for TIAM-ECN they are, respectively, 2.4 and 4.4 tln$/yr. PROMETHEUS generally projects lower additional costs than TIAM-ECN. This is directly related to the lower energy use projected by the former model in all end-use sectors, resulting from its detailed and disaggregated representation of end-use technologies with different levels of efficiencies, in line with Fotiou et al., (2019). In both models, the imposition of energy efficiency policies on top of the climate objective in the 2DC_eff scenario causes on the one hand the use of (expensive) high-efficiency end-use processes and more efficient technologies, cars, appliances and equipment in the demand sectors – which leads to an increase in system costs – and on the other hand a reduction in fossil fuel consumption and carbon price – which push system costs down. The two effects result in 2050 in additional costs that are 6% and 30% lower with respect to the 2DC scenario for, respectively, PROMETHEUS and TIAM-ECN. Both model projections thus consistently indicate that stimulating the adoption of high-efficiency technologies on top of a climate mitigation target might reduce overall energy system costs to meet the same climate target.

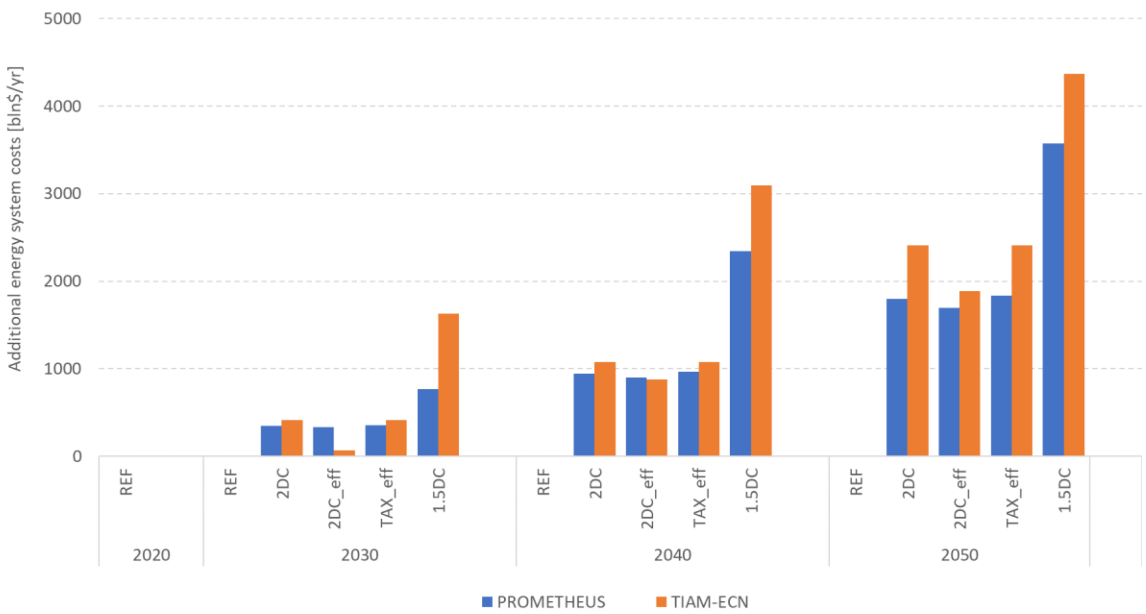

Figure 7: Additional energy system costs with respect to REF.

4. Discussion and Policy Recommendations

In this paper we explore a set of alternative mitigation pathways compatible with the Paris Agreement goals, under different scenario assumptions, using two established global IAMs: PROMETHEUS and TIAM-ECN. The analysis shows that the Paris goals are technologically possible but require large-scale, structural transformations in energy systems and societies at the global scale. The necessary changes should be driven by accelerated uptake of multiple mitigation strategies, including renewable energy deployment, electrification of end-uses, energy efficiency, hydrogen and CCS. The remaining carbon budget consistent with 1.5°C or 2°C goals highly influences the speed and magnitude of the required energy system transformation. To meet strong climate targets, global CO_2 emissions should peak before 2025, followed by a steep reduction induced by the decarbonization of the power sector, driven by the expansion of renewable energy and the phase-out of coal. Our analysis highlights the importance of strengthening climate action and revising upwards the ambition of current policies and NDCs, while developing the required clean energy infrastructure in the 2020-2030 decade.

Considering the main outcomes from the two models in the various combinations of climate mitigation and energy efficiency policies that our low-carbon scenarios entail, several pillars to achieve global decarbonization targets can be identified. First, a large expansion of energy generation from renewable sources is projected for all sectors, and is especially prominent in the power generation sector, which in some cases becomes almost carbon-free by 2050 (see e.g. the TIAM-ECN projection for TAX_eff scenario in Figure 2). Second, the dependence of end-use energy services from fossil fuels can be lessened through an increase in electricity shares across the demand sectors, complemented by the deployment of low-carbon fuels (e.g. advanced biofuels and hydrogen) when electrification is neither technically feasible nor economically efficient (e.g. high-temperature industrial processes). Third, energy demand savings through uptake of enhanced energy efficiency technologies or through improved thermal insulation of buildings proves to be a robust strategy to reduce CO_2 emissions across the economy, as it is endogenously triggered by high carbon prices in the cost-optimal 2DC and 1.5DC scenarios. Fourth, the deployment of carbon removal technologies, such as CCS, is necessary in order to achieve ambitious decarbonization targets. CCS requirements are, however, considerably lower if ambitious energy efficiency policies are implemented, thus reducing society's reliance on a costly and risky technology, currently not used at scale.

Policies combining the promotion of high energy efficiency with a carbon cap (as in 2DC_eff) can lead to lower carbon prices – possibly accompanied by lower energy system costs – than those focusing solely on capping emissions. Utilizing energy efficiency policies together with a moderate carbon price (as in TAX_eff) could provide the required additional effort to move from a well-below-2°C future down to a well-below-1.5°C one, without requiring very high CO_2 prices. This, in turn, might increase the likelihood of social acceptance and support of ambitious climate policies (Fragkos et al., 2021). Our analysis shows that the adoption of high efficiency standards can contribute to mitigating the environmental, economic, ethical and social risks that emerge from relying on currently immature carbon removal technologies, such as CCS (Van Vuuren et al., 2018). The extent to which enhanced energy efficiency can reduce the need for CCS deployment is, however, highly uncertain, and may well vary between extremes as low as 13% and as high as 90%. The diffusion of high energy efficiency technologies also leads to lower supply-side investments and may bring important co-benefits, e.g. in terms of job creation (see e.g. IEA, 2020a), reduced air pollution and lower dependency on energy imports. Our analysis, using two leading IAMs under a range of policy and technology assumptions, confirms the findings of previous literature, showing that scenarios driven by energy demand reductions provide a robust alternative to technology-driven scenarios, possibly entailing some significant economic, social, and environmental benefits (Creutzig et al., 2018; Mundaca et al., 2019; Grubler et al., 2018). The energy efficiency assumptions simulated here are not considered extreme and thus do not reduce living standards of consumers (Rao et al., 2017) and do not constrain thermal comfort, the use of appliances, transport activity and industrial production (Levesque et al., 2019).

Despite the expected economic, health and environmental benefits of enhancing energy efficiency across the economy, the transition to a net-zero emissions world still requires a large transformation of the global energy and transport systems, as well as of human. For example, the uptake of already-existing clean technologies should be upscaled (e.g. solar PV, wind, BEVs and FCEVs, heat pumps), while new mitigation technologies have to emerge (e.g. advanced biofuels, green hydrogen), driven by targeted investments. Simultaneously, human behavior needs to change through modal shifts to less-emitting transport options, more rational use of energy, and uptake of more efficient fuels and equipment. All these changes cannot be realized easily, and require increased funding, ambitious and early action by governments, businesses, and citizens, increased low-carbon innovation, lifestyle changes, and strong policy signals targeting the cost-efficient and just transformation of the global economy. In the quest towards achieving the Paris long-term temperature goals, energy efficiency can be considered a robust and efficient strategy to reduce both demand and supply-side emissions, as well as the required carbon price.

In order to go a step further in understanding and quantifying the direct and indirect effects of high energy efficiency policy in combination with climate targets, more detailed modeling is needed. This can partly still be achieved with IAMs, by enhancing the granularity of the analysis along several dimensions. First, an assessment of our scenarios at regional level would bring additional insights in how the energy mix might change across different latitudes and economies, especially focusing on major emitters (USA, Europe, China and India). This should be combined with a region- and sector-specific analysis of mitigation costs, i.e. additional system costs per unit of CO_2 emission reduction achieved, in different scenarios and time periods. Second, some of the uncertainties highlighted in this paper may be partly removed by improving the IAM representation of some key technologies and processes in the energy demand sectors. These include demand response mechanisms, consumer characterization, mode-shifting in transport, building-stock classification, deep dwelling renovation options, decarbonization pathways in specific industrial subsectors (especially in energy-intensive manufacturing), and material flows supporting enhanced circularity in the economy (Capros et al., 2019). Third, while the energy efficiency improvement factors we adopted in this study (see Table 2) are well within the range of what is technically achievable, more detailed results can be obtained by further specifying energy efficiency increases at the process level. The factors in Table 2 are suitable for the illustrative scenario analysis presented in this paper, targeting large geographic areas and adopting a long-term perspective. A technology-specific assessment of possible energy efficiency improvements at the regional level is needed in order to devise suitable policy instruments to stimulate the adoption of high-efficiency technologies. In addition, our scenario design assumes global cooperation to achieve the climate targets starting by 2025, which is optimistic given the current international policy landscape. Thus, new research should explore the impacts of delayed or regionally fragmented climate action, while also assessing the feasibility of transformation not only in technical terms, but also integrating societal, governance and political economy considerations (Brutschin et al., 2021). Finally, (enhanced) IAM analysis should be complemented by detailed modeling at urban and suburban scale, possibly also including elements for which IAMs are not particularly well-suited, such as consumer behavior, lifestyle changes and representation of short-term targets and policy instruments at (sub-)national level. Improving the way some of these aspects can be simulated in different types of models (including, but not limited to IAMs) is the core focus of the WHY research project (WHY, 2021). As the tools developed in WHY evolve including granular representation of technical and behavioral aspects, we will integrate them in our IAMs in order to address some of the open questions presented here.

In this study we consider the global post-COVID context in terms of an adjusted global GDP projection in our models. This adjustment stylistically accounts for the expected long-term economic trends by triggering a reduction the final energy demand in all regions and (sub)sectors. In our scenarios, however, we do not explicitly take into account other possible long-term impacts related to the COVID pandemic. For example, in 2020 and 2021, with the emergence of remote working and schooling , energy use has partly shifted from the commercial to the residential sector, while the demand for specific transport (e.g. in aviation and in private cars) has decreased significantly during general lock-down periods. If this pattern persists in the future, it may trigger significant changes in the energy system, and correspondingly require specific policy adjustments. Similarly, the COVID outbreak also affected energy use in the transport and industrial sectors. It is still uncertain whether these changes in the demand sectors will lead to long-term impacts on the energy system (see e.g. Kikstra et al., 2021). Analyzing this in detail falls beyond the scope of our present study, and we defer it to future research.

Our model comparison analysis shows that pushing enhanced energy efficiency can be an effective strategy to pursue ambitious emission reduction objectives and pave the way for the transformation required to meet the Paris goals. From a policy perspective, however, achieving efficiency acceleration remains a challenge. Large upfront investments are needed in order to expand the deployment of high-efficiency processes and scale up the implementation of renovation strategies in the residential and commercial sectors. Advancing the uptake of high efficiency end-use technologies, such as household appliances and passenger vehicles, may prove particularly difficult for low-income households, and policy makers are already concerned about this, as shown in the EU 'Fit for 55' policy package (EC, 2021b). Energy efficiency policies should be designed so as to target a just and inclusive energy transition, paying special attention to the social groups that are most at risk of energy poverty (see e.g. Dalla Longa et al., 2021b). Important policy measures in this regard are those that explicitly address behavior and lifestyle changes (educational campaigns, among others). These should always complement traditional economic instruments, such as offering economic support (e.g. subsidies and low-cost loans) and enforcing the adoption of building or technology standards.

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References

Bertram C., Riahi K., Hilaire J. et al., 2021, "Energy system developments and investments in the decisive decade for the Paris Agreement goals", Environmental Research Letters 16, 074020.

Brugger H, Eichhammer W., Mikova N., Dönitz E., 2021, "Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries?", Energy Policy, 152, 112216.

Brutschin E., Pianta S., Tavoni M., Riahi K. et al., 2021 "A multidimensional feasibility evaluation of low-carbon scenarios", Environmental Research Letters, 16, 064069.

Capros P., De Vita A., Tasios N., et al., 2016, "EU Reference Scenario 2016, Energy, transport and GHG emissions, Trends to 2050".

Capros P., Zazias G., Evangelopoulou S., Kannavou M., Fotiou T., Siskos P., De Vita A., Sakellaris K., 2019, "Energy-system modelling of the EU strategy towards climate-neutrality", Energy Policy, 134, 110960.

COP-21, 2015, In: Paris Agreement, United Nations Framework Convention on Climate Change, Conference of the Parties 21, Paris, France.

Creutzig F., Roy J., Lamb W.F. et al., 2018, "Towards demand-side solutions for mitigating climate change", Nature Climate Change, 8, 4, 260-263.

Dafnomilis I., Chen H.H., Elzen M., Fragkos P. et al., 2021, "Targeted green recovery measures in a post-COVID-19 world enable the energy transition", Research Square, DOI: 10.21203/rs.3.rs-667715/v1.

Dalla Longa, F., Detz, R., and van der Zwaan, B., 2020, "Integrated assessment projections for the impact of innovation on CCS deployment in Europe", International Journal of Greenhouse Gas Control, 103, 103133.

Dalla Longa, F. and van der Zwaan, B.C.C., 2021a, "Heart of light: an assessment of enhanced electricity access in Africa", Renewable and Sustainable Energy Reviews, 136, 11039.

Dalla Longa, F. and van der Zwaan, B.C.C., 2021b, "Exploring the complex origins of energy poverty in The Netherlands with machine learning", Energy Policy, 156, 112373.

DG ECFIN, 2021, "Summer Economic Forecast 2021", https://ec.europa.eu/info/business-economy-euro/economic-performance-and-forecasts/economic-forecasts/summer-2021-economic-forecast_en

EC, 2021a, "EU Reference Scenario 2020: Energy transport and GHG emissions – Trends to 2050", European Commission, Brussels, Belgium.

EC, 2021b, "'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality", COM(2021) 550, European Commission, Brussels, Belgium.

Fleiter T., Rehfeldt M., Herbst A., Elsland R., Klingler A.-L., Manz P., Eidelloth S., 2018, “A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model”, Energy Strategy Reviews, 22, S. 237-254.

Fotiou T., de Vita A. and Capros P., 2019, "Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonisation in the EU", *Energies* 12 (14), 2745.

Fragkos P., 2020, “Global Energy System Transformations to 1.5 °C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets”, Energy Technology, 8 (9), 2000395.

Fragkos, P. and Kouvaritakis, N., 2018, “Model-based analysis of Intended Nationally Determined Contributions and 2 °C pathways for major economies”, Energy, 160, 965-978.

Fragkos, P., 2021. "Assessing the Role of Carbon Capture and Storage in Mitigation Pathways of Developing Economies", *Energies,* 14 (7), 1879.

Fragkos P., Fragkiadakis K., Sovacool B., Paroussos L., Vrontisi Z., Charalampidis I., 2021, “Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union”, Energy, 237, 125, 121591.

Fricko O., Havlik P., Rogelj J., Klimont Z. *et al.*, 2017, “The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century”, Global Environmental Change, 42, 251-267.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, et al., 2018, “Negative emissions-Part 2: Costs, potentials and side effects”, Environmental Research Letters, 13, 6.

Grubler, A., Wilson, C., Bento, N. et al., 2018, “A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies”, Nature Energy 3, 515–527.

Hummel M., Büchele R., Müller A., Aichinger E., Steinbach J., Kranzl L., Toleikyte A., Forthuber S., 2021, "The costs and potentials for heat savings in buildings: Refurbishment costs and heat saving cost curves for 6 countries in Europe", Energy and Buildings, 231, 1 - 19.

IEA, 2016, “Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems”, Paris, France

IEA, 2020a, “Sustainable Recovery report”, IEA, Paris https://www.iea.org/reports/sustainable-recovery.

IEA, 2020b, Energy Efficiency 2020.

IEA, 2021, “World Energy Investment Outlook”, IEA, Paris, France (Vol. 23).

IPCC, 2018, “Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.”

Kikstra J., Vinca A., Lovat F. et al., 2021, "Climate mitigation scenarios with persistent COVID-19-related energy demand changes", Nature Energy **10.**

Kober T., Falzon J., van der Zwaan B.C.C., Calvin K., Kanudia A., Kitous A., Labriet M., 2016, "A Multi-Model Study of Energy Supply Investments in Latin America under Climate Control Policy Energy Economics", Energy Economics, 56, 543-551.

Kober T., van der Zwaan B.C.C., Rösler H., 2014, "Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2˚C Climate Change Control Target", Climate Change Economics, 5, 1, 1440001, 1-32.

Levesque A., Pietzcker R. C., Baumstark L., De Stercke S., Grübler A. and Luderer G., 2018, "How much energy will buildings consume in 2100? A global perspective within a scenario framework", Energy, 148, 514.

Loulou R. and Labriet M., 2008, "ETSAP-TIAM: the TIMES integrated assessment model, Part I: Model structure", Computational Management Science, 5, 1-2, 7-40.

Loulou R., 2008, "ETSAP-TIAM: the TIMES integrated assessment model, Part II: mathematical formulation", Computational Management Science, 5, 1-2, 41-66.

Marcucci A., Panos E., Kypreos S. and Fragkos P., 2019, "Probabilistic assessment of realizing the 1.5 °C climate target", Applied Energy, 239, 239-251.

McCollum D.L., Zhou W., Bertram C. et al., 2018, "Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals", *Nature Energy* 3**,** 589–599.

Mundaca L., Ürge-Vorsatz D. & Wilson C., 2019, "Demand-side approaches for limiting global warming to 1.5 °C", Energy Efficiency 12**,** 343–362.

Nemet G., Callaghan M., Creutzig F., Fuss S., *et al.,* 2018, "Negative emissions—Part 3: Innovation and upscaling", Environmental Research Letters, 13,6.

OECD, 2020, "OECD Economic Outlook, Interim Report Coronavirus (COVID-19): Living with uncertainty".

Riahi, K., Bertram, C., Huppmann, D. et al., 2021, "Cost and attainability of meeting stringent climate targets without overshoot", Nature Climate Change, 11**,** 1063–1069 (2021).

Rao N.D. & Min J., 2017, "Decent living standards: material prerequisites for basic human wellbeing" Social Indicators Research, 1-20.

Rauner, S., Bauer, N., Dirnaichner, A. et al., 2020, "Coal-exit health and environmental damage reductions outweigh economic impacts", Nature Climate Change, 10, 308–312.

Reuter M., Patel M., Eichhammer W., Lapillonne B., Pollier K., "A comprehensive indicator set for measuring multiple benefits of energy efficiency", Energy Policy, 139, 2020, 111284.

Rochedo P.R.R., Fragkos P., Garaffa R., Couto, L.C., Baptista L.B., Cunha B.S.L., Schaeffer R., Szklo, A., 2021, "Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages", Energies, 14, 5567.

Roelfsema, M., van Soest, H.L., Harmsen, M. *et al.* "Taking stock of national climate policies to evaluate implementation of the Paris Agreement", 2020, Nature Communications, 11, 2096.

Rösler H., van der Zwaan B. C. C., Keppo I. J. and Bruggink J. C. C., 2014, "Electricity versus Hydrogen for Passenger Cars under Stringent Climate Change Control", Sustainable Energy Technologies and Assessments, 5, 106-118.

Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, et al., 2018, "Scenarios towards limiting global mean temperature increase below 1.5 degrees C", Nature Climate Change, 8, 325.

Swan L.G., Ugursal V.I., 2009, "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques", Renewable and Sustainable Energy Reviews, 13, 1819–1835.

Syri S., Lehtilä A., Ekholm T., Savolainen I., Holttinen H. and Peltola E., 2008, "Global energy and emissions scenarios for effective climate change mitigation – Deterministic and stochastic scenarios with the TIAM model", Int. Journal of Greenhouse Gas Control, 2, 2, 274-285.

UNFCCC, 2015, "FCCC/CP/2015/L.9/Rev.1: Adoption of the Paris Agreement", Paris, France, 1-32.

van der Zwaan B.C.C., Rösler H., Kober T., Aboumahboub T., Calvin K. V., Gernaat D. E. H. J., Marangoni G., McCollum D. L., 2013, "A Cross-Model Comparison of Global Long-Term Technology Diffusion under a 2°C Climate Change Control Target", Climate Change Economics, 4, 4, 1-24.

van der Zwaan B.C.C., Kober T., Calderon S., Clarke L., Daenzer K., Kitous A., Labriet M., Lucena A. F. P., Octaviano C. and Di Sbroiavacca N., 2016, "Energy Technology Roll-Out for Climate Change Mitigation: A Multi-Model Study for Latin America", Energy Economics, 56, 526-542.

van der Zwaan B.C.C., Kober T., Dalla Longa F., van der Laan A. J. and Kramer G. J., 2018, "An Integrated Assessment of Pathways for Low-Carbon Development in Africa", Energy Policy, 117, 387-395.

van Soest, H.L., Aleluia Reis, L., Baptista, L.B. et al., 2021, "Global roll-out of comprehensive policy measures may aid in bridging emissions gap", Nature Communications **12**, 6419.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J. et al., 2018, "Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies", Nature Climate Change, 8, 391–397.

Vona F., 2019, "Job losses and political acceptability of climate policies: why the 'job-killing' argument is so persistent and how to overturn it", Climate Policy, 19, 4, 524-532.

WHY, 2021, https://www.why-h2020.eu/.

Wilson, C., Grübler, A., Gallagher, K. S. & Nemet, G. F., 2012, "Marginalization of end-use technologies in energy innovation for climate protection", Nature Climate Change 2, 780–788.

World Bank, 2021, "Global Economic Prospects", https://openknowledge.worldbank.org/bitstream/handle/10986/35647/9781464816659.pdf

Appendix

Figure A1 presents the post-COVID global GDP projection used in this paper. This has been obtained by the authors based on the SSP2 projection from Fricko et al.(2017), also shown in the plot. The short-term GDP assumptions have been modified to include the socio-economic impacts of COVID-19 and recovery plans. The short-term GDP assumptions were modified to better account for recent socio-economic developments and are consistent with GDP trajectories presented in detail in (Dafnomilis et al., 2021)

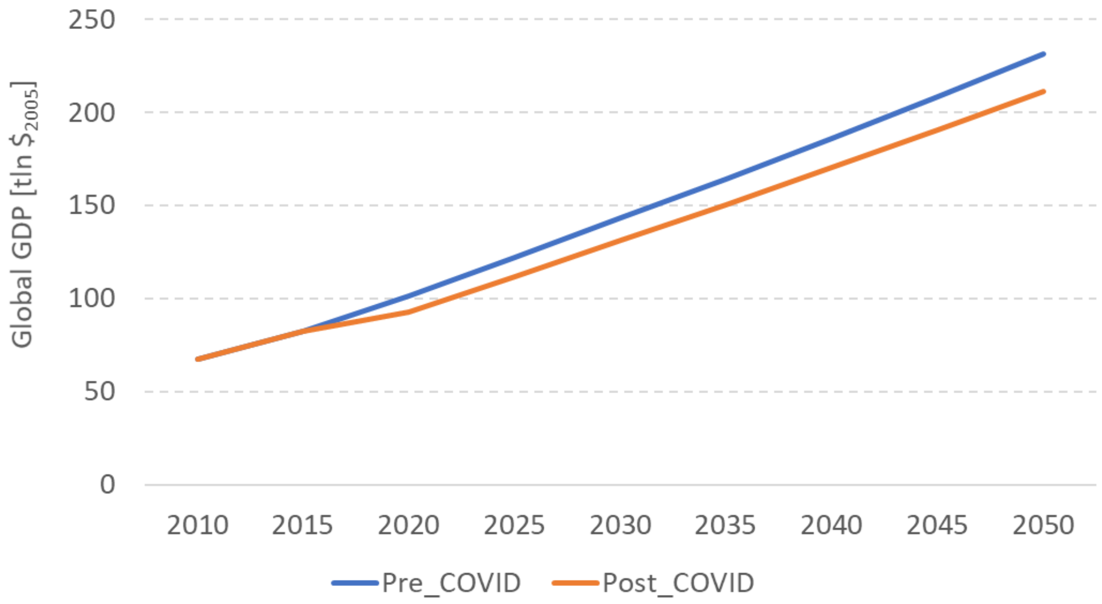


Figure A1: Pre- and post-COVID GDP projections, expressed in 2005 international dollars.

Table A1: Modified 2020 GDP growth rates at country/regional level (from OECD economic outlook, consulted in November 2020).

	2020 GDP growth rate [%]
Argentina	-12.9
Australia	-3.8
Austria	-8.0
Belgium	-7.5
Brazil	-6.0
Bulgaria	-4.1
Canada	-5.4

Chile	-6.0
China (People's Republic of)	1.8
Colombia	-8.3
Costa Rica	-5.6
Czech Republic	-6.8
Denmark	-3.9
Dynamic Asian Economies	-4.6
Estonia	-4.7
Euro area (17 countries)	-7.5
Finland	-4.0
France	-9.1
Germany	-5.5
Greece	-10.1
Hungary	-5.7
Iceland	-7.7
India	-9.9
Indonesia	-2.4
Ireland	-3.2
Israel	-4.2
Italy	-9.1
Japan	-5.3
Korea	-1.1
Latvia	-4.3
Lithuania	-2.0
Luxembourg	-4.4
Mexico	-9.2
Netherlands	-4.6
New Zealand	-4.8

Non-OECD Economies	-3.0
Norway	-1.2
OECD - Total	-5.5
Other oil producers	-6.5
Poland	-3.5
Portugal	-8.4
Rest of the World	-4.3
Romania	-5.3
Russia	-4.3
Slovak Republic	-6.3
Slovenia	-7.5
South Africa	-8.1
Spain	-11.6
Sweden	-3.2
Switzerland	-4.7
Turkey	-1.3
United Kingdom	-11.2
United States	-3.7
World	-4.2
EEU	-4.8

In Figure A2 we present sector-level emission reductions with respect to REF. Both models project that the largest reductions occur in the power generation, industry and transport sectors. The latter two sectors' contributions become more sizeable towards the middle of the century. For PROMETHEUS the electricity sector provides the largest contribution in all time periods and scenarios while for TIAM-ECN Industry becomes the most prominent contributor in 2050. TIAM-ECN also projects a substantial role for the Upstream sector, mainly driven by the possibility to deploy CCS technologies in fuel production, as also evident from Figure 6. While emission reduction in the residential and commercial sectors are relatively small, it is worth noticing that, in the 2050 TIAM-ECN projection, the moderate carbon price assumed in the TAX_eff scenario triggers, for these sectors, a drop in emissions of approximately the same magnitude as that observed in the 1.5DC scenario. This is yet another indication that carbon pricing in combination with enhanced energy efficiency can prove an effective strategy to decarbonize the residential and commercial sectors.

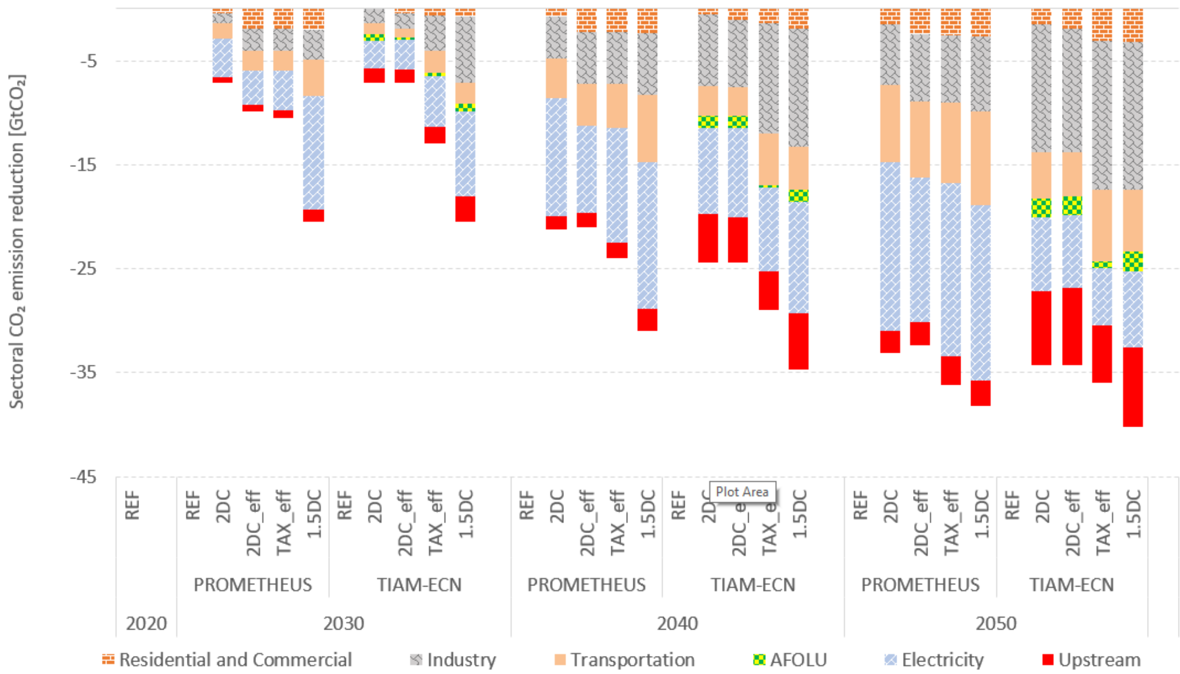


Figure A2: Sectoral CO_2 emission reduction with respect to the REF scenario.

ANNEX 2: System-level Effects of Increased Energy Efficiency in Global Low-carbon Scenarios: a Model Comparison

The annex presents the already published paper in the peer-reviewed scientific journal "AIMS Energy". The reference can be found here:

P Fragkos, Analysing the Systemic Implications of Energy Efficiency and Circular Economy Strategies in the Decarbonisation Context, AIMS Energy, 2022, Volume 10, Issue 2: 191-218. doi: 10.3934/energy.2022011

Abstract:
The Paris Agreement goals require a rapid and deep reduction in global greenhouse gas emissions. Recent studies have shown the large potential of circular economy to reduce global emissions by improving resource and material efficiency practices. However, most large-scale energy system and Integrated Assessment Models used for mitigation analysis typically ignore or do not adequately represent circular economy measures. This study aims to fill in this research gap by enhancing a leading global energy system model with a representation of

energy efficiency and circular economy considerations. The scenario-based analysis offers an improved understanding of the potentials, costs and impacts of circular economy in the decarbonisation context. The study shows that enhanced energy efficiency and increased material circularity can reduce energy consumption in all sectors, but most importantly in the industrial sector. They can also reduce the required carbon price to achieve Paris goals and the dependence on expensive, immature, and risky technologies, like Carbon Capture and Storage. Circular economy measures should be properly integrated with broad climate policies to provide a holistic and self-consistent framework to deeply reduce carbon emissions.

Keywords: PROMETHEUS model; circular economy; energy and resource efficiency; demand-side mitigation options

1 Introduction

The consumption of materials forms one of the foundations of human development. The rapid growth of population and wealth resulted in a large increase in global material consumption from 27 to 90 billion tonnes per year in 1970-2018 period [1]. Materials including chemicals, food and structural materials are used to manufacture products, such as appliances, buildings, cars, and infrastructure and are commonly discarded after use. This "linear model" from extraction to manufacturing, use and disposal has led to resource depletion, production of waste and extensive use of energy [2]. As a result, greenhouse gas (GHG) emissions associated with the production of structural materials have increased rapidly from 5 to 12.1 GtCO2eq over 1990-2019, while their share in global GHG emissions has also grown from 15% in 1990 to 23% in 2019 [3]. This poses increasing challenges for meeting the Paris climate goals of limiting global warming to well-below 2^{o}C by the end of the century [4], while the increase in the deployment of renewable energy reduces emissions from manufacturing sectors, but at moderate levels [46].

In this context, the 'circular economy' is introduced as an alternative to the current linear model [5]. Despite the various definitions found in the literature [5], the transition to circular economy aims to reduce primary material consumption, keep products and materials longer in use, recover or recycle materials and reduce losses [6]. By reducing primary material consumption, the circular economy will reduce the depletion of resources and environmental degradation risks, while also cutting the energy consumption and GHG emissions related with all stages of materials' production. Therefore, there are strong synergies between the circular economy and climate change mitigation towards achieving net zero emissions by mid-century, which are highlighted in recent literature including the International Resource Panel [1]. The role of circular economy (CE) towards the transition to climate neutrality has been acknowledged by the European Commission, as an integral part of the EU Green Deal, the Circular Economy

Action Plan [7] and the “Clean Planet for all” long-term mitigation strategy [8], while CE is also discussed in the 14th 5-year China’s plan.

Circular economy presents a great potential for emissions reduction, while creating new opportunities for the industry. The study of Material Economics [9] has shown that ambitious demand side measures in the form of materials recirculation, increased product efficiency and circular business models can reduce emissions from the heavy industry[1] by up to 60% in 2050 compared to 1990. Circular economy offers large opportunities for a more efficient use of materials, complementing the efforts in increasing energy efficiency, but requires large socio-economic structural changes and industrial re-organisation. It is therefore important that circular economy considerations are integrated in national low-emission development plans and should be jointly assessed with low-emission strategies, as [47] showed that there is a lack of literature scientifically scrutinizing the relationships between a hydrogen economy and the United Nations Sustainable Development Goals (SDGs). The transition towards a circular economy has several social, political, and sustainability aspects that should be investigated. The study [48] provides useful insights into how green recovery stimulus, driven by circular economy (CE)-based solid waste management (SWM) could assist in attaining the UN-SDGs and how green jobs can be created by investing in recycling infrastructure. The literature argues that CE-based product designs and business models would emphasize multifunctional goods, extending the lifespan of products and their parts, and intelligent manufacturing to help the public and private sectors maximise product utility (reduce waste generation) while providing long-term economic and environmental benefits. However, practical demonstrations of CE impacts in real-world contexts are currently limited, but one of them [49] showed that service-oriented, event-driven processing and information models can support the integration of smart and digital solutions in current CE practices at the factory level. The links of CE strategies with social and sustainable development and further analysed in [50].
Despite its potentially large contribution to achieving the climate targets, there is relatively limited analysis on the potential role of circular economy (CE) in the context of the energy transition. Circular economy is not adequately (and in most cases not at all) represented in most energy-economy and Integrated Assessment Models (IAMs) which are often used for climate policy analysis [10]. Most studies analysing the challenges and opportunities of circular economy use bottom-up methodologies focusing on the technical processes related to the CE and are often based on case studies, without considering the fully-scale CE implications on the entire energy system and associated emissions. This is an important research gap, which makes it difficult to analyse the interplay between climate policies and CE strategies. The paper aims

[1] Heavy industry refers to an industry that produces large industrial products, which requires large and heavy machinery and facilities and involves complex and energy-intensive production processes. Heavy industry is dominated by large companies, as it is very capital intensive and requires significant investment in heavy equipment, massive buildings, large machine tools, and extensive infrastructure.

to expand the current literature by consistently integrating circular economy in a state-of-the-art global energy system model with a focus on the most energy-intensive industrial activities. The novelty of the study is related to the consistent integration of CE strategies into a comprehensive energy system model that enables the assessment of their systemic implications on energy and economy systems. Through detailed scenario analysis, the potential synergies and trade-offs between ambitious climate action and resource efficiency are analysed, examining the role that CE strategies may play on the road to achieving the Paris goals. The study provides a detailed assessment of the systemic effects of circular economy on the future evolution of emissions, energy system transformation in major sectors, and related investment needs and improves the understanding of the interlinkages between climate mitigation, energy efficiency and circular economy measures.

The rest of the paper is structured as follows: Section 2 reviews the interplay between circular economy and the transition to a low-carbon economy and introduces the methodology used in the study. Section 3 presents in detail the model-based scenario results, focusing on the role of circular economy towards meeting ambitious climate targets. Section 4 discusses the key findings of the analysis and concludes.

2. Materials and Methods

2.1 Review of circular economy in the transition to a low-carbon economy

Energy-intensive industries including iron and steel, chemicals, cement etc are commonly considered difficult to decarbonise due to the limited technological options available, their links with energy supply (to provide green electricity and hydrogen) and the high costs associated with shifting to low-carbon alternatives [4]. Reducing material consumption and production via CE strategies can complement other climate policies related to decarbonisation and energy efficiency [11]. The heavy industries can reduce their emissions and environmental footprint by decreasing the required amount of energy and raw materials through increased energy efficiency and the implementation of CE strategies, requiring the conversion of most material fluxes into closed loops. Due to the required speed of emission reductions and challenges in difficult-to-decarbonise energy-intensive sectors, CE strategies might play an important role in meeting ambitious climate targets [1, 12]. A circular economy would increase the availability of raw materials for the sectors that manufacture low-carbon technologies, such as cobalt and li-ion for batteries or rare earths for wind turbines. The huge volume of toxic electronic waste (e.g. from smart phones) could provide feedstock for materials with the potential to increase electrification of the energy system, including the electronic components of batteries and photovoltaics. In addition, industrial symbiosis can offer a decarbonisation opportunity for some industrial sectors by re-using waste from other sectors as raw material input.

The current economic model in most countries is close to linear, often described by extraction, production, use and disposal of materials. In a circular economy, raw materials are sourced sustainably and used more efficiently in the entire chain of activities from product design, manufacturing, use, repair, disassembly, remanufacturing and reuse of products. The product components are gradually recycled after degradation minimising waste, with each component allowing for a different number of reuse cycles (Figure 1). The current model could lead to a moderate circular economy, with increased recycling and some limited reuse. However, the transition to a circular paradigm requires the transformation of the current value chain in the economy; the purchase and consumption of products will decline, their durability will increase and sharing practices need to emerge [8]. The manufacturing processes should be redesigned so that material losses are minimised in all lifecycle phases of materials and products, potentially leading to a diversified reuse across the value chain; for example, cotton clothing first reused as second hand apparel, then as fibre-fill in wood industry and in stone wool insulation for construction.

In a circular economy, companies may sell less products than in the current linear paradigm and may experience reduced revenues, but new value creation opportunities will arise aiming to retain values in the economic system. First, energy and material costs per product are expected to decline due to lower needs for primary resources, while new services – enabled by the digitalisation of the economy- will support reusing or sharing the use of products and offer lifetime prolongation for products. This will maximise the utility of the customers, while significantly reducing environmental impacts, the use of raw materials, energy resources and associated GHG emissions. The quantities of virgin materials used as feedstock in manufacturing processes will reduce, as they will be increasingly replaced by recycled and uncontaminated materials, which require much less energy intensive processes, and by the cascading use of materials and reduced material loss during the processing phase. However, some materials, like plastics, are more difficult (due to their chemical features and/or economic costs) to recycle than others, such as metals, glass, and paper [1,2]. Materials like metals and glass can either be recycled infinitely with proper recycling and circular strategies, while paper can be recycled 5 or more times before material integrity is compromised [8]. This means that while recycling of metals, glass, and paper brings energy savings, with the current infrastructure it is not chemically possible or economically viable to reintegrate a large portion of plastics with current technology [8]. Most plastics cannot be recycled at all, only downcycled to a different plastic of inferior mechanical quality, to which virgin plastic is added to maintain performance. As such, recycling will have much greater impact in achieving a transition to a CE in some sectors and products than in others.

Figure 1: A circular economy

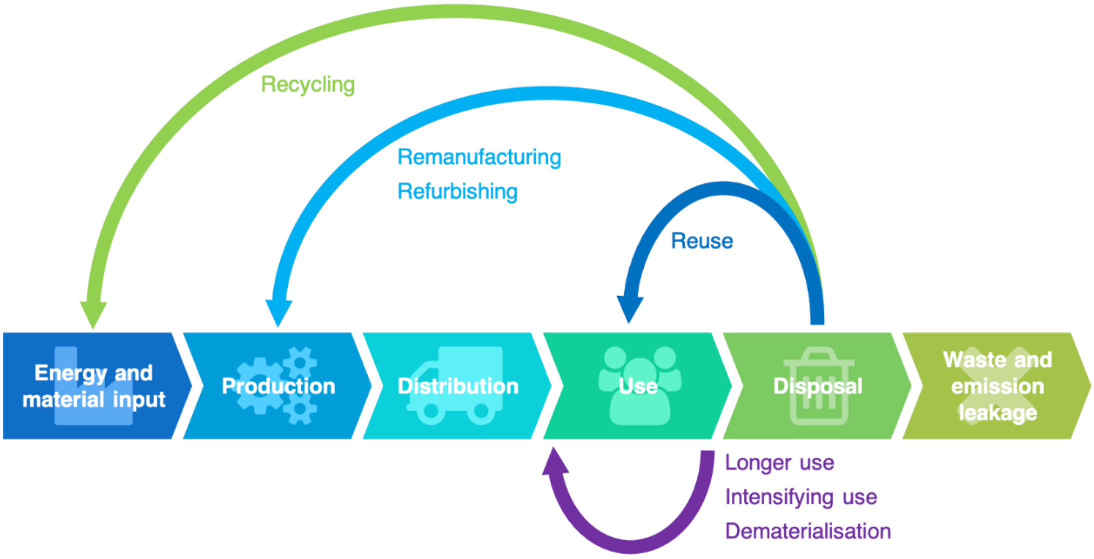


Figure adapted from [13]

The transformation towards a circular economy paradigm requires changes to product design and business models of involved industries. Manufacturing firms would be required to develop genuinely new products, with similar functionality for end users but lower energy and material use and associated emissions. The circular economy paradigm may also be complemented by the emergence of mobility-as-a-service with cars increasingly shared and operated in fleets; this will increase the car occupancy rate but will reduce the total car fleet and the materials required for their production.

Resource efficiency in industry is key for the circular economy, as it results in reduced needs for raw materials, increased recycling, and minimisation of waste and material loss across all lifecycle phases of each product. Circularity of metals and recycling of raw materials from low carbon technologies is an integral part of the low carbon transition. The EU is at the forefront of the circular economy and has increased the use of secondary raw materials with recycling rates of metals such as iron, aluminium, zinc, chromium, or platinum already reaching 50% [1]. However, additional effort is required to increase the secondary production of rare earths and gallium, which are needed in high-tech applications and renewable energy technologies and storage batteries [14]. Despite the potential recyclability of raw materials, a large part of future material demand will be provided by primary raw materials. In addition, recycling opportunities will fully materialise with a lag of several years or several decades (in the case of buildings) due to the long-time spans until the various products (e.g. cars, infrastructure, equipment, appliances) reach the end of their lifetime.

Materials and products consumed today are largely produced from raw materials (e.g., metal ores, hydrocarbons, biomass) and disposed of after use, creating waste. However, CE strategies including re-use, remanufacturing, and recycling, can reduce the reliance to primary resources and transform the supply chain in more, or even entirely, circular ways [15]. According to the International Resources Panel [16] resource efficiency policies could reduce global extractions by 28% by 2050. Combined with ambitious climate action, such policies can reduce global GHG emissions by about 62%. A recent study [9], focused on energy-intensive sectors like steel, plastics, aluminium, or cement, estimates that the transition to CE could reduce EU emissions by 300 $MtCO_2$ and global emissions by 3.6 $GtCO_2$ annually until 2050. In addition, the full recycling of plastic waste would save the equivalent to 3.5 billion of oil barrels per year. However, the study shows that the future demand of such materials will lead to emissions exceeding the carbon budget compatible with Paris mitigation goals, even if implementing energy efficiency and low-carbon measures.

The potential contribution of the CE towards the EU transition to a low-carbon economy is widely recognised [1,7, 9]. In 2015, the European Commission published its Action Plan for the Circular Economy [7], which aims to stimulate EU's transition towards a circular economy, boost competitiveness, foster sustainable growth and generate new jobs. It covers the whole chain of activities from production to consumption, waste management and the market for secondary raw materials. In 2018, the Commission launched the EU Strategy for Plastics in a Circular Economy [17], targeting the production and incineration of plastics. As part of its effort to transform Europe's economy into a more sustainable one and to implement the Circular Economy Action Plan, in January 2018 the Commission adopted a set of measures (COM (2018) 29 final), including: a Europe-wide EU Strategy for Plastics in the Circular Economy, a Communication on options to address the interface between chemical, product and waste legislation that assesses how the rules on waste, products and chemicals relate to each other, a Monitoring Framework on progress towards a circular economy at EU and national level. It includes ten key indicators which cover each phase – i.e. production, consumption, waste management and secondary raw materials – as well as economic aspects –investments and jobs - and innovation. The Report on Critical Raw Materials and the circular economy highlights the potential to make the use of the 27 critical materials in our economy more circular.

The partnership of industries, sharing their infrastructures and their material inputs and outputs (including waste), is another way to optimise resource use and reduce emissions, enabled by digitalisation[2]. Exploiting the strong interlinkages among industries, the intensified exchanges

[2] The carbon footprint of digitalization would increase driven by increasing requirements for servers and data centers that need to run constantly. But, in the decarbonization context, electricity would be carbon-free before 2050, indicating relatively limited emissions due to digitalization. A recent study has estimated that digitalization is responsible for about 3.5% of global emissions, but data centers account for only 15% of this impact, i.e. about 0.5% of total emissions [52].

of materials, energy and services, can enhance environmental sustainability and achieve mutual economic benefits [18]. This option is mostly applicable to specific industrial subsectors and selected industrial sites in Europe, which fulfil the requirements for infrastructure and access to specific resources. It is more efficient for industries closely located to each other, facilitating the exchange of materials and resources; for example, SPIRE project[3] systematically mapped and assessed the geographic dimension of industrial symbiosis for cement, steel, refining and chemical industries, identifying five potential symbiosis sites/hotspots in Europe.

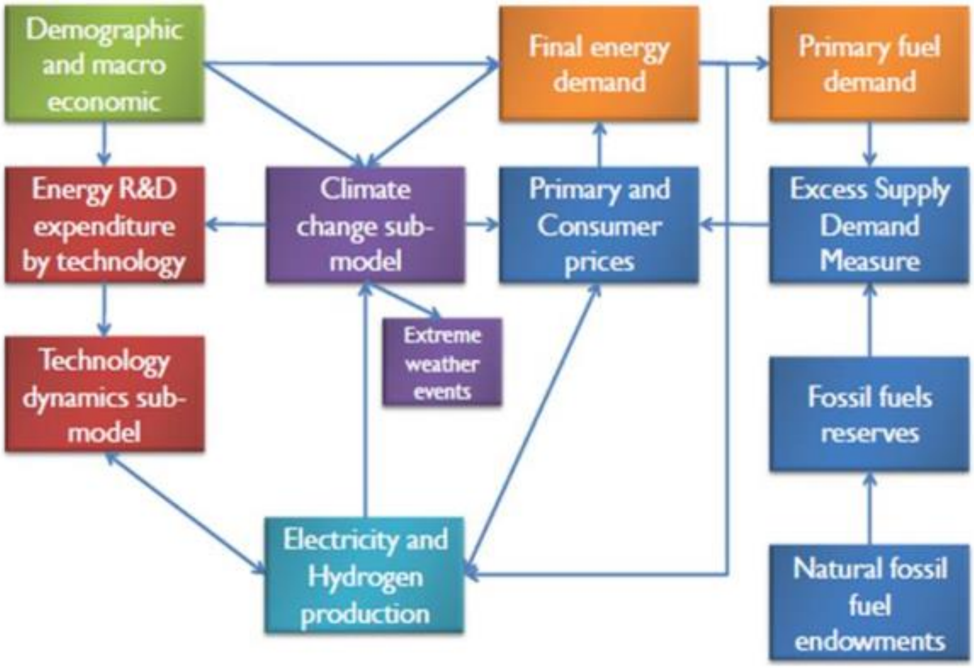
2.2 The PROMETHEUS model

PROMETHEUS is a comprehensive energy system model focusing on technology uptake analysis, energy price projections, and assessment of climate policies [19, 20]. It captures the interactions between energy demand and supply at regional and global level and provides detailed projections of energy consumption by sector, fuel mix, electricity production mix by technology, carbon emissions, energy prices and investment to the future. PROMETHEUS can provide medium- and long-term energy system projections up to 2050, exploring the impacts of alternative energy and climate policy measures (e.g., carbon pricing, subsidies for renewable energy, energy efficiency standards, fossil fuel taxation, promotion of clean fuels etc).

In PROMETHEUS, market equilibrium is ensured with each representative agent (e.g., energy producer or consumer) using information on prices to make decisions about the allocation of resources. The interactions of agents are governed by market dynamics with market-derived prices to balance energy demand and supply in each sector (e.g., electricity production). The national fuel markets are also integrated to form an international (global or regional) market equilibrium for crude oil, natural gas, and coal. The model produces projections of global and regional fossil fuel prices, which depend on demand, supply, technology, and resources. Thus, PROMETHEUS covers in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level. Its main objectives are: (1) to assess climate change mitigation pathways and low-emission development at national or global levels; (2) to analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, and (3) to explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices [21].

Figure 2: PROMETHEUS Flow Chart

[3] https://www.spire2030.eu/epos



PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (such as various renewable energy sources, electric vehicles, heat pumps, biofuels, energy efficiency, Carbon Capture and Storage, Carbon Dioxide Removal options) and policy instruments, such as carbon pricing schemes that may differentiate by region and economic activity. The model includes a complete accounting of energy demand and supply by sector and energy product and endogenous representation of energy prices. PROMETHEUS represents: the EU, China, India, the USA, Western Pacific region (Japan, S. Korea, Australia, New Zealand), Russia and CIS economies, MENA region (Middle East and North Africa), Emerging economies and Rest of world [22]. In PROMETHEUS, the regional developments of energy demand and supply, the inter-fuel substitutions, energy and climate policies and hydrocarbon resource assumptions influence the evolution of the global energy system and international fossil fuel prices. The modelling framework can be used for the impact assessment of energy and environment policies, including carbon or energy taxation, subsidies, clean energy and energy efficiency promoting policies, and technology standards [22, 23].

A detailed representation of the major energy- and carbon-intensive industrial sectors is included in PROMETHEUS, which represents the Iron and Steel sector, building materials (including cement), production of chemicals, non-ferrous metals and paper and pulp industries. In each industrial sector the model represents several types of industrial processes, technologies and energy forms and models the link between technology and processing types based on substitution possibilities (e.g. steel produced from integrated steelworks vs steel produced from electric arcs) as well as complementarities. The substitution possibilities combined with the structure of industrial processes represented in PROMETHEUS is a solid basis to estimate the realistic possibilities of the transformation in the industry sector, induced e.g., by the direct electrification and the uptake of low-emission fuels. Recent modelling improvements enable the explicit representation of primary versus secondary production of energy-intensive materials, including steel, paper, aluminium, glass, and clinker. These projections depend mostly on activity assumptions and policy drivers, regarding recycling and circular economy, which may differentiate by scenario. The modelling framework is therefore designed and well-equipped to address the questions about the medium- and long-term effects of circular economy and its contribution to meeting ambitious global climate targets. The specific operationalisation of energy efficiency and circular economy in applied models in discussed in section 2.3.

2.3 Operationalisation of energy and resource efficiency in models

Energy efficiency strategies are key pillars towards achieving deep emissions reduction, but they are often neglected or poorly represented in energy-economy models, which tend to focus more on supply-side mitigation options [24]. However, recently the most advanced energy system models have improved the representation of efficiency measures and demand-side mitigation options, given the increasing importance of energy efficiency for climate strategies [19, 25]. In this context, PROMETHEUS includes a detailed and self-consistent representation of energy efficiency policies and related instruments, including efficiency standards, energy labelling, regulation, promotion of more efficient energy forms and technologies, strategies for renovation of buildings etc. These measures are inserted in the model either in the form of price incentives (e.g., cost subsidies, changes in energy and carbon taxation) or in the form of constraints, i.e., on the rate of buildings' renovation or the phase-out of energy and carbon-intensive technologies (e.g., oil boilers or diesel cars). These efficiency measures often apply to the buildings and transport sector influencing consumer decisions related to the investment and/or operation of energy equipment, appliance, and passenger cars.

In the industrial sector, on top of energy efficiency measures, resource and material efficiency strategies and circularity play a prominent role driving energy and emission savings [5, 26]. Thus, modelling should capture the potentials and costs of product recycling and re-use, improved waste management, substitution towards more efficient materials, reduced need for virgin materials, and the shift of manufacturing processes to secondary, recycled materials that have lower energy and carbon requirements (e.g. scrap steel, recycled paper, plastics etc). This means that primary industrial output (in volumes) of specific sectors would decline [8], while the impacts on respective value added depend also on the emergence of recycling and circular services. Overall, the literature on circular economy is growing, but so far it does not provide analytical information [9]. The EU's long-term strategy [8] and relevant literature ([9], [13], [27]) include a detailed review on the circular economy impacts on industrial production by sector, which are also utilised in the current study. Table 1 presents the assumed effects of resource efficiency and circular economy on primary industrial production based on a realistic implementation of circularity in energy intensive sectors, without assuming overly ambitious transformation and disruptive options (e.g., 3D printing). It should be noted that the assumed levels of output reduction can be considered conservative compared to the circular economy literature, which is presented below. If buildings, infrastructure, and cars are produced and used more efficiently, this would trigger additional reductions in material requirements.

Table 1: Impact of Circular Economy on primary energy-intensive production in 2050

	% Reduction of primary material volumes from Baseline	Most important Circular economy strategies by sector
Iron & Steel	6%	Higher steel recycling; Increased use of scrap steel; reduced demand for steel (e.g., from cars, constructions etc)
Chemicals & Plastics	9%	Improved recycling rates of plastics; Product standardisation, improved collection, and sorting; Cascading use of plastics with down- and up-grading; Wood fibre products replacing plastics
Paper & Pulp	12%	Maximise recycling and re-use of paper; Improve material efficiency; Improve the collection, sorting and Ecodesign for recycling; New technologies like steam forming without wetting and drying;
Non-metallic minerals (including cement)	8%	Recover up to 30-40% of unused clinker from concrete at end to life; lower cement demand (e.g., re-use of building components, wood-based construction);

The Iron and Steel sector accounts for about 8% of global emissions in 2019, so it is a key sector for emission reduction efforts. There are different routes by which steel is produced. Crude or primary steel is produced from iron ore and secondary steel is produced from recycled steel, but this is constrained by limited scrap availability and thus scrap accounts for about 35%

of global steel production [28]. These two routes use different technologies and different energy sources [28], but secondary steel production is about 70% less energy intensive than making steel from iron ore (primary production) [29]. The share of scrap in primary steel production varies among countries and years. In the context of circular economy, the shift from primary steelmaking to secondary smelting of steel scrap depends on various factors, including the availability and quality of scrap metal in international markets and the quality of the final product. Currently, many factors reduce the steel amounts that can be recycled including low collection rates, downgrading of steel, lack of incentives to recycle steel, losses in recycling processes and copper contamination. These can be resolved by improving circular economy practices, increasing the availability of scrap steel from the current share of 35%-40% up to 80% according to [9] and significantly reducing energy requirements and CO_2 emissions. In the circular economy context, demand measures (e.g., reduced number of cars) could further reduce primary steel production to the point where the available scrap steel would be able to cover most of the steel demand [9].

Significant potential lies also in the increased material efficiency and substitution, especially related to carbon-intensive materials like cement. Although cement cannot be recycled as other materials, there is an opportunity to recover up to 30-40% of unused clinker from concrete at end to life, replacing up to 60% of new cement production and saving almost half of associated emissions [30]. In addition, cement requirements could be reduced if buildings are designed for disassembly and building components can be re-used, while wood-based construction can also reduce energy requirements and carbon emissions (despite its risks due to reduced stability and shorter lifecycle).

In the chemicals and plastics sector, the improved recycling of plastics can play an important role in the transition towards circular economy. Plastic waste can be significantly reduced by increasing the mechanical and feedstock[4] recycling up to 60-70% of yearly plastic waste volumes [26]. Another study finds that up to 60% of the global production of chemicals can be recycled and re-used [31], but this requires product standardisation, improved collection, and sorting. Increased circularity would result in both reduced use of raw material (of fossil origin), as well as less energy since recycled plastic is a less energy demanding process. However, with the current infrastructure it is not chemically possible or economically viable to reintegrate a large portion of plastics with current technology. In circular economy context, a cascading use of plastics would be introduced with downgrading or upgrading (with mechanical and feedstock recycling respectively) or after the plastics have degraded to energy recovery [8].

[4] Mechanical recycling refers to the mechanical processing of waste plastics to produced recycled polymers. Feedstock recycling refers to the chemical or thermal processes breaking down polymers into products that can directly replace raw materials.

Paper and pulp sector also have a great potential for increased resource efficiency based on maximum recycling and re-use of paper, improved material efficiency and wood fibre products replacing plastics. Recycled fibre quality can be enhanced by improving the collection, sorting and Ecodesign for recycling. New recycling technologies like steam forming without wetting and drying could even further decrease energy demand in the paper industry [32]. Digitalisation might also provide the next generation of efficient recycling technologies [8].

Transport benefits from integrating the sharing economy and connected, cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service. The vehicle fleet is smaller relative to the Baseline, but it is utilised more, has higher occupancy rates, and it is renewed faster. The reduced vehicle fleet results in lower requirements for materials used in the automotive industry. Improved logistics and shifts from long-distance freight to near-sourcing, together with shifts towards rail and waterborne transport lead to further energy and emission savings. In the energy system, circular economy implies increased waste heat recovery, and conversion of waste material into useable heat, electricity, or fuel. Improved management and collection of organic waste and biomass cascading, increases the sustainable biomass use either as a feedstock or for biogas production in local bio-refineries.

2.4 Scenario design

The paper aims at exploring the effects of a strong push in circular economy and energy efficiency across the global energy system, with a focus on energy-intensive industries, under stringent decarbonisation policies. For this purpose, we design five scenarios (Table 2) based on specific assumptions with regard to (i) climate change mitigation targets, (ii) energy efficiency improvements, and (iii) circular economy considerations. These scenarios are then implemented in the PROMETHEUS model.

Table 2: Summary of key assumptions used in the series of scenarios

Scenario name	Scenario Description	Key assumptions
REF	Continuation of existing energy and climate policies, no strengthening of policies after 2030	Energy system follows current trends, energy efficiency improves at historical levels
2DEG	Global 2016-2050 carbon budget of 850 Gt CO_2 (compatible with well-below 2°C)	Cost-optimal transition to 2°C, based on universal application of carbon pricing
2DEG_CI	Same carbon budget as 2DEG. Increased	The transition to 2°C based

	energy and resource efficiency, including circular economy	on accelerated energy efficiency and circular economy
1.5 DEG	Global 2016-2050 carbon budget of 600 Gt CO_2 (compatible with a 1.5°C)	Cost-optimal transition to 1.5°C, based on universal application of carbon pricing

The REF scenario is based on the continuation of already legislated energy and climate policies, in consistency with [33]. The global energy system develops in line with current trends including existing climate policies until 2030 and further cost improvements in low-carbon technologies; beyond 2030, no binding emissions reduction targets are imposed. The energy intensity of GDP is assumed to keep improving at rates close to historical rates in each region. The REF scenario serves as a benchmark to compare the results of other scenarios, which explore possible realizations of a low-carbon energy system driven by decarbonization policies and energy efficiency targets [34], including circular economy considerations.

The 2DEG scenario achieves a cost-optimal emissions reduction trajectory compatible with a well-below 2°C increase in global temperature, in line with the Paris Agreement goal. Global CO_2 emissions from fossil fuels and industrial processes over 2016-2050 are constrained to a budget of 850 Gt CO_2 in line with [35]. A global carbon pricing scheme applies uniformly across all regions and sectors. The carbon price emerges endogenously in PROMETHEUS as the dual variable related to the maximum allowed carbon emissions by 2050. Energy system decarbonization is induced by high carbon pricing that incentivizes the uptake of renewable energy, electrification, clean fuels, and energy efficiency improvements.

The 2DEG_CI scenario achieves the same carbon budget constraint as the 2DEG, but higher energy and resource efficiency improvements are realized in all demand sectors by 2050. This is induced by the imposition of energy efficiency policies (e.g., subsidies for the renovation of buildings or the purchase of electric cars), the uptake of more efficient technologies (e.g., heat pumps), which are usually accompanied by higher capital costs [25], and transition to circular economy paradigm with increased recycling rates of materials and accelerated resource efficiency. The scenario aims at showing the effects of demand-side changes on the road to decarbonization, including consumers' shift towards purchasing efficient technologies and energy forms and industries' shift to circular economy. These changes can be induced by policy measures targeting the stringent implementation of energy labeling, efficiency standards, and building codes, the gradual phase-out of inefficient energy appliances and equipment, increased renovation rates, and a move towards circular economy. These may include measures to enhance resource efficiency, increase recycling rates of materials and products, standardise recyclable material and improve systems for waste management [31]. In this way, the demand for primary resources and materials is lower relative to 2DEG as shown in Table 1, due to the increased reuse and recycling of products and materials, reduced waste, and the replacement away from resource-intensive products. These are accompanied by changes in consumer lifestyles with adoption of environmentally friendly practices, including e.g., more rational use of energy in the built environment, shifts towards less carbon-intensive transport modes, emergence of Mobility-As-A-Service, sharing mobility and active mobility forms [8]. In the industry sector, the scenario includes several circular economy measures, e.g., increased use of scrap steel, ambitious recycling of plastics and paper, substitution of plastics by bio products, improved material efficiency, material substitution by biomass, concrete recycling and re-use, which are combined with increased use of biomass, renewable energy, and RES-waste.

The last scenario of the study (1.5 DEG) has the same logic as 2DEG but aims to achieve a more ambitious climate target. In particular, global cumulative carbon emissions in 1.5DEG are constrained to 600 Gt CO_2 over the 2016-2050 period, resulting in a global temperature increase of 1.5°C by the end of the century [36]. This scenario explores the impacts of ambitious and coordinated climate action by all countries to limit global warming to below 1.5°C (as introduced in the Paris Agreement) by implementing universal carbon pricing across all regions and sectors.

Assumptions for future development of the main socio-economic drivers – population and GDP growth – in PROMETHEUS are based on the second Shared Socioeconomic Pathway (SSP2) developed in [37]. However, in this paper the SSP2 trajectory is modified to reflect the impacts from COVID-19 and the expected developments in the post-COVID era. These modifications entail short-term GDP projections from official sources, including OECD Economic Outlook (November 2020) [38], and World Bank Global Economic Prospects (June 2021) [39]. PROMETHEUS is calibrated to reproduce the impacts of COVID-19 on economic activity in 2020: a 4.5% lower global GDP relative to 2019 levels. After 2021, assuming a strong and effective vaccination programme and no further major outbreaks, GDP projections follow a V-shape growth recovery or an L-shaped recovery in level terms [40].

3 Results

3.1 Impacts on emissions and carbon pricing

The policy scenarios examined influence the development of energy-related CO_2 emissions, as shown in Figure 3. The REF scenario shows a modest increase in global emissions over 2020-

2050, despite the robust growth of global GDP [33], indicating a relative decoupling of emissions and energy use from GDP growth, in line with recent multi-model comparison exercises [4, 40, 45] and the IPCC Special Report on 1.5°C [36]. This is induced by the expansion of low-carbon and energy-efficient technologies in energy supply and demand induced by technology cost reductions (e.g., PV, wind turbines, batteries, electric vehicles) and the continuation of already legislated climate policies. The latter are realized in PROMETHEUS through constraints in model equations which influence the development of the energy mix and the uptake of fossil-fuel or low-carbon technologies in each sector. The impacts of the European Emission Trading System (ETS) are also simulated, resulting in the small increase in global average carbon price in the REF scenario (Table 3).

Global carbon prices increase with the level of emissions mitigation effort. In 2DEG scenario, the global carbon price increases to 81 $ 2015/tn CO_2 in 2030 and further to about $ 290 in 2050 as the ambition of climate action increases and further uptake of available mitigation options faces constraints. The scenario with high energy efficiency and circularity requires lower carbon prices to achieve the same climate target, as shown in Table 3 where the carbon price in 2DEG_CI is 35% lower than in 2DEG in 2050. The implementation of ambitious energy efficiency policies, standards and regulation combined with the transition to a circular economy may reduce the need for high carbon pricing to achieve the same mitigation target. In turn, this is expected to positively influence the social and political acceptance of climate policies, as carbon and energy taxation has regressive distributional impacts, posing a high cost burden to low-income households [41], and often raises social concerns as manifested in the Yellow Vests movement [42]. The exhaustion of available emission reduction options and the uptake of more expensive technologies to meet the 600 Gt carbon budget in the 1.5DEG scenario requires even higher carbon prices, which increase to about 450$/tn CO2 in 2050, indicating the difficulties to reach close to net zero emission levels.

Table 3: Global carbon price in alternative scenarios by 2050 ($ 2015/tn CO2)

	2030	2040	2050
REF [5]	10	12	16
2DEG	81	153	291
2DEG_CI	68	128	188
1.5DEG	175	267	457

The implementation of high carbon pricing results in large emissions reductions, as mid-century global CO_2 levels in 2DEG scenarios are 80%-85% lower than in REF. The emission cap imposed triggers an increase in carbon price which applies to all regions and sectors to

[5] This refers to the average carbon price across regions (as there is no global carbon price in REF)

ensure that the global climate target is achieved with the lowest possible cost through the equalization of marginal abatement costs globally. The 2DEG and 2DEG_CI scenarios achieve the same carbon budget by definition, but emissions are reduced faster in 2DEG_CI over 2025-2035 triggered by the increased energy and resource efficiency and circularity. This is reversed after 2040 as 2DEG requires higher carbon prices and thus incentivizes larger changes in energy supply in the longer term. This scenario shows that utilizing energy efficiency and circular economy measures could prove an effective way to bridge the effort gap between 2°C and 1.5°C without requiring very high CO_2 prices. Moreover, the 1.5DEG scenario imposes a more ambitious constraint on global carbon budget resulting in emissions reduction of more than 92% (hence close to net zero) in 2050 but requiring very high carbon prices – almost twice as high as in 2DEG.

Figure 4 shows the global cumulative emissions over 2016-2050 for major emitting sectors by scenario. In REF, most emissions come from the energy supply sector which accounts for about 44% of total emissions, mostly due to coal and gas-fired power plants. Energy demand accounts for about 50% of global emissions, with transport accounting for 48% of those, as a result of rapid motorisation in developing regions due to rising incomes and the continuous dominance of oil products. The 2DEG scenarios result in large emissions reductions in all demand and supply sectors. The cost-optimal 2DEG scenario leads to a rapid decarbonisation of electricity generation, and thus the share of energy supply in global emissions declines, while the share of energy demand increases from 50% in REF to 59% in 2DEG. High energy efficiency improvements and increased circularity in 2DEG_CI lead to drastic emission reductions in the demand side, which are projected to decline by an additional 15% below 2DEG levels; this is accompanied by increased supply-side emissions in the form of reduced Carbon Capture and Storage (CCS) due to lower carbon pricing. The industrial sector is heavily impacted, as the transition to circular economy combined with the uptake of low-carbon energy forms would drive a reduction in sectoral global cumulative emissions of 37% below REF levels and 17% below 2DEG levels, indicating high emission abatement potential relative to previous studies [45, 51] which did not explicitly account for circular economy strategies. The high carbon pricing imposed in the 1.5DEG scenario would lead to further emission reductions in all energy demand and supply sectors and increased uptake of CCS to compensate for emissions in hard-to-abate sectors.

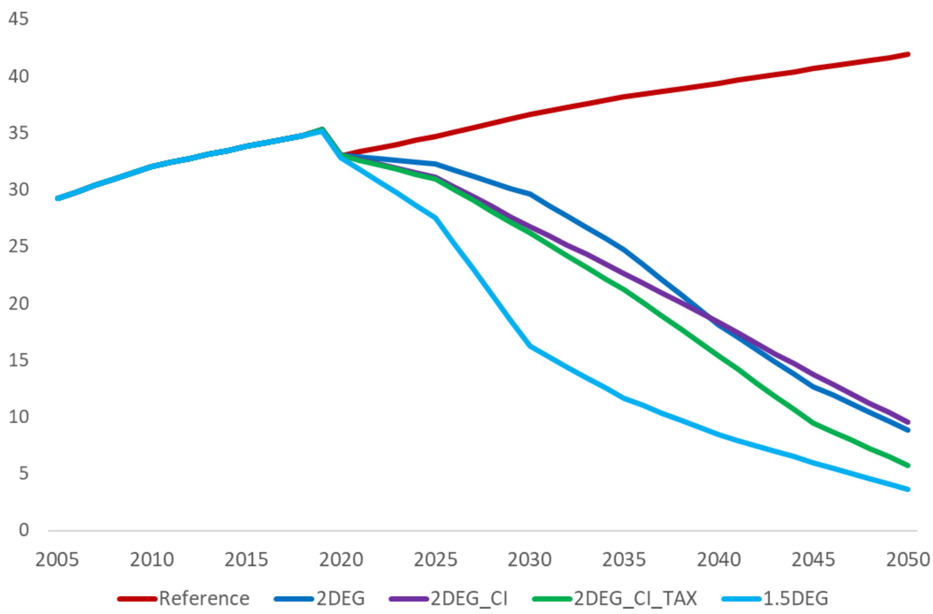


Figure 3: Evolution of global CO2 emissions (in Gt CO2)

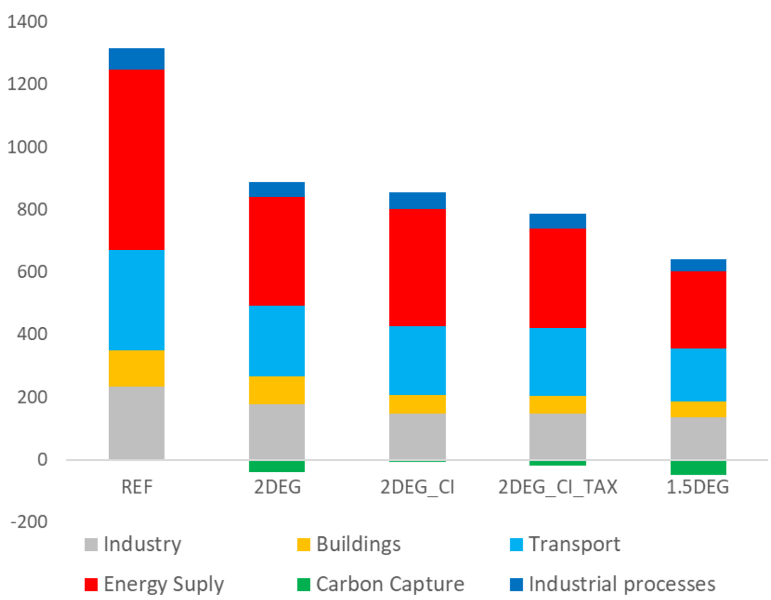


Figure 4: Global cumulative CO2 emissions by sector over 2016-2050 (Gt CO2)

3.2 Impacts on energy demand

The section analyzes projections of final energy consumption (FEC) across policy scenarios in industry, buildings (including the residential and commercial sectors) and transport. The REF scenario shows a constant increase in energy consumption driven by robust growth of economic activity, rising standards of living especially in developing countries, and the lack of ambitious climate policies. Global FEC is projected to grow by 1.2% annually in the 2020-2050 period, with developing economies representing most of this growth and developed economies facing saturation in their energy requirements. The imposition of strong carbon pricing would lead to reduced FEC globally, induced by the uptake of more efficient energy forms and technologies (e.g. electricity instead of oil products in passenger cars). The implementation of ambitious efficiency measures, standards and policies and the transition to circular economy would lead to further energy savings with energy consumption in 2DEG_CI declining by 14% below 2DEG and 33% below REF levels in 2050. The final energy mix is also heavily impacted by strong climate policies with the consumption of coal and oil rapidly reducing in all demand sectors, while oil in 2050 is mostly used in specific transport segments (e.g. freight transport, aviation, navigation) and in petrochemicals production. The major trend in ambitious decarbonisation scenarios is the increasing electrification of energy end uses with electricity share in global FEC increasing from 20% in 2020 to about 43%-46% in 2DEG scenarios and more than 50% in 1.5DEG scenario in 2050.

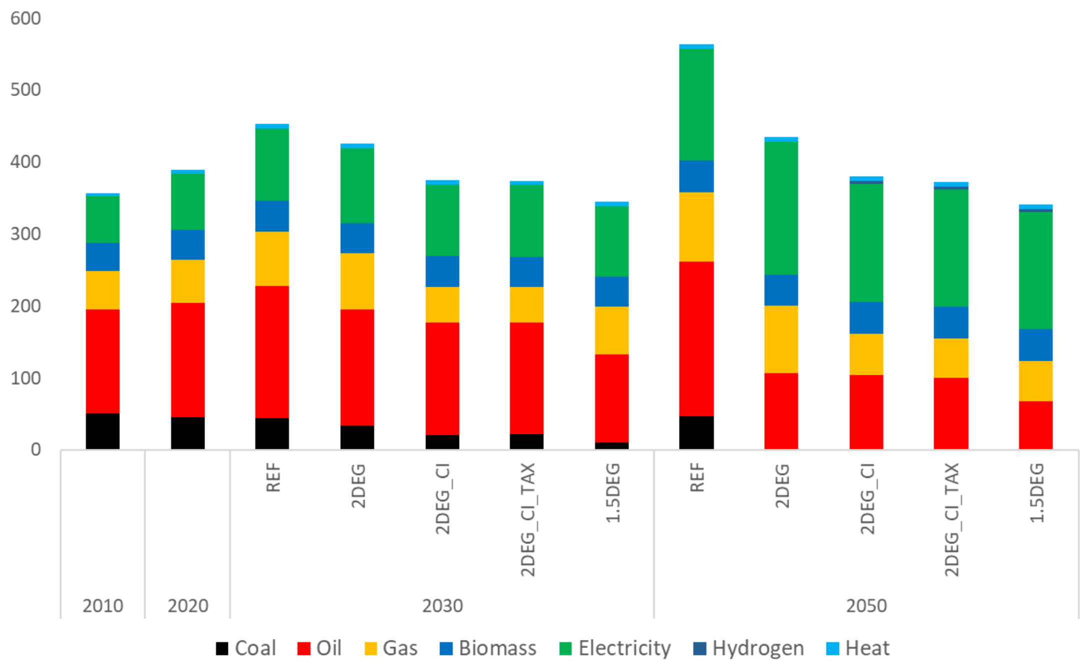


Figure 5: Evolution of global final energy consumption by fuel (in Mtoe)

Looking specifically in the industry sector, the REF projections show a steady increase in global energy consumption driven by increasing industrial manufacturing activity. In the absence of additional climate policies in REF, there are limited changes in the energy mix used with coal, gas, oil, and electricity being the main industrial fuels with a small contribution from biomass and heat. The imposition of ambitious climate mitigation policies causes a decrease in energy consumption, as more efficient technologies and energy forms increasingly replace the use of less efficient products. Ambitious energy efficiency policies and increased circularity of materials lead to further reductions of energy requirements in industry, with global FEC declining by 10% and 30% below 2DEG and REF levels respectively in 2050, which is relatively higher compared to previous studies [45, 51] which do not include circular economy considerations. This happens as the 2DEG_CI scenario assumes reduced industrial output in certain industrial subsectors and increased secondary production of materials, which is less energy intensive than primary production (Table 1). The model-based analysis shows that fuel switching and accelerated energy and resource efficiency (e.g. increased circularity of cement, steel, paper, plastics, improved waste management etc) are the primary options towards industrial decarbonisation. In this context, all mitigation scenarios show that electrification of industries increases by 2050 but reaches a saturation level of around 50%-55% as some industrial activities and processes cannot be fully electrified, especially in energy-intensive high-temperature manufacturing [43]. To further reduce industrial emissions from hard-to-electrify processes, the use of hydrogen[6] emerges as a key transformation option for specific sectors (Figure 6), including steel making [8]. In addition, PROMETHEUS shows that CCS technologies in biomass and fossil-fired industrial processes should be applied in low-emission scenarios.

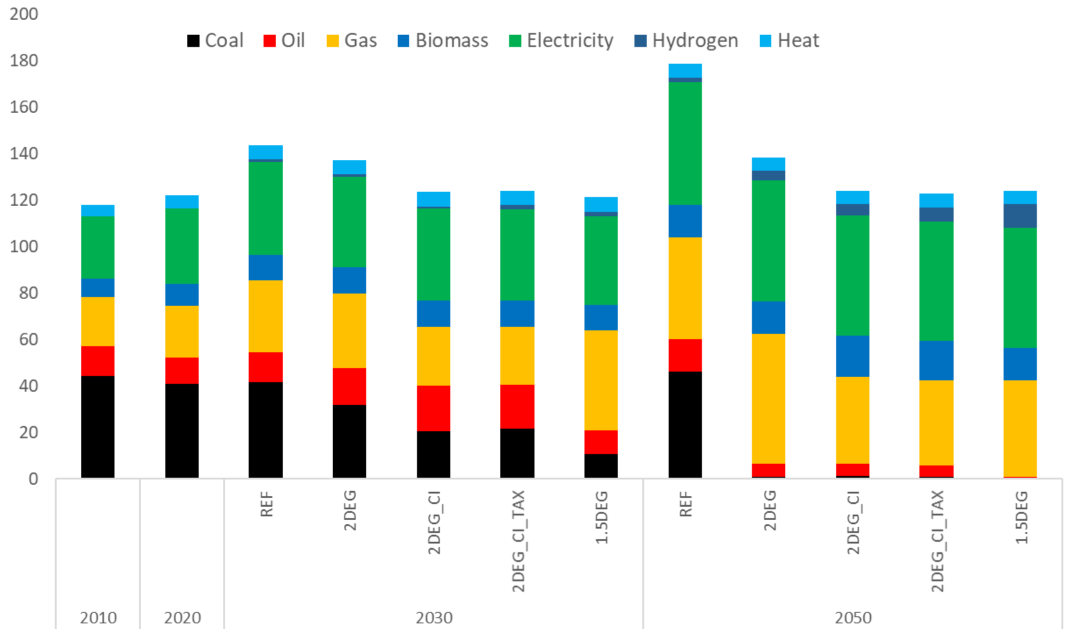


Figure 6: Evolution of global final energy consumption by fuel in industries (in Mtoe)

[6] In the decarbonisation scenarios, hydrogen is mostly produced through electrolysis of renewable-based electricity (green hydrogen) with smaller amounts produced by Steam Methane Reforming with CCS, especially in regions with cheap gas resources like MENA and Russia.

The buildings sector will also be transformed due to ambitious climate and energy efficiency policies (Figure 7). Energy consumption in REF is projected to increase with an annual rate of 1.1% per annum over 2020-2050, induced by growing global population and economic activity, increasing urbanization, and rising living standards that trigger increased purchase and use of heating and cooking equipment and electric appliances, mostly in developing economies. The imposition of ambitious energy efficiency measures and emission reduction constraints leads to a reduction of FEC in buildings, supported by the uptake of more efficient technologies, fuels and equipment, energy audits, LEED[7] certifications, energy efficiency building standards, the emergence of electricity for heating, the increased rate and depth of renovation and a more rational use of energy by consumers. Strong efficiency standards and policies cause a large reduction of energy requirements, with global FEC of buildings declining by 30% from REF levels (and 20% from 2DEG) in 2050, compatible with [44] showing that under strong efficiency measures, energy consumption in buildings can decline by more than 40% compared to a current trends scenario. The use of oil in buildings is phased out by 2050 in mitigation scenarios, with only a small amount remaining in low-income African countries where the full switch to low-emission alternatives faces high challenges. The low-emission scenarios drive drastic changes in the global energy mix in buildings with a large-scale reduction of fossil fuels and traditional biomass, combined with increasing electrification of end-uses -- with the share of electricity increasing from 35% in 2020 to 62%-68% in 2050 in low-carbon scenarios in line with [45]-- and uptake of green hydrogen and modern biofuels.

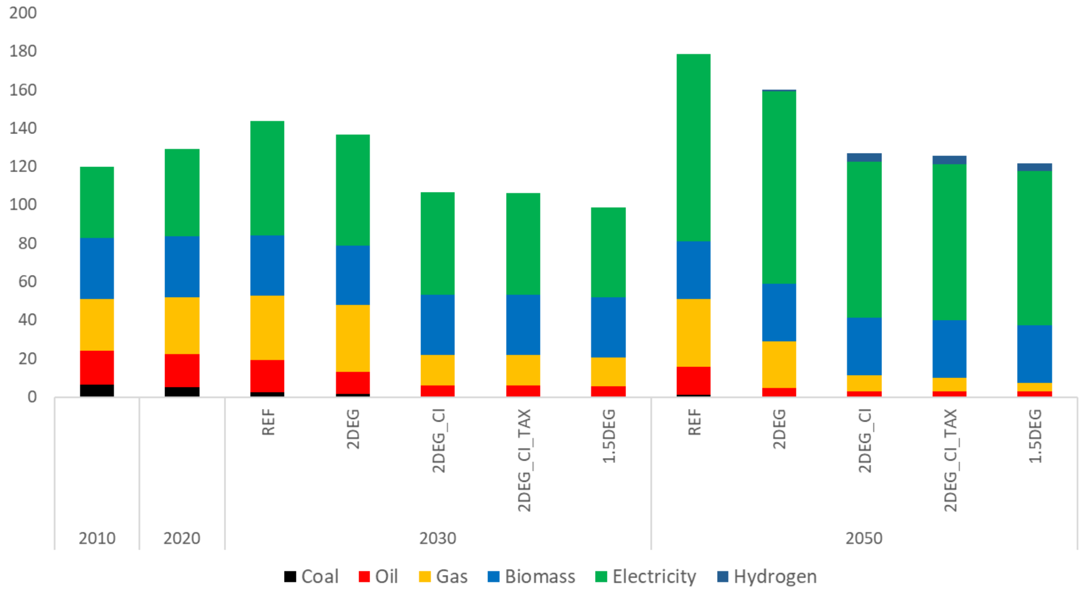


Figure 7: Evolution of global final energy consumption by fuel in buildings (in Mtoe)

[7] Leadership in Energy and Environmental Design

Similar to the other demand sectors, global energy consumption for transport increases in REF by 1.4% p.a. over 2020-2050, driven by increasing population, activity and motorization in developing economies combined with lack of policies to facilitate the switch to low-emission fuels and less energy-intensive modes. In REF oil products remain the dominant transport fuel, as ICEs are widely used in transport modes, while biofuels and electricity gain a small share in transport energy mix by 2050. In mitigation scenarios, total energy consumption declines due to the switch to more efficient vehicles and energy forms (e.g., electricity instead of oil products) and the emergence of new business models (e.g. Mobility as a Service, shared cars) and less energy-intensive mobility practices (e.g. walking, using trains instead of aviation when available). High carbon pricing and energy efficiency measures radically change the transport fuel mix, as consumption in 2050 (that is close to current levels) is met by a combination of oil products, electricity, and biofuels at almost equal shares, while hydrogen also emerges mostly in freight transport. Energy consumption is further reduced in 1.5DEG scenario, induced by the phase-out of conventional ICEs and hybrid fleets that are rapidly replaced by EVs in road passenger transport – supported by significant cost declines- and hydrogen fuel cells in freight transport [26]. Biofuels have a substantial contribution in the transport energy mix by 2050, to decarbonize transport segments that are difficult or expensive to be electrified, including aviation and navigation. However, their increased uptake does not raise sustainability issues and does not put pressure on land resources and food prices, as total biomass demand remains below sustainability thresholds as specified in [36] and [37].

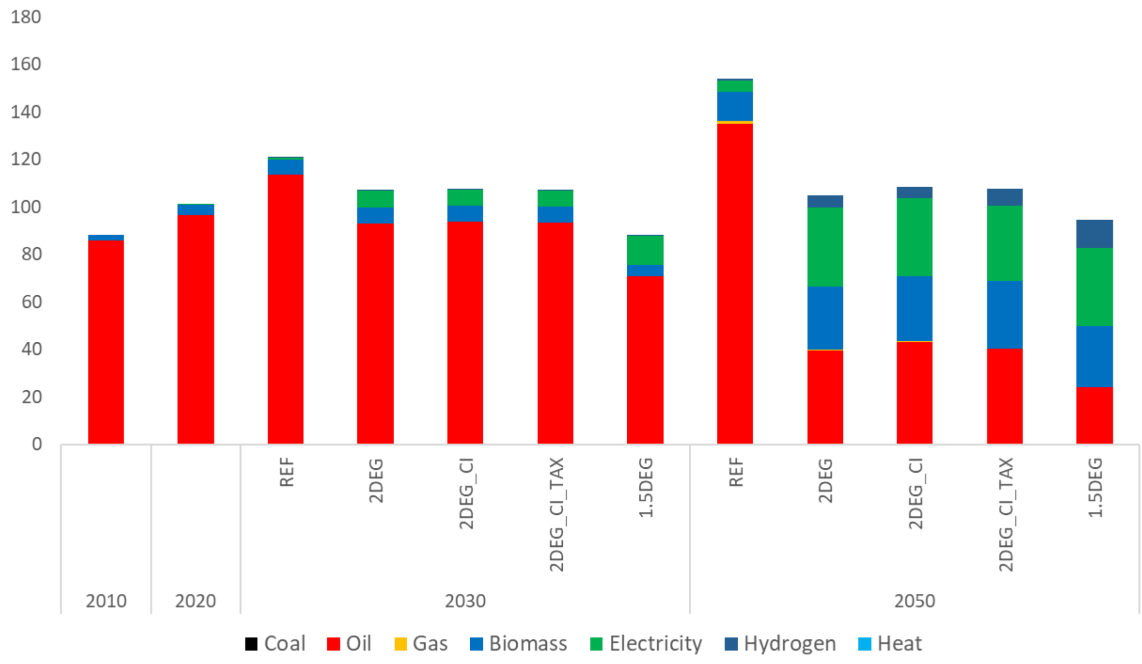


Figure 8: Evolution of global final energy consumption by fuel in transport (in Mtoe)

3.3 Impacts on energy supply and immature technologies

The imposition of strong emission reduction and energy efficiency policies would cause drastic changes in electricity production mix (Figure 9). In all scenarios, global electricity production is projected to increase by 2.1%-2.5% p.a. over 2020-2050 because of increasing economic activity and population, rising standards of living and increasing electrification of energy end uses (section 3.2). The development of electricity requirements and the projected technology mix depend on various model assumptions for the evolution of energy consumption in each region, technology cost reductions, carbon price levels, technology potentials and changes in fuel mix and consumption patterns across demand sectors.

The REF scenario shows that global electricity requirements increase by 110% over 2015-2050. The changes in technology mix are driven by the increased uptake of renewable energy (especially PV and wind) triggered by their cost reductions. This leads to a growing share of renewable energy in global power mix, increasing from 23% in 2015 to 32% in 2030 and to 40% in 2050. Due to the lack of strong carbon pricing, coal-based generation maintains a share of 27% in 2050 (albeit reduced from 39.5% in 2015). Oil-fired production is phased-out before 2050, while the shares of nuclear and gas-fired generation remain close to their 2020 levels.

The implementation of strong climate policies drastically affects the levels and structure of the global power mix. Electrification of energy and transport services is a key mitigation option in all low-carbon scenarios, resulting in 13%-19% higher global power generation in 2DEG and 1.5DEG scenarios with respect to REF in 2050, as global electricity use expands in transport, industries, and buildings to substitute for fossil fuels. Strong efficiency measures and increased circularity reduces electricity use in 2DEG_CI scenario relative to 2DEG, but power requirements are still higher than REF due to increasing electrification. High carbon pricing penalises the use of fossil fuels, with the share of unabated coal, oil, and gas in global power mix declining from 66% in 2015 to 39%-43% in 2030 and further to 2%-6% in 2050 across 2DEG scenarios. The reduction is even faster in 1.5DEG with fossil fuel share dropping to less than 10% in 2030 followed by a complete phase-out by 2040. In this context, renewable-electricity production scales up rapidly to compensate for declining fossil fuels with the share of renewable energy increasing from 23% in 2015 to about 47% in 2030 (67% in 1.5DEG) and further to 70%-77% in 2050, mostly driven by expansion of PV and wind (Figure 9). Nuclear power, hydrogen, and CCS (with fossil fuels and biomass) cover the remaining 23%-29% of electricity supply, which is fully decarbonised by 2050. The uptake of CCS technologies depends on the specific scenario assumptions and is generally lower in scenarios assuming strong efficiency measures (2DEG_CI) relative to 2DEG and 1.5DEG driven by carbon pricing. BECCS technologies are deployed in 2DEG and 1.5DEG, but this option is not required when ambitious efficiency measures and circularity are adopted in 2DEG_CI, as emissions from the demand sector decline below 2DEG without the need to invest in BECCS.

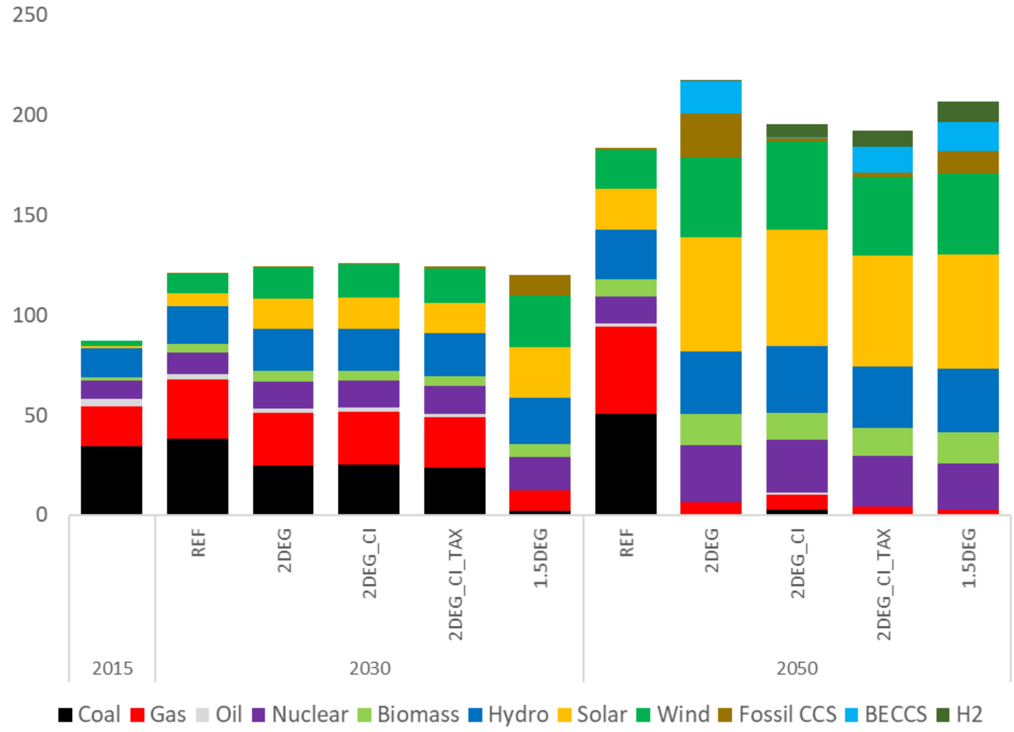


Figure 9: Global power generation by main technology in policy scenarios (in EJ)

In addition to reducing emissions from fossil fuel combustion, ambitious climate targets may require the uptake of technologies to remove CO2 from the atmosphere [33, 35]. The main mechanism for CO_2 removal considered in this study is the deployment of CCS in electricity production, industry, and fuel production. The uptake of CCS is triggered by high carbon pricing in low-emission scenarios, in quantities depending on scenario-specific assumptions. The highest CO_2 capture levels of around 5.2 $GtCO_2$/yr are reached in 2050 in 2DEG and 1.5DEG scenarios. However, CCS structure differs across scenarios with 1.5DEG requiring more BECCS to compensate remaining emissions from fossil fuel use and meet the stringent carbon budget. In contrast, in 2DEG scenarios most CCS is used to retrofit coal and gas-fired power plants. The strong efficiency and circularity push causes a large reduction in the need for deployment of CCS technologies, as shown in Figure 10, where CCS uptake is 84% lower in 2DEG_CI compared to 2DEG, as carbon prices are considerably lower. Overall, the model-based analysis shows that reliance on expensive, immature, and risky CCS technologies may drastically decline if the speed of energy transition accelerates, through increased uptake of renewable energy, low-emission cars, electrification, and energy efficiency.

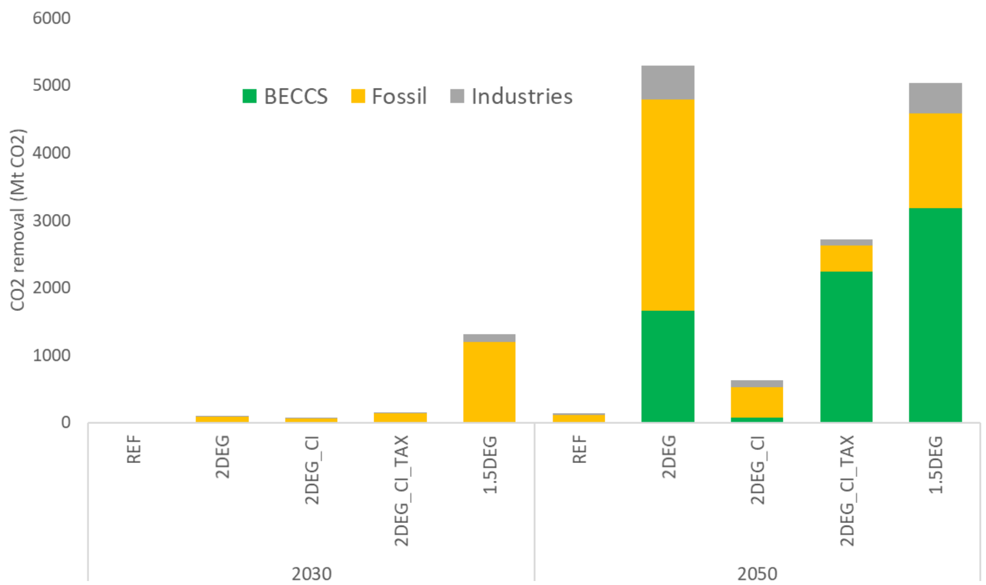


Figure 10: Deployment of Carbon Capture and Storage technologies across scenarios

3.4 Impacts on investment requirements and energy costs

Ambitious climate mitigation targets drive energy system costs up by inducing additional investment in expensive low-carbon technologies, energy efficiency and zero-emission cars. As shown in [19] and [33], energy system costs generally increase with the level of mitigation effort, driven by increased capital expenditure for low-carbon investment and lower operation costs to purchase energy products driven by lower energy requirements. The cost-optimal 2DEG scenario results in limited mitigation costs of about 0.5% of global GDP cumulatively over 2025-2050, with the decline in fuel costs partially counterbalancing the increased capital expenditure. The imposition of energy efficiency policies and circularity on top of the climate target would result in higher uptake of efficient – but more expensive -- technologies, processes and equipment in the demand sectors, pushing system costs upwards. On the other hand, they lead to reduced carbon price and fossil fuel consumption thus reducing the operating costs. On balance, the adoption of high-efficiency technologies on top of a climate target might increase the overall mitigation costs by 0.2% of GDP relative to the 2DEG scenario, which is cost-optimal by definition, but is based on a higher carbon price.

Because of the reduced energy demand, the 2DEG_CI scenario requires the lowest additional supply-side investment among the mitigation scenarios. However, this is more than compensated by increased investment on the demand side, directed to renovation of buildings, uptake of zero-emission vehicles, purchase of efficient appliances and emergence of circular economy in industries. The modelling also shows the potential of the circular economy and lifestyle changes to reduce emissions without posing large additional investment needs. However, high uncertainty surrounds the investment required to implement extreme energy savings and circular economy structures, while energy models cannot capture fully the related investment needs and costs of the circular economy or lifestyle changes [8]. The analysis of socio-economic impacts of decarbonisation requires a detailed representation of energy intensive sectors and a robust estimation of how trade and production patterns will be affected by decarbonisation, which for example drives a switch from internal combustion engines to electric drive trains with ambiguous employment impacts.

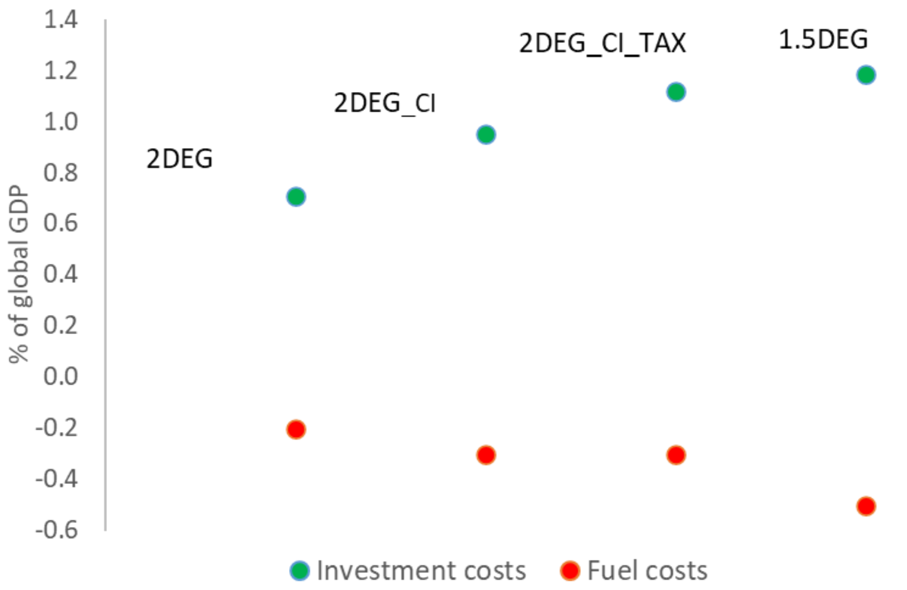


Figure 11: Scenario impacts on global cumulative energy investment and fuel costs over 2025-2050 (in % of global GDP)

4 Discussion and Conclusions

The systemic transformation towards deep decarbonisation is a complex process that requires coordinated action by all nations, businesses, citizens, and major emitting sectors. Industrial sectors currently account for more than 25% of global emissions, while most manufacturing processes have a low energy and material efficiency and experience low circularity rates. In recent years, many studies have shown that circular economy can play a large role for the deep decarbonisation required to meet the ambitious Paris goals. However, there is an increasing gap between theory and practice with respect to circular economy strategies. The scenario analysis presented in the current study shows that accelerated energy and resource efficiency improvements coupled with circular economy measures can bring multiple benefits: on the one hand they can stimulate more efficient use of energy and material resources, while reducing the need for high carbon pricing, which may raise social acceptability issues [41]; and they may also reduce the reliance on supply-side investment, especially in expensive and currently immature technologies, such as Carbon Capture and Storage.

The scenarios have been developed with the PROMETHEUS global energy system model, which is enhanced with a representation of circular economy measures, especially in energy-intensive industrial sectors. The scenarios introducing a circular economy structure together with accelerated energy efficiency result in a considerable reduction of energy consumption, driven by changes in sectors manufacturing metals, chemicals, plastics, and non-metallic minerals. Energy efficiency or other ways of limiting energy consumption (circular economy and lifestyle changes) as well as switching to domestically produced low-carbon energy vectors (electricity, hydrogen) can contribute to reducing energy imports, especially in major fossil fuel importers like the EU, China, Japan. Therefore, promoting a circular economy through a smarter use of materials such as plastics and steel can reduce emissions while also contributing to cleaner land, water, and oceans and enhancing security of energy supply, eliminating the exposure of energy importers to geopolitical tensions and import price increases, as shown by the recent unprecedented increases in gas import prices in the EU

The comprehensive quantification of alternative scenarios with the PROMETHEUS model confirms that circular economy may lead to large emissions reduction in the industry sector resulting in further changes in demand and supply and related investment in all energy system sectors. The circular economy scenario assumes high efficiency improvements in energy end uses combined with an average reduction of physical output for energy-intensive industries of around 10% in 2050 through increased use of scrap steel, higher recycling and reuse rates for plastics, paper and cement, reduced losses of materials, and overall improvements in resource use and material flows. These developments lead to a large reduction of global energy consumption which implies lower needs for investment in expensive and risky supply-side technologies like CCS and lower level of carbon price. Circular economy is a big opportunity to create new markets, technologies and synergies between the energy and industrial sectors by reducing primary raw material needs and developing more re-usable and recyclable products, while promoting economic transformation and creating new high-quality jobs. Therefore, circular economy considerations should be efficiently embedded into climate and sustainable development policies, as CE strategies contribute to meeting global climate goals, while also increasing energy efficiency, enhancing energy security and supporting economic restructuring towards a modern, more sustainable, resilient, low-emission paradigm.

However, full circularity would require significant behavioural changes, large capital investments, changes in the regulatory framework and business model transformation. The transition towards a more energy and resource efficient economy comes with high challenges, including large investment requirements to develop the new energy-efficient technologies and processes, acceleration of technology innovation and the emergence of new business models to exploit the new opportunities from the transition. All these should be combined with changes in consumer behaviour towards less carbon-intensive options with wider acceptance of environmentally friendly lifestyles in everyday decisions. Ambitious and coherent policies should be developed to consistently bring together emissions reductions, energy system transformation and environmental policy (waste, pollution) with industrial policy (e.g., recycling, resource efficiency and new materials) and with research and innovation policy. In this way, policy makers can leverage the synergies between deep decarbonisation targets and other policy priorities (e.g. energy security, economic transformation, resilience), by setting broader goals covering all these dimensions, while exploiting their synergies and minimising potential trade-offs and negative social impacts.

The literature review and the quantitative model-based analysis have shown that low-carbon technology development and deployment combined with circular measures can drastically reduce emissions from the industrial sector towards contributing to the Paris climate goals. The combination of best available techniques in energy efficiency and fuel switching with other options including innovative low carbon production technologies, circular economy, material efficiency, low carbon energy carriers (e.g., green electricity and hydrogen[8]) and / or CCS. It also requires the full decarbonisation of the electricity sector and the substitution of natural gas by zero carbon gases (e.g., green hydrogen) to the largest degree possible. The industrial transition towards a low-emission, circular paradigm requires a profound alteration of current business models and supply chains, and the development of a systemic approach covering: the sustainable supply of raw materials, optimised material flows in supply chains supporting circular economy and industrial symbiosis, innovative decarbonisation technologies and materials, enhanced energy and resource efficiency and demand-side measures to stimulate the creation and the development of markets for low and zero-carbon products and solutions.

Transforming the linear economy, which has remained the dominant model since the Industrial Revolution, into a circular one is by no means an easy task. Such a radical change entails a major transformation of the current production and consumption patterns, which in turn will have significant impacts on the economy, the environment and society. Understanding these impacts is crucial for climate and industrial policy makers and researchers. This requires developing an in-depth knowledge of the concept of the circular economy, its processes and their expected effects on sectors and value chains as well as the overall impacts on the economy and society. It also requires a dedicated effort to bridge the gap between theory and practice, which appears to be particularly large in circular economy strategies. The current study provides a first attempt to map and quantify the potential contribution of circular economy in the transition to a low-carbon economy. Future research should capture the complex

[8] Green electricity refers to electricity produced from zero-emission technologies like renewable energy, while green hydrogen is produced through electrolysis of renewable-based electricity.

interactions between circular economy and the process of decarbonisation – which are not captured in current modelling frameworks. Moreover, a detailed bottom-up quantification of the costs, potentials and emission savings of various circular economy strategies and the associated challenges is critical to identify opportunities for CE strategies to have the largest impact on mitigation. The financial sustainability of projects and infrastructure related to CE should also be explicitly analysed, while research should identify the sources of green finance that can provide the required resources for the transformation towards a circular economy paradigm. Particular attention should be paid to how the long lifetimes of products, technologies, buildings, and infrastructure influence the transition dynamics towards a circular economy, and how the recycling rates of the raw materials needed for renewable energy and high-tech applications can be increased in order to meet the fast-growing materials demand and increase overall circularity.

References

[1] IRP, Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel. 2019, United Nations Environment Programme.: Nairobi, Kenya.

[2] Van der Voet, E., et al., Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. Journal of Industrial Ecology, 2018. 23(1): p. 141-155.

[3] Hertwich, E.G., Increased carbon footprint of materials production driven by rise in investments. Nature Geoscience, 2021. 14(3): p. 151-155.

[4] Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., M. Schaeffer, V. Krey, K. Riahi (2015). Energy system transformations for limiting end-of-century warming to below 1.5C. Nature Clim. Change, 5, 519–527

[5] Kirchherr, J., D. Reike, and M. Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 2017. 127: p. 221-232.

[6] Bocken, N., K. Miller, and S. Evans, *Assessing the environmental impact of new Circular business models*. 2016

[7] European Commission, Circular Economy Action Plan, Available online at: https://op.europa.eu/en/publication-detail/-/publication/45cc30f6-cd57-11ea-adf7-01a75ed71a1/language-en/format-PDF/source-170854112

[8] European Commission, 2018, In-Depth Analysis in Support of the Commission Communication COM (2018) 773, A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy

[9] Material Economics AB (2018), The Circular Economy, Available at: http://materialeconomics.com/latest-updates/the-circular-economy

[10] Fragkos P., Fragkiadakis K. et al, 2018, Coupling national and global models to explore policy impacts of NDCs, Energy Policy, Volume 118, July 2018, Pages 462-473

[11] Pauliuk, S., et al., Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. Nature Communications, 2021. 12(1): p. 5097.

[12] Edelenbosch, O.Y., et al., Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. Energy, 2017. 122: p. 701-710.

[13] M. Geissdoerfer, M. P.P.Pieroni, D. Pigosso, K. Soufani, Circular Business Models: A Review, Journal of Cleaner Production, Volume 277, 20 December 2020, 123741

[14] European Commission, Study on the review of the list of critical raw materials: Non-critical raw materials factsheets, Available online at: https://op.europa.eu/en/publication-detail/-/publication/6f1e28a7-98fb-11e7-b92d-01aa75ed71a1/language-en

[15] Mayer, A.S., et al., Measuring Progress towards a Circular Economy: A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. Journal of Industrial Ecology, 2019. 23(1): p. 62-76

[16] UNEP (2017), Resource Efficiency: Potential and Economic Implications, http://www.resourcepanel.org/reports/resource-efficiency

[17] European Commission, 2018, A European strategy for plastics in a circular economy, https://www.europarc.org/wp-content/uploads/2018/01/Eu-plastics-strategy-brochure.pdf

[18] Trinomics (2018), Cooperation fostering industrial symbiosis: market potential, good practice and policy actions, https://publications.europa.eu/en/publication-detail/-/publication/174996c9-3947-11e8-b5fe01aa75ed71a1/language-en

[19] Fragkos, P. Global Energy System Transformations to 1.5 °C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets. Energy Technol. 2020, 8, 2000395.

[20] Fragkos, P.; Kouvaritakis, N. Model-based analysis of Intended Nationally Determined Contributions and 2 °C pathways for major economies. *Energy* **2018**, *160*, 965–978

[21] Capros, P.; DeVita, A.; Tasios, N.; Siskos, P.; Kannavou, M.; Petropoulos, A.; Evangelopoulou, S.; Zampara, M.; Papadopoulos, D.; Paroussos, L.; et al. *EU Reference Scenario 2016—Energy, Transport and GHG Emissions Trends to 2050*; European Commission Directorate General for Energy, Directorate General for Climate Action and Directorate General for Mobility and Transport: Brussels, Belgium, 2016.

[22] Fragkos, P.; Kouvaritakis, N.; Capros, P. Incorporating uncertainty into world energy modelling: The Prometheus model. *Environ. Model. Assess.* **2015**, *20*, 549–569

[24] Grubler, A., C. Wilson, N. Bento, et al, (2018) A low energy demand scenario for meeting the 1.5C target and sustainable development goals without negative emission technologies, Nature Energy, 3, 515-527

[25] Fotiou, T.; de Vita, A.; Capros, P. Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonisation in the EU. *Energies* **2019**, *12*, 2745. https://doi.org/10.3390/en12142745

[26] P. Capros, G. Zazias, S. Evangelopoulou, M. Kannavou, T. Fotiou, P. Siskos, A. De Vita, K. Sakellaris, 2019, Energy-system modelling of the EU strategy towards climate-neutrality, Energy Policy, Volume 134, November 2019, 110960

[27] Towards the Circular Economy vol.1, 2013, Ellen McArthur Foundation

[28] IEA (2020) Iron and Steel. Paris. Available at: https://www.iea.org/reports/iron-and-steel.

[29] ISRI (2019) 2019 Recycling Industry Year Book

[30] WSP, Parsons Brinckerhoff, DNV GL (2015), Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Cement

[31] Accenture (2017), Taking the EU chemicals industry into the circular economy, https://www.accenture.com/us-en/_acnmedia/PDF-45/Accenture-CEFIC-Report-Exec-Summary.pdf

[32] JRC (2018), Prospective scenarios for the pulp and paper industry, http://publications .jrc.ec.europa.eu/repository/bitstream/JRC111652/kjna29280enn_jrc111652_online_revised_by_ipo.pdf

[33] van Soest, H.L., Aleluia Reis, L., Baptista, L.B. *et al.* Global roll-out of comprehensive policy measures may aid in bridging emissions gap. *Nat Commun* **12,** 6419 (2021). https://doi.org/10.1038/s41467-021-26595-z

[34] Fragkos, P. Assessing the Role of Carbon Capture and Storage in Mitigation Pathways of Developing Economies. Energies 2021, 14, 1879. https://doi.org/10.3390/en14071879

[35] McCollum, D.L., Zhou, W., Bertram, C. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat Energy* **3,** 589–599 (2018). https://doi.org/10.1038/s41560-018-0179-z

[36] Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, 2018: Mitigation pathways compatible with 1.5°C in the context of sustainable development In Global Warming of 1.5 °C: *an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels,* Geneva, Switzerland: IPCC, In press

[37] Fricko, O., Havlik, P., J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Stubberger, H. Valin, M. Amann, M. Obersteiner, K. Riahi (2017). The marker quantification of the shared socioeconomic pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251-267.

[38] OECD. *OECD Economic Outlook*; OECD Publishing: Paris, France, 2020; Volume 2020

[39] The World Bank. Global Economic Prospects (Issue June 2021).

[40] Rochedo, P.R.R.; Fragkos, P.; Garaffa, R.; Couto, L.C.; Baptista, L.B.; Cunha, B.S.L.; Schaeffer, R.; Szklo, A. Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages. *Energies* **2021**, *14*, 5567. https://doi.org/10.3390/en1417556

[41] Fragkos P, K. Fragkiadakis, B. Sovacool, L. Paroussos, Z. Vrontisi, I. Charalampidis, 2021, Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union, Energy, Volume 237, 15 December 2021, 121591

[42] Vona F., 2019, Job losses and political acceptability of climate policies: why the 'job-killing' argument is so persistent and how to overturn it, Climate Policy, 19:4, 524-532, DOI: 10.1080/14693062.2018.1532871

[43] Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, P., Ajith Kumar, K., Krüger, C., Luderer, G. (2020). The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). Environ. Res. Lett. 15 124004. https://doi.org/10.1088/1748-9326/abbd02

[44] Levesque A, R. Pietzker, G. Luderer, 2019, Halving energy demand from buildings: The impact of low consumption practices, Technological Forecasting and Social Change, Volume 146, September 2019, Pages 253-266

[45] Rodrigues R., R. Pietzker, P. Fragkos, J. Price, P. Siskos, T. Fotiou, G. Luderer, P. Capros, 2021, Narrative-driven alternative roads to achieve mid-century CO2 net neutrality in Europe, Energy, Volume 239, Part A, 15 January 2022, 121908

[46] Jarosław Brodny, Magdalena Tutak, Analysis of the efficiency and structure of energy consumption in the industrial sector in the European Union countries between 1995 and 2019, Science of The Total Environment, Volume 808, 2022, 152052, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.152052.

[47] P. M. Falcone, M. Hiete, A. Sapio, Hydrogen economy and sustainable development goals: Review and policy insights, Current Opinion in Green and Sustainable Chemistry, Volume 31, 2021, 100506, ISSN 2452-2236, https://doi.org/10.1016/j.cogsc.2021.100506.

[48] Hari Bhakta Sharma, K.R. Vanapalli, B. Samal, V.R. Sankar Cheela, B. K. Dubey, J. Bhattacharya, Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery, Science of The Total Environment, Volume 800, 2021, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.149605.

[49] Rocca, R.; Rosa, P.; Sassanelli, C.; Fumagalli, L.; Terzi, S. Integrating Virtual Reality and Digital Twin in Circular Economy Practices: A Laboratory Application Case. *Sustainability* **2020**, *12*, 2286.

[50] D'Adamo, I.; Falcone, P.M.; Martin, M.; Rosa, P. A Sustainable Revolution: Let's Go Sustainable to Get Our Globe Cleaner. *Sustainability* **2020**, *12*, 4387. https://doi.org/10.3390/su12114387

[51] Francesco Dalla Longa, P. Fragkos, L. P. Nogueira, B. van der Zwaan, System-level effects of increased energy efficiency in global low-carbon scenarios: A model comparison, Computers & Industrial Engineering, Volume 167, 2022, 108029

[52] Bordage, F. (2019). The Environmental Footprint of the Digital World. GreenIT.fr, p. 39. https://www. greenit.fr/wp-content/uploads/2019/11/GREENIT_EENM_etude_EN_accessible.pdf.