EUCALC

Explore sustainable European futures

Technological transition and innovation pathways

D1.5

February 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730459.

Project Acronym and Name	EU Calculator: trade-offs and pathways towards sustainable and low-carbon European Societies - EUCalc
Grant Agreement Number	730459
Document Type	Report
Work Package	Climate, Lifestyles & Technological Transition
Document Title	D1.5
Main authors	Hannes Warmuth, Bianca Pfefferer, Monika Auer
Partner in charge	ÖGUT
Contributing partners	
Release date	February 2020
Distribution	*All involved authors and co-authors agreed on the publication*

Short Description

This report describes how technological advancement and disruptive change is covered in various sector within the European Calculator (EUCalc). We introduce a framework to systematically assess future technological development of existing as well as new, emerging technologies by establishing a technology matrix. Key performance indicators include specific energy consumption and specific emissions, as well as costs of corresponding technologies. Finally, this report provides a number of technology-dependent transition pathways and scenarios for the European Union and its integration into the EUCalc model.

Quality check

Name of reviewer	Date
Patricia Osseweijer (TU Delft)	**October 29th, 2019**
Boris Thurm (EPFL)	**October 25th, 2019**

Statement of originality:

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

Table of Contents

List of Tables

List of Figures

List of abbreviations

PPP – Purchasing Power Parities

TRL – Technology Readiness Level

BF-BOF – Blast furnace - basic oxygen furnace

CAPEX – Capital expenditure

OPEX – Operational expenditure

CC – Carbon capture

CCS – Carbon capture and storage

CCU – Carbon capture and usage

CHP - Combined heat and power

FCV – Fuel cell vehicles

EAF – Electric arc furnace

EV – Electric vehicles

EE – Energy efficiency

DRI – Direct reduced iron

DSM – Demand side management

GHG – Greenhouse gases

ICE – Internal combustion engine

1 Introduction

To achieve the targets laid down in the Paris Agreement, the energy system has to undergo a profound transformation from one largely based on fossil fuels to an energy efficient and renewable low-carbon energy system. However, the total decarbonisation of certain sectors, such as transport, buildings, industry and agriculture may be difficult and require novel technologies, process improvements, switches in the energy mix or large-scale deployment of storages. Enabling technologies continue to evolve and to strengthen the deployment of renewable energy technologies in all sectors but the change is not happening fast enough to meet the energy and climate policy objectives. A more rapid transition is needed.

The energy transition is the pathway for transforming the energy sector from fossil-based to zero-carbon by the second half of this century. There are many routes to such a destination, with different combinations of technologies that can be implemented. The objective is to identify the best strategies to guide the transition so that it happens in the optimal manner, maximising economic and social benefits, wealth creation and inclusion of all stakeholders.

This report shall provide a structured, documented and transparent view on the technology module within the general model architecture of EUCalc leading to decarbonisation pathways of the European Union (+Switzerland). The overarching objective of the technology module is to assess the status of and future needs for low-carbon technologies and provide a robust basis for identifying the elements of a flexible framework that nurtures their innovation for enabling the decarbonisation of our economy between now and 2050. It also covers specific innovations and trends in the energy sector that may have the potential for larger impact and could lead to new niches or technology regimes. Relevant technological drivers and trends for the reduction of energy demand and emissions are identified and described in different stages of development analysed in key scenarios including ambition levels, ranging from low level – business as usual – to a ground-breaking change.

The four ambition levels are:

- **LEVEL 1: Business as usual**
  This level contains projections that are aligned and coherent with the observed trends of the last 15 years (No TRL below 9).
- **LEVEL 2: Ambitious but achievable**
  This level is an intermediate scenario, more ambitious than business as usual but not reaching the full potential of available solutions (No TRL below 9).
- **LEVEL 3: Very ambitious but achievable**
  This level is considered very ambitious but realistic, given the current technology evolutions and the best practices observed in some geographical areas (No TRL below 7).
- **LEVEL 4: Transformational breakthrough**
  This level is considered transformational and requires additional breakthrough and efforts such as a very fast market uptake of deep measures, an extended deployment of infrastructures, major technological advances, or strong societal changes, etc.
  (No TRL below 5).

Tracking of technological progress and innovation needs to balance the long-term technology needs that will emerge, with the particular challenges of moving solutions that will meet those needs. To address this, the technology module within the European Calculator (EUCalc) aims to track and centralise information on current status of and innovation needs for more than 200 technologies. It is the intention, to systematically build and provide a repository of technology development and cost evolution, helping policy makers and companies to better set innovation priorities. System-level transitions include innovations in mobility systems, end-use technologies in buildings, manufacturing and production technologies in industrial sectors, power generation, distribution, storage and balancing strategies, and the agriculture sector. Although technological change and innovation are important, a wide-scale, equitable, and accessible transformation to energy systems for sustainable development needs to be tackled as a socio-political issue.

2 Technological transition and innovation pathways

2.1 Overall logic

The debate on decarbonizing Europe evolved over time from being the concern of national governments to encompassing a cross-border heterogeneity of economic sectors, businesses, regional decision makers and individuals. In this context, low-carbon technologies and innovations are integral to research and policy on transformation for climate change mitigation. Innovations from solar PV and offshore wind, to low-carbon manufacturing technologies and large-scale storage, to electric vehicles and energy-efficient buildings are strongly emphasised in energy system modelling. The distinguishing feature of these low-carbon innovations is that they offer more efficient or lower carbon substitutes for the incumbent forms of energy generations, distribution or use [Wilson, 2018]. Common energy-economy-environment models are typically designed to inform policymakers on technology or economic scenarios for achieving low-carbon transformations. However, they do not currently address in the required detail some of the key features of low-carbon innovation, including the necessary investment of technology transitions, leaving unanswered questions for actual policy application [Grubb, Hourcade, & Neuhoff, 2014; Mercure et al., 2016b; Pollitt & Mercure, 2018]

To bridge this gap, EU Calculator (EUCalc) comprises a user interface, the Transition Pathway Explorer, where users can define their own pathways using ambition levers and a temporal horizon of 2050. A lever offers the possibility to choose among different options regarding one question, e.g. the degree of refurbishment in old buildings or the deployment ambitions for district heating networks. This tool has identified as potential users mainly European policymakers, businesses, NGOs amongst other societal actors. Its goal is to equip these potential users with the means to create their own low-carbon transformation pathways at the European and its member states scales and compare them to other integrated pathways. The results will enable EU policymakers to support the energy, emissions and resources debate on a low carbon transition.

The underlying methodology — a mixed bottom-up and top-down approach — is rooted between pure energy simulation and integrated impact assessment, which is harmonized across all sectors to link 1) the activities in terms of lifestyle, technology availability and climate context, 2) the consumption and production of energy to fulfil the lifestyle, 3) the socio economic impacts, 4) the environment and resource impacts. This is all performed in an economic context, reflecting national productions, consumptions, imports and exports and with a related policy narrative. This wide analysis scope also integrates trade-offs like the impact of eating habits on land-use, of consumers goods purchases on resources, or of buildings renovation on material demand.

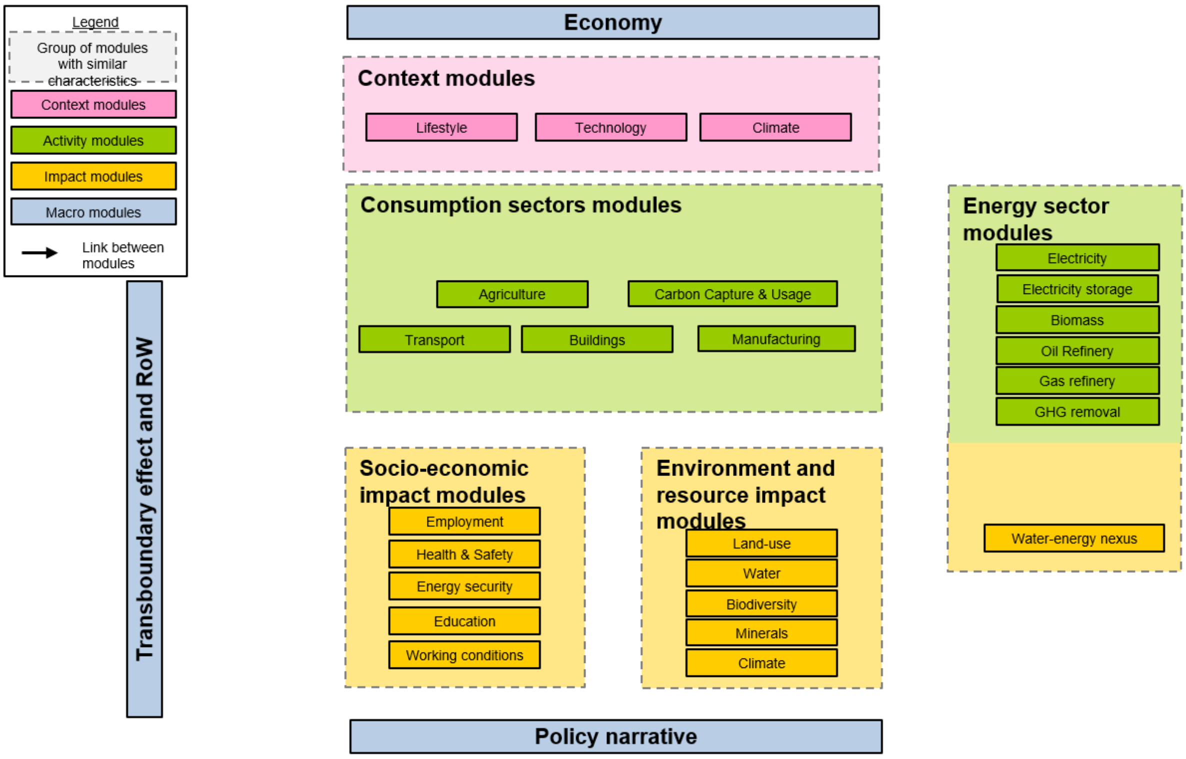


Figure 1: Modular structure of the EUCalc model

The European Calculator model consists of interconnected modules (Figure 1). Technological transition is located within the context modules serving as a central hub for information relevant to technology development and innovations.

2.2 Scope

Climate and energy targets could be met via different pathways and combinations of supply-side and demand-side technological and behavioural options. Significant debate exists on strategies for achieving an efficient and cost-effective sustainable energy transition (Edenhofer et al., 2010; IPCC, 2014b; Kriegler et al., 2014; Nordhaus, 2010; Nordhaus, 2015; Rogelj et al., 2015; Rogelj et al., 2018).

The speed of transitions and of technological change required to limit global warming to 1.5°C above pre-industrial levels has been observed in the past within scientific sectors and technologies. But the geographical and economic scales at which the required rates of change in the energy, land, urban, infrastructure and industrial systems would need to take place are larger and have no documented historic precedent [IPCC, 2018]. Demand-driven disruptive innovations that emerge as the product of political and social changes across multiple scales can be transformative (Christensen et al., 2015; Green and Newman, 2017). Such innovations would lead to simultaneous, profound changes in behaviour, economies and societies, but are difficult to predict in supply-focused economic models (Geels et al., 2016a; Pindyck, 2017) which are also found to produce typically pessimistic outcomes in comparison to observed diffusion trends [Wilson et al., 2013].

We therefore follow a dynamical systems simulations approach which is driven by the demand. Primary assumptions on technology development and the potential for disruptive innovation are defined by demand sectors and located in the technology module. The module serves as central hub providing all relevant information on future technology development, learning rates, technology costs, energy and emission factors, and material demand. The functional requirements of the technology module are:

Data completeness: It is of course rather trivial to state that the module needs to include all the indicators contained within the criteria hierarchy developed for EUCalc. However, the data delivered from the various work packages did not contain all or exactly the same indicators as called for. In particular, a number of cost indicators were calculated (e.g. for transport, buildings, manufacturing) or assessed based on relevant literature (energy supply), and several indicators adjusted for use in the final matrix.

Differentiated: The module includes average EU-wide data, however will take into account that countries differ in a number of ways. These differences include technology (or resource) availability or costs for example. To facilitate this, country specific indicators were applied in order to take variations in operating conditions, and general differences into consideration.

Comprehensible: The module is structured so that it will be easy to understand and use, particularly as it will be available as stand-alone reference product of the EUCalc project.

Flexible: It is a functional requirement of the module that it should be easy to update to reflect ongoing changes in database values, due to either updated contributions or error corrections. This means that the module will be easy to update in the future.

Modelling scenarios for development of the energy system is highly dependent on the assumptions, especially when it comes to the development of technologies - both in terms of performance and costs. While today one cannot have complete knowledge of all technologies that will be deployed on the pathway towards decarbonisation of the energy system, we include technologies that are currently being developed, incorporate their current costs and performance as well as their likely evolution in the future. The following chapters provide a mapping of technologies present in the European Calculator. Whereas basic technology-specific assumptions can be found in the module content documents[1], the purpose of this report is to outline future technological transitions and innovation pathways in various sectors and provide a deeper understanding of energy transitions.

2.3 Technological transitions and innovation pathways in EUCalc sectors

Transforming the energy systems requires directed, aligned and consistent efforts to innovate more sustainable ways of producing, distributing and using energy and materials. Following Christensen, disruptive low-carbon innovation needs to take into account widespread adoption leading to substantial emission reductions

[1] http://www.european-calculator.eu/documentation/

[Christensen, 1997]. Achieving deep decarbonisation pathways and scenarios in 2050 requires a broad range of mitigation options. The European Calculator considers the following mitigation options:

- Technology energy efficiency (incremental and radical change)
- Fuel switching (to renewable and low-carbon energy carriers)
- Novel technologies (such as carbon capture storage and use)
- Circular economy and recycling
- Material efficiency and substitution down the value chain
- Technology investment and operation costs
- Technology share in demand and supply sectors

In each of the respective sectors (like transport, buildings, manufacturing, etc.), a comprehensive literature review was performed in order to identify and select technologies and to justify the assumptions on future evolution. Selection criteria was made on the basis of the existing technology mix in each sector relying on historical data [2], the future potential for decarbonisation as well as novel technologies. To identify novel technologies the literature review primarily focused on sectoral (decarbonisation) roadmaps, foresight studies and scientific literature. The option space and assumptions made in each subsector on technological change were presented and discussed in the consultation process, documented on http://www.european-calculator.eu/deliverables [3]. The expert feedback was critically assessed, consolidated and if possible, implemented in the model.

In the following sections the feasibility and importance of systemic technological changes, expressed by sector-specific system transitions, is discussed. It should be noted that no single (technological) solution or option can enable a transition or adopting to projected impacts. It is rather the speed of the change, accelerating simultaneously and at different scales that could provide the impetus for these transitions. The feasibility of individual options and the potential for synergies and reducing trade-offs depend on user choices in setting the ambition levels in various sectors.

In total, the technology module combines 204 technologies of the following sectors:

- 62 Transport
- 37 Buildings and Appliances
- 30 Manufacturing and Production
- 21 Power Generation and Storage
- 42 Agriculture
- 6 Carbon Capture Storage and Use

[2] for example D2.1 Comprehensive database of EU vehicle fleet, broken down by country http://www.european-calculator.eu/deliverables/

[3] D2.3 Transport / D2.7 Buildings / D3.4 Manufacturing and Minerals / D4.2 Land, Land Use and Carbon Stock Dynamics / D4.3 Biodiversity and Water / D5.4 Electricity and Fossil Fuels / D6.3 Socio-Economy / D6.4 Air Pollution and Health / D7.3 Transboundary Effects

Table 1: Technology Matrix in the European Calculator

Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name
tra	LDV	ICE diesel	ind	Steel	BF-BOF	elc	Power generation	Wind Onshore
tra	LDV	ICE gasoline	ind	Steel	scrap-EAF	elc	Power generation	Wind Offshore
tra	LDV	ICE CNG	ind	Steel	DRI-EAF	elc	Power generation	PV utility scale
tra	LDV	PHEV diesel	ind	Steel	Hisarna	elc	Power generation	PV rooftop
tra	LDV	PHEV gasoline	ind	Cement	Wet-kilns	elc	Power generation	CSP
tra	LDV	BEV	ind	Cement	Dry-kilns	elc	Power generation	Geothermal
tra	LDV	H2	ind	Cement	Geopolymers	elc	Power generation	Ocean
tra	Bus	ICE diesel	ind	Chemicals	Tech ammonia	elc	Power generation	Hydropower
tra	Bus	ICE gasoline	ind	Chemicals	Tech chemicals	elc	Power generation	Nuclear
tra	Bus	ICE CNG	ind	Paper	Pulp	elc	Power generation	Coal
tra	Bus	PHEV	ind	Paper	Recycled	elc	Power generation	Gas
tra	Bus	BEV	ind	Aluminium	Primary	elc	Power generation	Oil
tra	Bus	H2	ind	Aluminium	Secondary	str	Energy storage	Electro-chemical battery, stationary
tra	Light HDV	ICE diesel	ind	Glass	Glass	elc	Power generation	CCS_new
tra	Light HDV	ICE gasoline	ind	Lime	Lime	elc	Power generation	CCS_old
tra	Light HDV	ICE CNG	ind	Steel	BF-BOF CCS	elc	Power generation	Biomass
tra	Light HDV	PHEV (trolley)	ind	Steel	scrap-EAF CCS	elc	Power generation	Biogas
tra	Light HDV	PHEV diesel	ind	Steel	DRI-EAF CCS	str	Energy storage	Pumped hydro
tra	Light HDV	PHEV gasoline	ind	Steel	Hisarna CCS	str	Energy storage	Compressed air storage
tra	Light HDV	BEV	ind	Cement	Wet-kilns CCS	str	Energy storage	Flywheel
tra	Light HDV	H2	ind	Cement	Dry-kilns CCS	str	Energy storage	Power to gas
tra	Medium HDV	ICE diesel	ind	Cement	Geopolymers CCS	agr	domestic-production	Animal fats
tra	Medium HDV	ICE gasoline	ind	Chemicals	Tech chemicals CCS	agr	domestic-production	Eggs

Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name
tra	Medium HDV	ICE CNG	ind	Paper	Pulp	agr	domestic-production	Milk products
tra	Medium HDV	PHEV (trolley)	ind	Chemicals	Tech ammonia	agr	domestic-production	Animal offals
tra	Medium HDV	PHEV diesel	ind	Food & beverages	Fbt	agr	domestic-production	Bovine
tra	Medium HDV	PHEV gasoline	ind	Machinery Equipment	Mae	agr	domestic-production	Sheep
tra	Medium HDV	BEV	ind	Transport equipment	Tra-equip	agr	domestic-production	Pigs
tra	Medium HDV	H2	ind	Textiles and leather	Textiles	agr	domestic-production	Poultry
tra	Heavy HDV	ICE diesel	ind	Other industries	Ois	agr	domestic-production	Other animals
tra	Heavy HDV	ICE gasoline	bld	Appliances	Dryer	agr	domestic-production	Algae
tra	Heavy HDV	ICE CNG	bld	Appliances	Dishwasher	agr	domestic-production	Rice
tra	Heavy HDV	PHEV (trolley)	bld	Appliances	Refrigerator and freezers	agr	domestic-production	Cereals
tra	Heavy HDV	PHEV diesel	bld	Appliances	Refrigerator and freezers	agr	domestic-production	Oil crops
tra	Heavy HDV	PHEV gasoline	bld	Appliances	Washing machine	agr	domestic-production	Pulses
tra	Heavy HDV	BEV	bld	Appliances	Television	agr	domestic-production	Fruits
tra	Heavy HDV	H2	bld	Appliances	Computer	agr	domestic-production	Vegetables
tra	Aviation	ICE	bld	Appliances	Smartphone	agr	domestic-production	Starchy roots
tra	Aviation	BEV	bld	Heating	oil	agr	domestic-production	Sugar crops
tra	IWW	BEV	bld	Heating	gas	agr	domestic-production	Insects
tra	IWW	FCEV	bld	Heating	bioenergy_solid_woodlogs	agr	liv-population	Lying hens
tra	IWW	ICE	bld	Heating	bioenergy_solid_pellet	agr	liv-population	Dairy cattle
tra	Marine	BEV	bld	Heating	electric_heating_systems	agr	liv-population	Bovine
tra	Marine	FCEV	bld	Heating	coal	agr	liv-population	Pigs
tra	Marine	ICE	bld	Heating	waste	agr	liv-population	Sheep
tra	Rail	CEV	bld	District heating	DH - CHP	agr	liv-population	Poultry

Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name	Sector	Sector / Classification	Technology name
tra	Rail	FCEV	bld	District heating	DH - Waste	agr	liv-population	Other animals
tra	Rail	ICE	bld	District heating	DH - Geothermal	agr	demand	Algae meals
tra	2W	BEV	bld	District heating	DH - Solar thermal	agr	demand	Insect meals
tra	2W	FCEV	bld	District heating	DH - Centralised heat pump	agr	demand	Sugar crops
tra	2W	ICE diesel	bld	District heating	DH - Gas Boilers	agr	demand	Fish meals
tra	2W	ICE CNG	bld	District heating	DH - Biomass Boilers	agr	demand	Rice
tra	2W	ICE gasoline	bld	District heating	DH - Oil Boilers	agr	demand	Meat meal
tra	2W	PHEV	bld	District heating	DH - Coal Boilers	agr	demand	Sugar
tra	Infrastructure	New km of e-highways	bld	District heating	District heating pipes	agr	demand	Cereals
tra	Infrastructure	New private charging stations - BEV LDV	bld	Renovation	Low renovation - single family house	agr	demand	Oil crops
tra	Infrastructure	New public charging stations - BEV LDV	bld	Renovation	Medium renovation - single family house	agr	demand	Pulses
tra	Infrastructure	New fast charging stations - BEV LDV	bld	Renovation	Deep renovation - single family house	agr	demand	Fruits
tra	Infrastructure	New charging stations - FCEV LDV	bld	Renovation	Low renovation - appartment building	agr	demand	Vegetables
tra	Infrastructure	New charging stations - BEV HDV	bld	Renovation	Medium renovation - appartment building	agr	demand	Starchy roots
tra	Infrastructure	New depot stations - BEV HDV	bld	Renovation	Deep renovation - appartment building	agr	demand	Molasse
tra	Infrastructure	New charging stations - FCEV HDV	bld	Renovation	Low renovation - office	agr	demand	Oil crop cakes
ccu	CCU	Methane formation	bld	Renovation	Medium renovation - office	agr	demand	Oil
ccu	CCS	Enhanced oil recovery (EOR)	bld	Renovation	Deep renovation - office	bld	Renovation	Deep renovation - school
ccu	CCS	Depleted oil gas reservoirs (DOGR)	bld	Renovation	Low renovation - school	ccu	CCS	Saline aquifers
ccu	CCS	Unmineable coal seams (UCS)	bld	Renovation	Medium renovation - school	ccu	CCS	Transport

2.3.1 Transport

In the transport sector, in which the amount of greenhouse gas emissions has been continuously increasing in recent years in Europe, decarbonisation is challenging. From the technology perspective an increase in vehicle efficiency, a switch of the fuel mix and the electrification of the transport sector can contribute to the GHG reduction objectives.

The usage of **vehicles with a higher energy efficiency** will cause a lower energy consumption. The energy consumption of different vehicles is considered to decrease by 30 to 50% until 2050.

The **electrification of transport** and the switch to fully electric and fuel cell vehicles, as well as hybrid electric and gas-powered vehicles can reduce greenhouse gas emissions of the transport sector to a high amount, if electricity comes from renewable energy sources. New cars, busses and planes are considered to reach an amount of up to 100% of zero-emission vehicles (fully electric and fuel cell vehicles).

The change of the fuel mix towards an increased **usage of biofuels and e-fuels** has an impact on the emissions of the transport sector, while the energy consumption remains constant. Currently, biofuels account for 3% (gasoline) to 6% (diesel) of the fuel mix. Until 2050 biofuels and e-fuels are considered to be utilised up to their full potential in the most ambitious scenario – based on lever settings in the Transition Pathway Explorer (TPE).

2.3.2 Buildings

Buildings have a large energy saving potential with available and demonstrated technologies. Energy efficiency improvements by deep renovation of the existing building stock, new constructions as well as building renovation to be nearly-zero energy buildings (nZEB), energy efficient appliances with an increased lifetime and the use of less carbon-intensive construction materials can be summarised to have a major impact on buildings future emissions.

Heating and cooling demand of buildings can be reduced significantly by the **renovation of the existing building stock**. Also the change of energy supply systems to renewable and more energy-efficient ones (e.g. from the combustion of fossil fuels like oil or gas to the usage of heat pumps or solar hot water systems) in existing buildings highly effects energy demand and emissions. The energy need after renovation is reduced by 30% to 60%.

New, energy efficient buildings have also a reduced energy demand compared to the average buildings stock. The reduction goes from 30% up to 60% in the highly efficient category. The annual demolition rate and the needed overall floor area (input from the lifestyle module) define the new building rate.

An increase in the energy efficiency of **appliances** lowers energy demand and emissions of the building sector. Also the switch from fossil fuels to electricity in cooking appliances and the usage of more efficient lighting systems like LED bulbs are drivers for emission mitigation.

The materials used for the construction of buildings highly influence energy demand and carbon emissions. **Material switches** to less carbon-intensive materials (e.g. wood instead of steel) and an increase in the usage of recycled materials, as well as reducing the material demand by design improvements and the reduction of over dimensioning decreases energy demand and emissions of the building sector.

The supply of buildings with **district heating** can facilitate decarbonisation in dense urban areas. Especially historic buildings can hardly be renovated towards zero-energy buildings. In these cases district heating enables low emission heat supply.

2.3.3 Industry

Industrial decarbonisation is more likely to succeed with solutions involving most if not all supply chain actors (e.g. government, basic materials producers, manufacturers, and retailers) [Bataille et al, 2018]. Depending on the individual industrial sector, mitigation options include an increase of the rate of recycling as well as substitution of materials in high-carbon products with those made up of renewable materials, the electrification of production processes, hydrogen-based production technologies, the use of bio-based feedstock, and carbon capture and storage (as well as use) of CO_2 emissions.

Energy efficiency options are available for almost every individual technology in each industrial sector. In general, their feasibility and implementation strongly depend on lowering capital costs, raising awareness and expertise.

Electrification of manufacturing processes is an ongoing trend in many energy-intensive sectors and entails a more disruptive innovation in industry than bio-based or CCS options to get to low or even zero emissions, except potentially in steelmaking. Feasibility of electrification and **use of hydrogen** in production processes is affected by technical development (in terms of efficient hydrogen production and electrification of processes) and by geophysical factors related to the availability of low-emission electricity [MayKay, 2013].

Carbon Capture and Storage (CCS), especially retrofitting CCS on existing industrial plants would leave the production processes relatively untouched though significant investments and modifications are required. Some industries, in particular cement and chemicals, emit CO_2 as inherent process emissions and can therefore not reduce emissions to zero without CCS. For GHG accounting purposes the biogenic carbon (resulting from bio-based production) embodied in materials is considered as a reduction or a "negative emission".

Recycling technologies (such as in paper, aluminium or steel production) and a developing **circular economy** require organisational changes and advanced capabilities, but offer advantages in terms of cost, health, governance and environment [Ali et al., 2017]. Especially in the chemical industry, significant improvements in plastic recycling and **substitution by bio-based products** as well as re-use and lifetime extensions are assumed to show significant impacts.

2.3.4 Agriculture

The main drivers of GHG emissions in the agriculture sector consist of livestock production through the enteric fermentation emissions, the use of fertilizers and in a lower extent the rice cultivation process. Increased temperatures and the effects of droughts conclude that aggregate production of food are expected to decrease. Mitigation options include improved livestock management, increasing irrigation efficiency, the shift to a bio-based economy and the use of novel technologies.

The **self-sufficiency levels in local food systems** of European member states are very heterogeneous and also the self-sufficiency rates of plant-based food and meat-based food differ highly. Carbon intensity also varies highly in different EU countries, so one country may for example be self-sufficient while presenting high emission intensity, while another country may present low carbon intensity but is importing food goods from countries with higher carbon intensity. Therefore, the level of self-sufficiency is not directly connected to carbon emission mitigation (a higher ambition in self-sufficiency does not automatically cause higher GHG mitigation effort).

Climate smart crop production systems include the share of losses towards the agri-food production system, crop yields, the demand of fertilizers, pesticides and energy and the residues for soil quality. There is no direct connection to GHG mitigation by only increasing smart cropping systems because the diet and food trade balance widen or narrow the scope of sustainable agriculture practices. The agri-food system sustainability – including GHG emission balance – requires the diets, the trade balance and the agricultural practices to be relevantly aligned. A fully agro-ecological Europe in 2050 is possible, reducing GHG emissions by 40%, involving tremendous diet shifts in the current food trade balance [Poux and Aubert, 2018].

Livestock production is the major driver of GHG emissions in the agriculture sector. **Climate smart livestock production** includes the share of losses, yields for animal-based products, slaughter rates, manure management and the grazing intensity. Like at the smart cropping systems, there is no direct connection between increasing smart livestock production and reducing GHG emissions.

The use of industrial by-products, wastes and residues as feedstock for e.g. compost, fertilizer, biogas, electricity or heat towards a shift to a **bio-based economy** contributes positively to mitigation objectives. Feedstock types, used for recovery and recycling, range from only imported feedstock (low level) over using food-crops and energy-crops towards using all above mentioned types supplemented by residues and by-products in the most advanced ambition level.

2.3.5 Power generation and storage

The transition in the power generation system is increasingly being surmounted as that fossil fuels, in particular coal and oil, start to be phased out. An increasing share of renewable electricity, increased energy storage capacities, as well as demand-side options (see sections above) describe the future evolution in this sector. Carbon capture and storage also plays a role in the transition.

A significant increase in **renewable electricity**, in particular the capacity additions of wind and solar power generation as well as geothermal, marine and hydropower substitute the power generation from fossil fuels and therefore contribute positively to emission reduction.

Power **balancing and storage** strategies as well as power-to-x technologies, which transfer the excess electricity into other forms of energy, are considered for the transition of the power generation system. The influence on charging patterns of electric vehicles allows demand side management and load shift.

The **capture and storage of carbon** (CCS) emissions of different fossil fuel based power plants and oil refineries enables a decrease in greenhouse gas emissions released into the atmosphere. The captured CO_2 can then be either sequestered or turned to synthetic natural gas. As in manufacturing and production, the biogenic carbon (resulting from bio-based production) is considered as a reduction or a "negative emission".

2.4 Technology learning and costs in EUCalc

Generally, technological change is understood to be a gradual process of diffusion with different stages of progress. The diffusion of new technology is preceded by invention and consecutive innovation. In literature, endogeneity of technical change has been identified as a crucial aspect of modelling energy system transformations [Kouvaritakis et al., 2000]. One approach to analyse the process of technical change is based on the notion of learning curves (Jamasb 2007) as pioneered by Arrow (1962). Learning curves are usually used to assess the changes in unit costs compared to the cumulative capacity and are quantified as learning rate. The learning rate is then measured as a 'percentage cost reduction for each doubling of the cumulative capacity or production' and can be similarly conceptualized as a profitability driver of technology diffusion.

We therefore propose assumed learning rates and consequently future costs, which are a decisive parameter for energy system models [Nijs W et al., 2016]. Assessing future costs based on learning rates is an important topic in the scientific community [Nemet 2006; McDonald et al, 2001; Söderholm/Sundquist 2007] that illustrates the importance of dealing with uncertainty.

The fact, that many of the products and materials covered in EUCalc are internationally traded commodities, making it difficult to impose a carbon price at EU levels or a member state level. Hence the model approach **does not include a carbon price**.

2.4.1 Overall description

The calculation trees for costs are split in two steps:

- Pre-processing of unit costs parameters
- Calculation of total costs

The first step is performed in the technology module, while the second step is distributed in each of the sectors involved in cost calculation. The total cost of each technology included in the model is categorised by capital (CAPEX), operation and maintenance (OPEX) and fuel cost.

According to [Rubin et al., 2015] capital costs decline over time as they follow a learning curve. The fractional reduction in cost associated with a doubling of experience is referred to as the learning rate (LR) and is given by

$$LR = 1 - 2^b \qquad (1)$$

The factor 2^b in the above equation is the "progress ratio," a parameter also commonly reported in the literature indicating the fractional cost reduction after a doubling of cumulative capacity (or production). Eq. (1) is often transformed to a log-linear equation in which b is the slope of a line on a log-log scale [Yeh and Rubin, 2012]

$$log\, Y = \alpha + b(log\, x) \qquad (2)$$

where ɑ is the specific cost at unit cumulative capacity, b the progress ratio and the independent variable x, a surrogate for all the factors that affect the cost trajectory of a technology.

Where no learning rates for technologies were identified or no fundamental technology development is expected we assumed a linear (constant) decrease in the evolution of costs.

Current **fossil fuel prices** and projections were obtained from the World Energy Outlook 2012 [IEA, 2012] and interpolated to 2050 in order to be consistent with the economic baseline used by the GTAP-EUCalc model, described in Deliverable 7.1[4] [Yu & Clora, 2018].

Table 2 Fossil fuel price projections (based on IEA 2012)

	Interpolated values	
	y2015 in 2015 USD	**y2050 in 2015 USD**
Oil	115,70	137,00
Gas	10,13	11,30
Coal	125,80	90,00

For **country disaggregation**, we propose to employ Purchasing Power Parities (PPPs). In research PPPs are used to either generate volume measures with which to compare the size of economies and their levels of economic welfare, consumption, investment, government expenditure and overall productivity or to generate price measures with which to compare price levels, price structures, price convergence and competitiveness [Eurostat 2012].

4 http://www.european-calculator.eu/wp-content/uploads/2018/09/EUCalc_D7.1_Formulation-of-baseline-projections-and-documentation-on-modeling-approach-review.pdf

Table 3: PPPs for European countries

Belgium	2015	106,4
Bulgaria	2015	46,2
Czech Republic	2015	63,1
Denmark	2015	130,3
Germany	2015	103,5
Estonia	2015	71,5
Ireland	2015	107,7
Greece	2015	81
Spain	2015	88,4
France	2015	107,6
Croatia	2015	61,4
Italy	2015	98,3
Cyprus	2015	88,2
Latvia	2015	66,2
Lithuania	2015	59,3
Luxembourg	2015	117,3
Hungary	2015	56,9
Malta	2015	79,8
Netherlands	2015	107,8
Austria	2015	106,3
Poland	2015	56,1
Portugal	2015	77,8
Romania	2015	49,8
Slovenia	2015	79,2
Slovakia	2015	65,4
Finland	2015	120,8
Sweden	2015	126
United Kingdom	2015	127
Switzerland	2015	154

Detailed description of assumptions on specific costs for each respective sector covered in EUCalc can be found in the technical documents. The calculations in the sector modules are standardised using Knime metanodes so that they all conform to the same logic.

2.4.2 Pre-processing of unit cost parameters

As a reminder, two methods are implemented to estimate unit costs:

- Linear evolution, where unit costs evolve linearly over time between 2015 and 2050
- Learning rate, where unit costs evolve as a function of the cumulative experience in building the items.

The goals of this calculation step are, for each technology and resource, to:

- Harmonise all reference unit costs to 2015 for the 29 countries.
- Calculate unit cost evolution factors to be used in the sector modules (factors "b" or "d" depending on the method) for total cost calculation.

- Project fuel prices for all years between 2015 and 2050.

The inputs for this calculation step are:

- Technology costs: this input file includes a selector whereby sectors were able to specify which method is to be used, and provide the required parameters. Costs can be provided for any year and for any country or the EU28 aggregate.
- Harmonised index of consumer prices
- Price level index 2015
- Fuel prices for 2015 and 2050, consistent with the economic scenarios of the Employment and Transboundary modules

An illustrative example of a section of the input file for technology costs is presented below:

Table 4: Cost parametrisation in the European Calculator's technology module

basic description				Evolution	CAPEX						OPEX					
Sector	Sector / Classification	Technology name	Technology code	Cost evolution methodology	CAPEX Reference Unit	CAPEX ref year	CAPEX Country	CAPEX for ref year [EUR/ref unit]	CAPEX Learning Rate [cost change on doubling of experience]	2050 CAPEX [EUR per ref. unit]	OPEX Reference Unit	OPEX reference year	OPEX Country	OPEX for reference year [EUR/ref unit]	OPEX Learning Rate [cost change on doubling of experience]	2050 OPEX [EUR/ref unit]
ind	steel	BF-BOF	steel_BF-BOF	Linear	t	2015	EU28	192.26		192.26	t	2015	EU28	108.15		108.15
ind	steel	scrap-EAF	steel_scrap-EAF	Linear	t	2015	EU28	96.13		96.13	t	2015	EU28	38.45		38.45
ind	steel	DRI-EAF	steel_DRI-EAF	Learning rate	t	2015	EU28	175.00	0.08		t	2015	EU28	15.70	0.10	
ind	steel	Hisarna	steel_hisarna	Learning rate	t	2015	EU28	144.20	0.01		t	2015	EU28	97.33	0.06	
ind	cement	Wet-kilns	cement_wet-kilns	Linear	t	2015	EU28	14.99		14.99	t	2015	EU28	17.81		17.81
ind	cement	Dry-kilns	cement_dry-kilns	Linear	t	2015	EU28	14.99		14.99	t	2015	EU28	17.81		17.81
ind	cement	Geopolymers	cement_geopolym	Learning rate	t	2015	EU28	18.00	0.08		t	2015	EU28	21.37	0.08	
ind	chemicals	Tech ammonia	amm-tech	Linear	t	2015	EU28	670.00		670.00	t	2015	EU28	150.00		150.00
ind	chemicals	Tech chemicals	chem	Linear	t	2015	EU28	1 200.00		1 200.00	t	2015	EU28	180.00		180.00
ind	paper	Pulp	paper_woodpulp	Linear	t	2015	EU28	0.82		0.82	t	2015	EU28	0.76		0.76

The outputs of this calculation step are:

- Unit cost parameters that are distributed to all modules where a calculation needs to be done.
- Price level index for each country in 2015, to allow price differentiation by country.
- Fuel prices for the electricity module.

The detailed calculation tree is presented below.

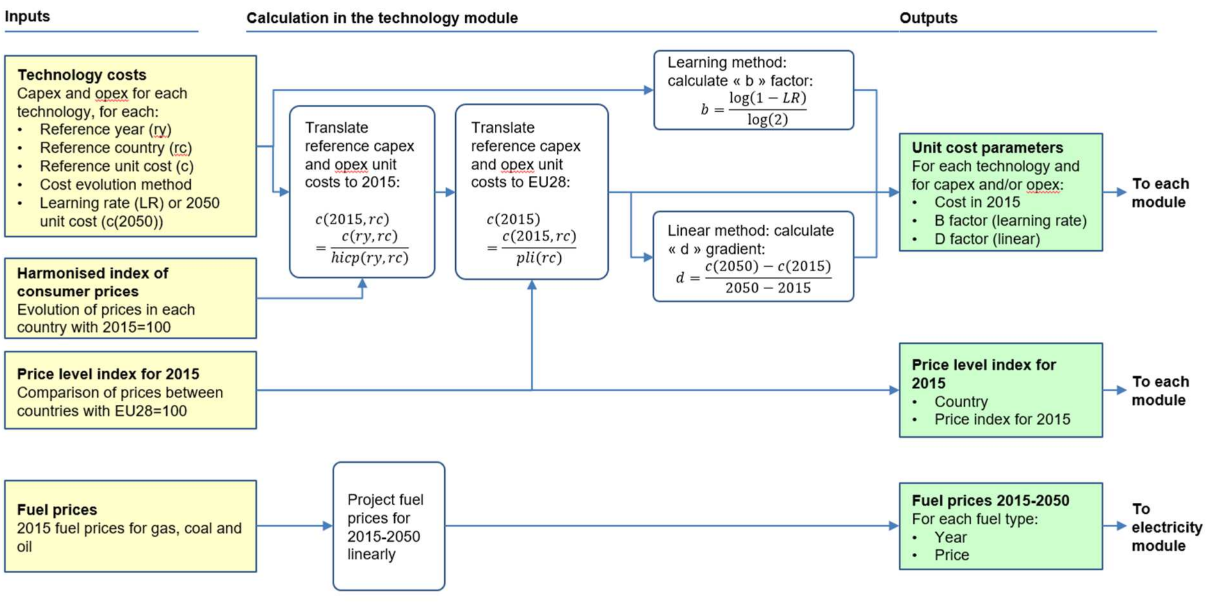


Figure 2: Calculation tree for costs considering learning rates or linear progression

2.4.3 Calculation of total costs

The calculation logic represented here uses the transport sector as an example, but the logic is the same across all sectors, except the fuel cost calculation in the electricity module, which is presented in the next section.

The goal of this step is to compute the total costs for the sector per technology. In the case of transport, the technology is either:

- For vehicles, a combination of transport mode and propulsion type, e.g. "bus ICE-diesel"
- For infrastructure, its type, e.g. "e-highways" or "private charging stations - BEV LDV"

The inputs required to compute the total costs are:

- Activity data:
    - Annual demand of new vehicles per country and technology
    - Annual demand of new infrastructure per country and technology
- Unit cost parameters calculated in the previous step

The outputs of this calculation are total costs in EUR:

- CAPEX: capital costs for new passenger and freight vehicles, new infrastructure (roads and charging stations).
- OPEX: associated costs for operation and maintenance of vehicles and infrastructure

The calculation implemented in this step are:

- For the learning method:
    - Calculate cumulative experience as the cumulative sum of the total European activity from 1990 to 2015
    - Calculate annual unit costs using the learning rate equation
- For the linear method:
    - Calculate annual unit costs using gradient and year
- Multiply these unit costs by the activity variables, to obtain total costs
- Differentiate these costs by country using the price level index.

They are presented in detail in the following figure:

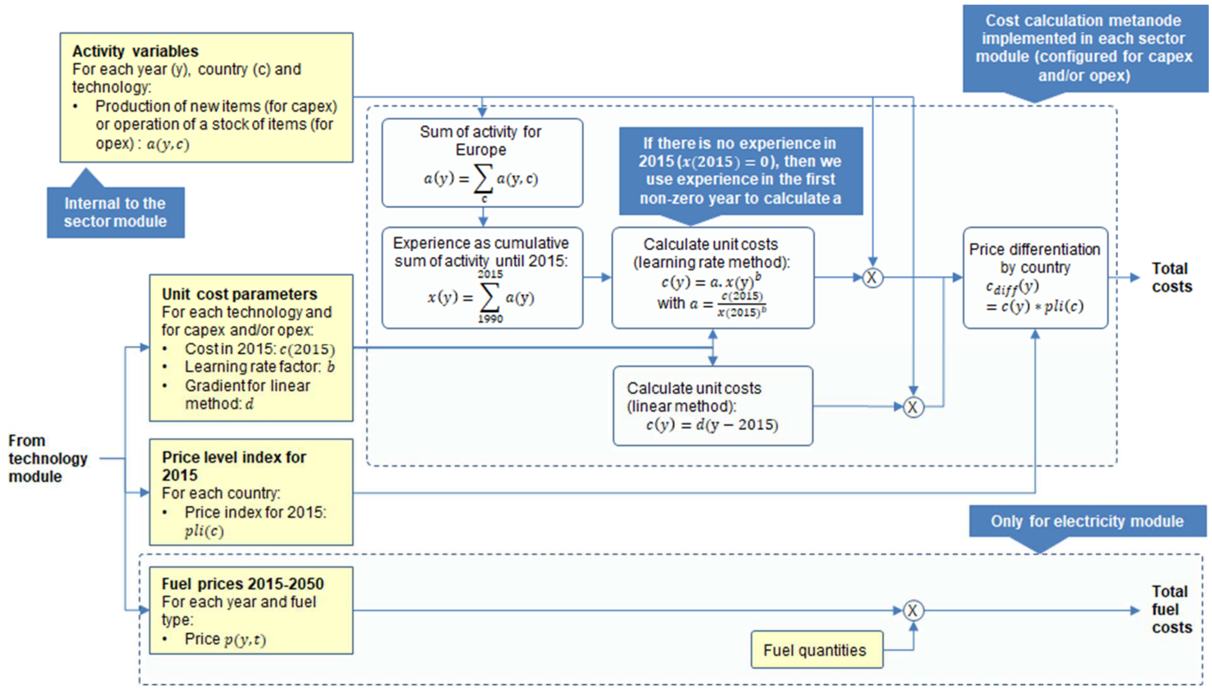


Figure 3: Example of calculation tree for costs (transport sector)

2.4.4 Cost assumptions

The technology module serves as a repository of cost assumptions made by various sectors in the European Calculator. As shown in Table 5 the following cost metrics are currently present:

Table 5: Cost assumptions and evolution in EUCalc

Country	Year	Sector	Technology code	Evolution method	Capex unit	Capex lr	Capex 2050	Opex unit	Opex lr	Opex 2050	Capex baseyear	Opex baseyear
EU28	2015	tra	LDV_ICE-diesel	linear	new vehicle	0,01	22770	km	0,01		25300	0,03
EU28	2015	tra	LDV_ICE-gasoline	linear	new vehicle	0,01	22770	km	0,01		25300	0,03
EU28	2015	tra	LDV_ICE-gas	linear	new vehicle	0,01	25274,7	km	0,01		28083	0,03
EU28	2015	tra	LDV_PHEV-diesel	learning rate	new vehicle	0,05		km	0,05		27989	0,03
EU28	2015	tra	LDV_PHEV-gasoline	learning rate	new vehicle	0,05		km	0,05		27989	0,03
EU28	2015	tra	LDV_BEV	learning rate	new vehicle	0,1		km	0,1		31087	0,02
EU28	2015	tra	LDV_FCEV	learning rate	new vehicle	0,1		km	0,1		39696	0,03
EU28	2015	tra	bus_ICE-diesel	linear	new vehicle	0,01	208800	vehicle/year	0,01		232000	5021
EU28	2015	tra	bus_ICE-gasoline	linear	new vehicle	0,01	208800	vehicle/year	0,01		232000	5021
EU28	2015	tra	bus_ICE-gas	linear	new vehicle	0,01	231768	vehicle/year	0,01		257520	5585
EU28	2015	tra	bus_PHEV	learning rate	new vehicle	0,05		vehicle/year	0,05		331000	4350
EU28	2015	tra	bus_BEV	learning rate	new vehicle	0,1		vehicle/year	0,1		285058	3345
EU28	2015	tra	bus_FCEV	learning rate	new vehicle	0,1		vehicle/year	0,1		700000	14907
EU28	2015	tra	HDVL_ICE-diesel	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVL_ICE-gasoline	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVL_ICE-gas	linear	new vehicle	0,01	137521,8	km	0,01		152802	0,22
EU28	2015	tra	HDVL_CEV	learning rate	new vehicle	0,05		km	0,05		150807	0,22
EU28	2015	tra	HDVL_PHEV-diesel	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVL_PHEV-gasoline	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVL_BEV	learning rate	new vehicle	0,1		km	0,1		214293	0,2
EU28	2015	tra	HDVL_FCEV	learning rate	new vehicle	0,1		km	0,1		186887	0,2
EU28	2015	tra	HDVM_ICE-diesel	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVM_ICE-gasoline	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVM_ICE-gas	linear	new vehicle	0,01	137521,8	km	0,01		152802	0,22
EU28	2015	tra	HDVM_CEV	learning rate	new vehicle	0,05		km	0,05		150807	0,22
EU28	2015	tra	HDVM_PHEV-diesel	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVM_PHEV-gasoline	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVM_BEV	learning rate	new vehicle	0,1		km	0,1		214293	0,2

Country	Year	Sector	Technology code	Evolution method	Capex unit	Capex lr	Capex 2050	Opex unit	Opex lr	Opex 2050	Capex baseyear	Opex baseyear
EU28	2015	tra	HDVM_FCEV	learning rate	new vehicle	0,1		km	0,1		186887	0,2
EU28	2015	tra	HDVH_ICE-diesel	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVH_ICE-gasoline	linear	new vehicle	0,01	122688,9	km	0,01		136321	0,22
EU28	2015	tra	HDVH_ICE-gas	linear	new vehicle	0,01	137521,8	km	0,01		152802	0,22
EU28	2015	tra	HDVH_CEV	learning rate	new vehicle	0,05		km	0,05		150807	0,22
EU28	2015	tra	HDVH_PHEV-diesel	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVH_PHEV-gasoline	learning rate	new vehicle	0,05		km	0,05		169142	0,2
EU28	2015	tra	HDVH_BEV	learning rate	new vehicle	0,1		km	0,1		214293	0,2
EU28	2015	tra	HDVH_FCEV	learning rate	new vehicle	0,1		km	0,1		186887	0,2
EU28	2015	tra	aviation_ICE	linear	new vehicle		126000000	new vehicle			140000000	
EU28	2015	tra	aviation_BEV	learning rate	new vehicle	0,1		new vehicle			172022924,9	
EU28	2015	tra	IWW_BEV	learning rate	new vehicle	0,1		new vehicle			63894229,25	
EU28	2015	tra	IWW_FCEV	learning rate	new vehicle	0,1		new vehicle			81588616,6	
EU28	2015	tra	IWW_ICE	linear	new vehicle		46800000	new vehicle			52000000	
EU28	2015	tra	marine_BEV	learning rate	new vehicle	0,1		new vehicle			127788458,5	
EU28	2015	tra	marine_FCEV	learning rate	new vehicle	0,1		new vehicle			163177233,2	
EU28	2015	tra	marine_ICE	linear	new vehicle		93600000	new vehicle			104000000	
EU28	2015	tra	rail_CEV	linear	new vehicle			new vehicle				
EU28	2015	tra	rail_FCEV	learning rate	new vehicle			new vehicle				
EU28	2015	tra	rail_ICE	linear	new vehicle			new vehicle				
EU28	2015	tra	2W_BEV	learning rate	new vehicle	0,1		new vehicle			6143,68	
EU28	2015	tra	2W_FCEV	learning rate	new vehicle	0,1		new vehicle			7845,06	
EU28	2015	tra	2W_ICE-diesel	linear	new vehicle		4500	new vehicle			5000	
EU28	2015	tra	2W_ICE-gas	linear	new vehicle		4995	new vehicle			5550	
EU28	2015	tra	2W_ICE-gasoline	linear	new vehicle		4500	new vehicle			5000	
EU28	2015	tra	2W_PHEV	learning rate	new vehicle	0,05		new vehicle			5531,42	

Country	Year	Sector	Technology code	Evolution method	Capex unit	Capex lr	Capex 2050	Opex unit	Opex lr	Opex 2050	Capex baseyear	Opex baseyear
EU28	2015	bld	bld_liquid-ff-heatingoil	linear	kW		174	kWh		0,21	162	0,21
EU28	2015	bld	bld_gas-ff-natural	linear	kW		179	kWh		0,24	157	0,24
EU28	2015	bld	bld_solid-bio-woodlogs	linear	kW		442	kWh		0,3	410	0,3
EU28	2015	bld	bld_solid-bio-pellets	linear	kW		442	kWh		1,93	410	1,93
EU28	2015	bld	bld_electricity	linear	kW		69	kWh		1,6	60	1,62
EU28	2015	bld	bld_solid-ff-coal	linear	kW		16,87	kWh		0,35	17,04	0,36
EU28	2015	bld	dh_chp	linear	kW		100	kWh		0,05	91	0,05
EU28	2015	bld	dh_solid-ff-waste	linear	kW		100	kWh		0,05	91	0,05
EU28	2015	bld	dh_heat-geothermal	linear	kW		1514,02	kW		56,17	1514,02	56,17
EU28	2015	bld	dh_heat-solar	linear	kW		717,76	kW		8,07	717,76	8,07
EU28	2015	bld	dh_heat-ambient	linear	kW		343,93	kW		11,96	343,93	11,96
EU28	2015	bld	dh_gas-ff-natural	linear	kW		58,79	kW		1,18	58,79	1,18
EU28	2015	bld	dh_solid-bio-woodlogs	linear	kW		114,96	kW		2,3	114,96	2,3
EU28	2015	bld	dh_liquid-ff-heatingoil	linear	kW		54,77	kW		1,18	54,77	1,18
EU28	2015	bld	dh_solid-ff-coal	linear	kW		114,95	kW		2,3	114,95	2,3
EU28	2015	bld	dryer	linear	new unit		680				587	
EU28	2015	bld	dishwasher	linear	new unit		539				533	
EU28	2015	bld	fridge	linear	new unit		72				580	
EU28	2015	bld	freezer	linear	new unit		72				580	
EU28	2015	bld	wmachine	linear	new unit		538				586	
EU28	2015	bld	tv	linear	new unit		700				700	
EU28	2015	bld	comp	linear	new unit		1500				1500	
EU28	2015	bld	phone	linear	new unit		300				300	
EU28	2015	bld	dh_pipes	linear	km		20000				20000	
EU28	2015	bld	reno-shl-sfh	linear	m2		28,7				41	
EU28	2015	bld	reno-med-sfh	linear	m2		69,3				99	
EU28	2015	bld	reno-dep-sfh	linear	m2		138,6				198	
EU28	2015	bld	reno-shl-mfh	linear	m2		11,9				17	
EU28	2015	bld	reno-med-mfh	linear	m2		28,7				41	

Country	Year	Sector	Technology code	Evolution method	Capex unit	Capex lr	Capex 2050	Opex unit	Opex lr	Opex 2050	Capex baseyear	Opex baseyear
EU28	2015	bld	reno-dep-mfh	linear	m2		57,4				82	
EU28	2015	bld	reno-shl-off	linear	m2		18,2				26	
EU28	2015	bld	reno-med-off	linear	m2		44,1				63	
EU28	2015	bld	reno-dep-off	linear	m2		88,2				126	
EU28	2015	bld	reno-shl-sco	linear	m2		10,5				15	
EU28	2015	bld	reno-med-sco	linear	m2		25,2				36	
EU28	2015	bld	reno-dep-sco	linear	m2		51,1				73	
EU28	2015	elc	RES_wind_onshore	learning rate	kW	0,05		kW	0,05		1487	45
EU28	2015	elc	RES_wind_offshore	learning rate	kW	0,11		kW	0,11		4185	84
EU28	2015	elc	RES_solar_Pvutility	learning rate	kW	0,2		kW	0,2		1020	17,34
EU28	2015	elc	RES_solar_Pvroof	learning rate	kW	0,2		kW	0,2		1250	28,13
EU28	2015	elc	RES_solar_csp	learning rate	kW	0,1		kW	0,1		5470	93
EU28	2015	elc	RES_other_geothermal	learning rate	kW	0,05		kW	0,05		7433	149
EU28	2015	elc	RES_other_marine	learning rate	kW	0,14		kW	0,14		7041	390
EU28	2015	elc	RES_other_hydroelectric	learning rate	kW	0,01		kW	0,01		2848	14
EU28	2015	elc	nuclear	linear	kW		4000	kW		149	5940	153
EU28	2015	elc	fossil_coal	linear	kW		1845	kW		56	1890	59
EU28	2015	elc	fossil_gas	linear	kW		840	kW		20,25	840	20,25
EU28	2015	elc	fossil_oil	linear	kW		1200	kw		23,5	1200	23,5
EU28	2015	elc	battery	learning rate	MWh	0,15		kW	0,15		600000	40,5
EU28	2015	str	PHS	learning rate	MWh	0,07		kW	0,07		100000	22,5
EU28	2015	str	CAES	learning rate	MWh	0,23		kW	0,23		125000	38,5
EU28	2015	str	flywheel	learning rate	MWh	0,19		kW	0,19		1750000	52,5
EU28	2015	str	Ptx	learning rate	MWh H2	0,18		kW	0,18		6000	0

Country	Year	Sector	Technology code	Evolution method	Capex unit	Capex lr	Capex 2050	Opex unit	Opex lr	Opex 2050	Capex baseyear	Opex baseyear
EU28	2015	ccu	methanol-formation	linear	tCO2-eq		630,63	-		0	630,63	0
EU28	2015	ccu	methane-formation	linear	tCO2-eq		807,21	-		0	807,21	0
EU28	2015	ccu	dimethyl-carbonate	linear	tCO2-eq		440,54	-		0	440,54	0
EU28	2015	ccu	dimethyl-ether	linear	tCO2-eq		513,51	-		0	513,51	0
EU28	2015	ccu	fischer-tropsch	linear	tCO2-eq		329,73	-		0	329,73	0
EU28	2015	ccu	enhanced-oil-recovery	linear	tCO2-eq		2,25	-		0	2,25	0
EU28	2015	ccu	depleted-oil-gas-reservoirs	linear	tCO2-eq		2,25	-		0	2,25	0
EU28	2015	ccu	unmineable-coal-seams	linear	tCO2-eq		2,25	-		0	2,25	0
EU28	2015	ccu	deep-saline-formation	linear	tCO2-eq		3,64	-		0	3,64	0
EU28	2015	ccu	ocean-storage	linear	tCO2-eq		8,74	-		0	8,74	0
EU28	2015	ccu	deep-ocean-injection	linear	tCO2-eq		13,74	-		0	13,74	0
EU28	2015	ccu	mineral-storage	linear	tCO2-eq		12,61	-		0	12,61	0

3 Results

This chapter aims to provide an overview of results, generated in the Transition Pathway Explorer (TPE) for the sectors electricity, manufacturing and production, transport, buildings and agriculture including greenhouse gas emissions and energy demand until 2050. Costs are shown for the sectors transport, buildings, and electricity production. The EU-Reference scenario is compared to the most ambitious scenario and the Behaviour & tech scenario.

The following table gives an overview of the levels set in the three described scenarios.

Table 6: Overview of the key parameters and respective defined levels of the three scenarios (EU-Reference scenario, technology & fuels scenario and behavior & tech scenario)

Parameters	***EU-Reference scenario 2050***	***Technology & fuels scenario 2050***	***Behaviour & tech scenario 2050***
	Ambition Level	**Ambition Level**	**Ambition Level**
Key behaviours			
Travel	**1**	**1,2** (+)	**4** (++)
Homes	**1,6**	**1,6**	**4** (++)
Diet	**1,6**	**1,5**	**4** (++)
Consumption	**1,3**	**1,8** (+)	**4** (++)
Technology and fuels			
Transport	**1,6**	**4** (++)	**3,6** (++)
Buildings	**1,5**	**4** (++)	**4** (++)
Manufacturing	**1,4**	**4** (++)	**4** (++)
Power	**1,4**	**4** (++)	**3,3** (++)
Resources and land use			
Land and food	**1,4**	**1,3**	**1,3**
Biodiversity	**1 / A**	**1 / A**	**1 / A**
Boundary conditions			
Demographics & long-term	**1,7**	**1,7**	**1,7**
Domestic supply	**2**	**2**	**2**
Constraints	**1**	**1**	**1**

EU-Reference scenario (EU-Ref)

The combination of lever positions under this scenario reproduces, as far as possible, the main sectoral assumptions and outputs of the EU-Reference scenario as detailed in [Capros et al 2016].

As an example, the following figure shows the graph of the greenhouse gas emissions under the EU-Reference scenario until 2050 in the Transition Pathway Explorer (TPE).

Figure 4: Greenhouse gas emissions of different sectors under the EU-Reference scenario

Technologies and fuel scenario (T&F)

In this scenario all levers of transport, buildings and manufacturing and power are set to level 4. These sectors are strongly affected by technology improvements.

In the transport sector the energy consumption of passenger vehicles decreases by 50 % for cars, 30 % for busses, 45 % for rail and 30 % for aviation. The energy consumption of the freight sector decreases by 50 % for trucks, 40 % for rail, 22 % for aviation and 40 % for shipping. Zero emission vehicles, which comprise battery electric vehicles and fuel cell electric vehicles, represent 100 % of new sales of passenger vehicles and trucks. Biofuels represent 100 % of total road, marine and aviation fuels. Figure 5 shows the passenger greenhouse gas emissions and the passenger energy demand for the T&F scenario.

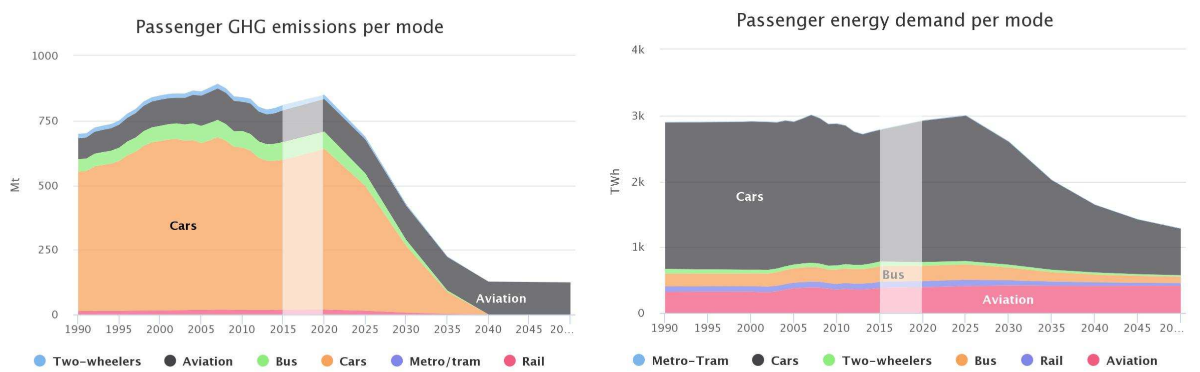


Figure 5: Passenger GHG emissions and passenger energy demand per mode in the technology & fuels scenario

In the buildings sector in the technology & fuels scenario 100 % of the building stock is renovated or new built and the energy demand of the buildings is decreased by 60 % in 2050. The share of district heating amounts for 16.5 % of residential heating and heating systems are 15 % more efficient. Appliances, like lighting or cooking devices are also more efficient – 'Label A' refrigerators for example have an efficiency of 0.0084 kWh/h. Figure 6 shows the greenhouse gas emissions and the energy demand per building use for the T&F scenario.

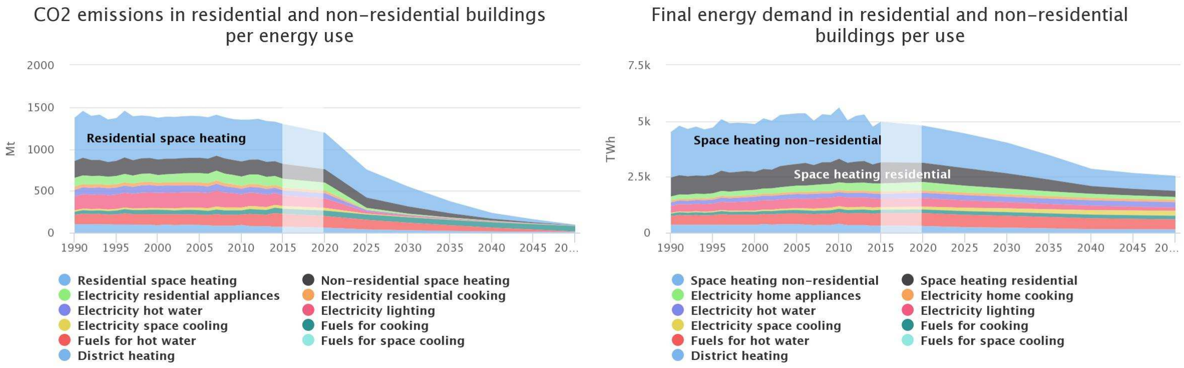


Figure 6: CO_2 emissions and final energy demand in residential and non-residential buildings per use in the technology & fuels scenario

The manufacturing sector shows improvement rates in material efficiency of 10 to 33 % due to smart product and material design, re-use of materials and circularity concepts of additive manufacturing. Lightweight-materials are substituting materials with a carbon-intensive production process by approximately 30 %. Changes in the production technologies take place – the iron and steel process is electrified or based on hydrogen coming from renewable energies, geopolymers make up to 20 % of total cement production – and cause savings of CO_2 of 35 %. The average share of secondary production routes, which describe recycling processes, of all technologies is 24 %. An increase in energy efficiency from 10 % (wood products) up to 35 % (food, beverages and tobacco) takes place. In energy-intensive sectors the range is between 13 % and 24 %. Savings of 38 % of CO_2 emissions can be reached by using the full potential of the electrification of heat, the use of zero-carbon hydrogen and a switch to sustainable biomass. Fossil fuels are reduced to a very small share. In this scenario up to 70 % of carbon emissions resulting from industrial processes of energy intensive sectors, such as the production of lime, cement, iron and steel, paper and ammonia, are captured. The total amount of carbon captured is used to produce fuels. Figure 7 shows the greenhouse gas emissions and the energy demand per manufactured material for the T&F scenario.

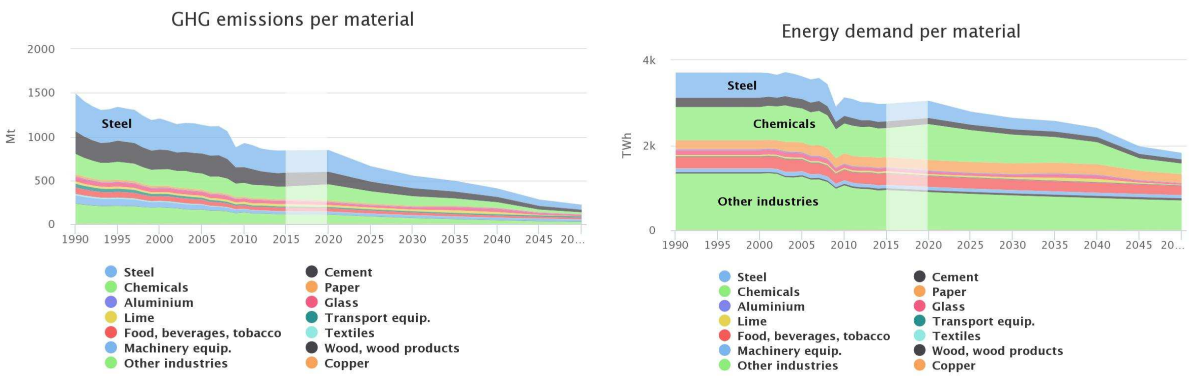
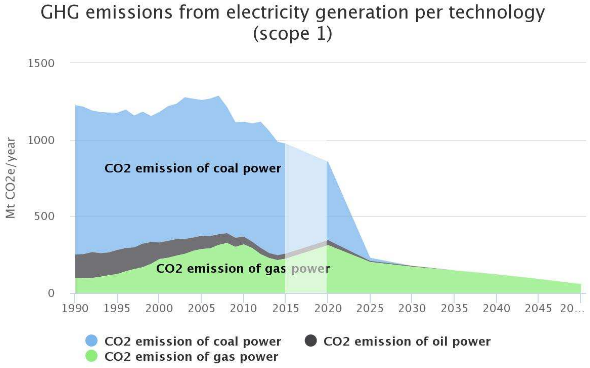


Figure 7: GHG emissions and energy demand per manufactured material in the technology & fuels scenario

The power sector shows a coal phase-out by 2025. Nuclear power plants are installed as planned, according to the different policies of European member states (phase-out, maintenance or expansion), with nuclear capacities in total decreasing to 76 % of the capacities installed in the base year. Carbon capture technologies are reducing the amount of CO_2 emissions of the power sector by 80 %. The installed capacities of renewable energies are enlarged – on- and offshore wind power capacities are exceeding 1500 GW in total, photovoltaics and concentrating solar power plants exceed 700 GW, hydropower, geothermal and marine capacities are fully exploited and exceed 300 GW. Storage technologies enable a balancing power potential of more than 5000 TWh by 2050.



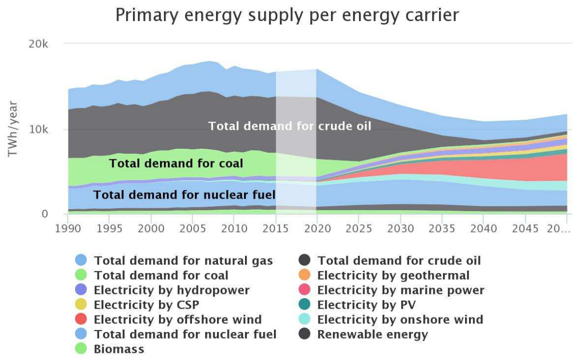


Figure 8: GHG emissions from electricity generation and primary energy supply per energy carrier in the technology & fuels scenario

Behaviour and tech scenario (B&T)

This scenario portraits Europe, where maximum efforts in key behaviours and technology and fuels are undertaken and where efforts in land and food evolve as in the EU-Reference scenario. Ambitions and measures from the technology and fuel scenario are applied and extended by changes in behaviour. Key behaviours are divided into the categories travel, homes, diet and consumption.

The travelling behaviours change by a decrease of 7.1 % concerning the travelled passenger distance per year. The share of travelling by car decreases from 78 % to 54 % in 2050 and the car occupancy increases from 1.6 to 2.6 people per car. Cars are running 900 % more km per year than in 2015, because they are used more efficiently through pooling and sharing concepts. Figure 9 shows the passenger greenhouse gas emissions and the passenger energy demand for the B&T scenario.

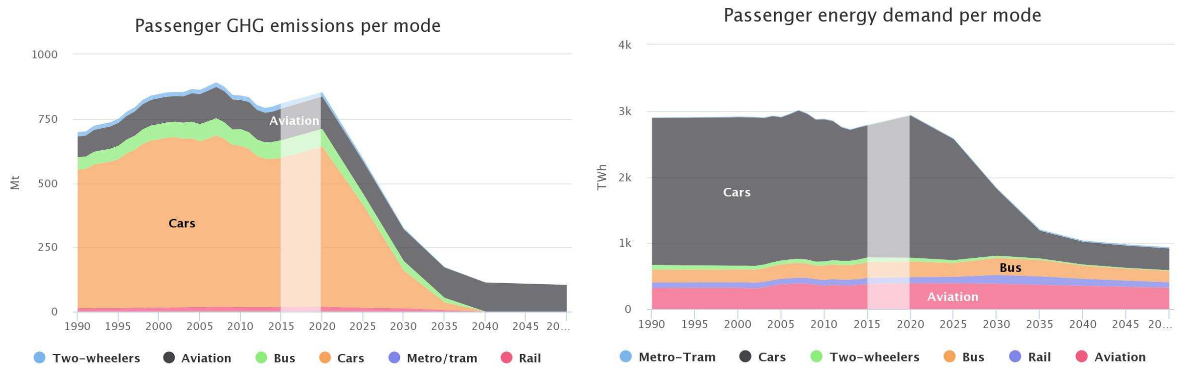


Figure 9: Passenger GHG emissions and passenger energy demand per mode in the behaviour & tech scenario

The living space per person is reduced to 37.4 m^2, a reduction of 19 % compared to 2015. The amount of cooled living space makes up 10.6 % in 2050 in level 4 – in 2015 approximately 10 % of the living space is cooled. The comfort temperature in summer and winter in 2015 is about 20 °C. In 2050 houses are cooled or heated exactly to the observed thermal-comfort temperature. The numbers of appliances in European households in 2050 are decreasing to 1.3 computers and 0.8 washing machines compared to 1.7 computers and 0.9 washing machines in 2015. The time of usage also decreases to 1.0 hour per capacity and day for TV and computers compared to 2.3 (TV) and 1.2 (PC) hours per day in 2015. Figure 10 shows the greenhouse gas emissions and the energy demand per building use for the B&T scenario.

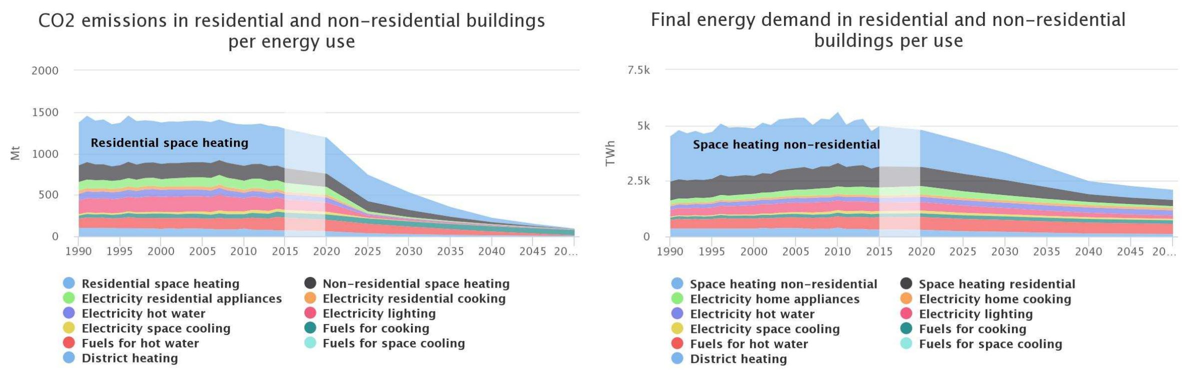


Figure 10: CO_2 emissions and final energy demand in residential and non-residential buildings per use in the behaviour & tech scenario

Diets change concerning calories consumed to sustain the body weight, from 2474 kcal/cap/day in 2015 to 2386 kcal/cap/day, which is a decrease of 3.7 %. The average meat calorie intake is reduced by 73 % to 92 kcal/cap/day, which goes in line with a flexitarian diet.

The behaviour concerning consumption in Europe changes to less use of plastic packaging (a decrease of 59 % compared to 2015) and longer lifetimes of appliances (computers are only replaced at 130 % of their lifetime). Food waste is reduced drastically by 75 % compared to 2015 and accounts for 130 kcal/cap/day. The freight transport demand in 2050 is decreased by 22%. Figure 11 shows the greenhouse gas emissions and the energy demand per manufactured material for the B&T scenario.

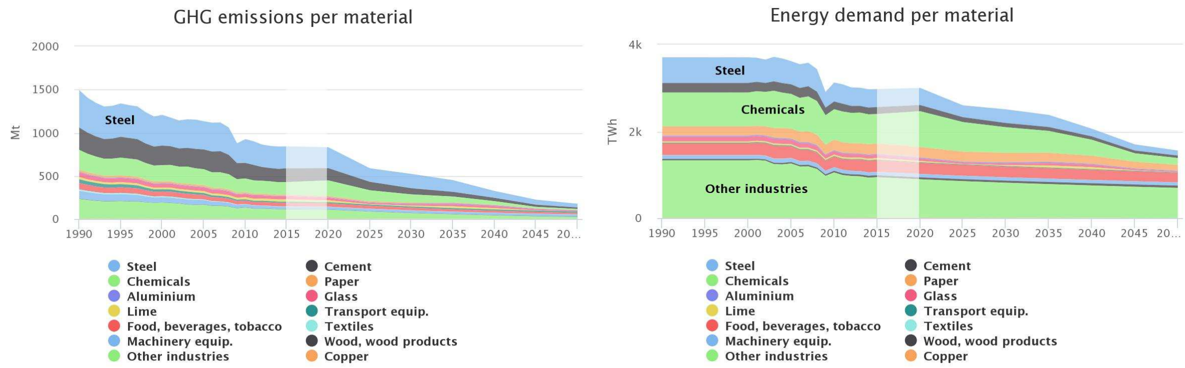


Figure 11: GHG emissions and energy demand per manufactured material in the behaviour & tech scenario

3.1 Greenhouse gas emissions

In the EU-Reference scenario, the greenhouse gas emissions of the four considered sectors decrease until 2050 compared to 2015 due to technology improvements.

The fossil fuels sector shows a reduction of GHG emissions of approximately 57 % in the EU-Ref scenario compared to 2015, while in the T&F and the B&T scenario emissions are even negative at -0.53 Mt (T&F) and -0.37 Mt (B&T) due to carbon capture and usage. The reductions in general are caused by a switch in the fuel mix from fossil fuels to renewable energies.

The GHG emissions from the electricity sector significantly decrease to reach 583.47 Mt in the EU-Ref scenario, which means a reduction of 43 % compared to 2015. In the T&F scenario (-89 %) and in the B&T scenario (-79 %) these emissions can be decreased even further compared to the EU-Ref scenario.

The emissions of the industry sector decrease in the technology and fuels scenario (-66 %) as well as in the behaviour and tech scenario (-72 %) compared to EU-Ref due to various optimisations e.g. more efficient production technologies, a higher share of the secondary production route and a higher material efficiency.

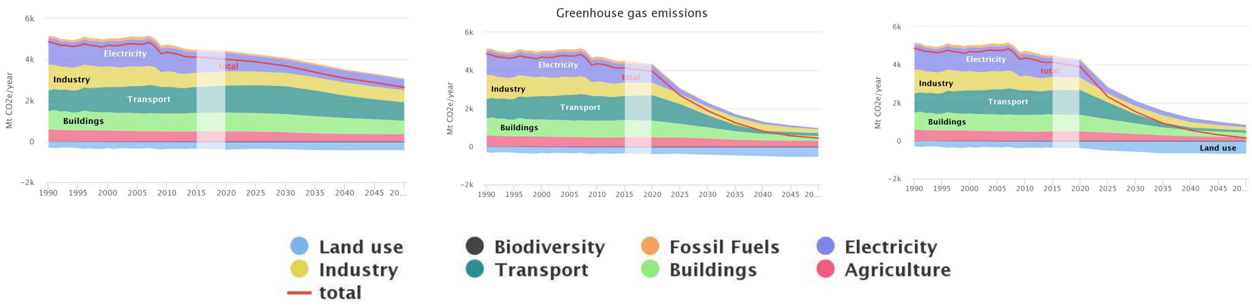
The emissions of the transport sector are also decreasing in the T&F (-83 %) and the B&T (-86 %) scenarios due to an increased electrification and up-take of electric vehicles in the transport sector (both passenger and freight), an increase in technology efficiency (approx. 45 %), and a high share of biofuels and synthetic fuels in the energy mix. The power generation is based on renewable energies (wind and PV), balancing strategies and storage capacities potentially exceed 5,000 TWh by 2050 on EU level.

The buildings sector shows very similar reductions of emissions in the two scenarios with approximately 86 % reduction compared to EU-Ref.

In agriculture emissions can be reduced by 14 % (T&F) and 50 % (B&T). The higher reduction effect in the behaviour & tech scenario can be explained by changes in diets, which have strong impacts on the agricultural sector.

The greenhouse gas emissions of the different scenarios are shown in Table 7.

Table 7: GHG emissions of the EU reference scenario, the technology & fuels scenario and the behavior & tech scenario



EU-Reference scenario:	***Technology & fuels scenario:***	***Behaviour & tech scenario:***
main sectoral assumptions and outputs of the EU-Reference scenario	*all levers of transport, buildings and manufacturing on level 4*	*maximum efforts in key behaviour as well as technology and fuels are undertaken*

Indicators	***Basis 2015***	***EU-Reference scenario 2050***	***Technology & fuels scenario 2050***	***Behaviour & tech scenario 2050***
GHG emissions [Mt]				
Fossil Fuels	116.31	50.05	-0.53	-0.37
rel to EU-Ref [%]		-	*-100*	*-100*
Electricity	1017.72	583.47	66.80	124.46
rel to EU-Ref [%]		-	*-89*	*-79*
Industry	699.63	601.51	202.06	165.77
rel to EU-Ref [%]		-	*-66*	*-72*
Transport	1265.93	899.47	155.05	123.04
rel to EU-Ref [%]		-	*-83*	*-86*
Buildings	901.45	592.87	85.59	80.87
rel to EU-Ref [%]		-	*-86*	*-86*
Agriculture	485.74	346.58	298.42	172.91
rel to EU-Ref [%]		-	*-14*	*-50*
Total	**4486.78**	**3073.95**	**807.39**	**666.68**
rel to EU-Ref [%]		**-**	***-74***	***-78***

In total, the greenhouse gas emissions are lower in the technology & fuels scenario and also in the behaviour & tech scenario compared to the EU-Reference scenario (T&F: -74 %; B&T: -78 %). An emission reduction of up to 3820 Mt CO_{2eq} can be reached.

The higher reduction in the behaviour & tech scenario can be explained by the strong effects of changes in living, travelling and consumption behaviours on the energy demand and therefore also on emissions. In the T&F scenario only technologies for mitigation are considered, the demand side remains constant.

3.2 Energy demand

In the EU-Reference scenario, the energy demand of all the considered sectors decreases until 2050 compared to 2015, except for the transport sector.

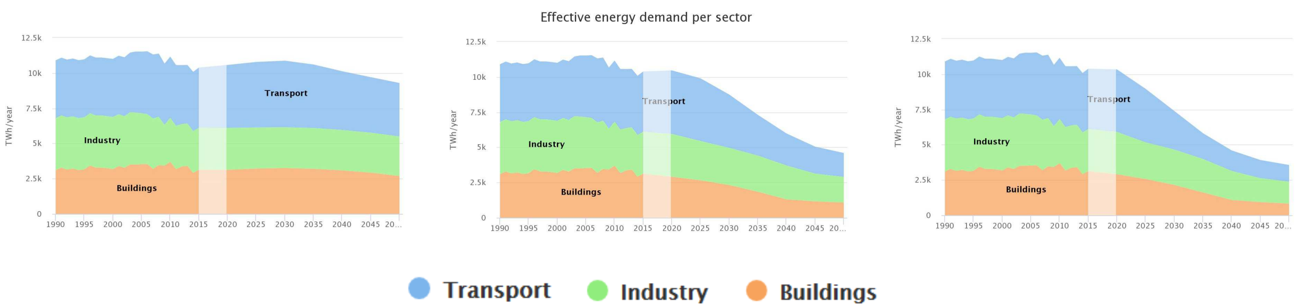
The industry sector shows small reductions in energy demand until 2050 in the two scenarios (T&F: -1.3 %; B&T: -13.6 %) compared to the EU-Reference scenario due to the usage of more energy efficient technologies.

The transport sector reduces its emissions in the T&F and B&T scenario by approximately 60% compared to EU-Ref. This development can be explained by different efficiency measures like changing modal shares of transport usage, vehicle efficiency or occupancy rates per vehicles.

In the building sector reductions of the energy demand of 20.5 % (T&F) and 37.5 % (B&T) can be reached due to restoration measures and highly efficient building envelopes.

The energy demands of the different scenarios are shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**Table 8.

Table 8: Energy demand of the EU reference scenario, the technology & fuels scenario and the behavior & tech scenario



EU-Reference scenario:	***Technology & fuels scenario:***	***Behaviour & tech scenario:***
main sectoral assumptions and outputs of the EU-Reference scenario	*all levers of transport, buildings and manufacturing on level 4*	*maximum efforts in key behaviour as well as technology and fuels are undertaken*

Indicators	***Basis 2015***	***EU-Reference scenario 2050***	***Technology & fuels scenario 2050***	***Behaviour & tech scenario 2050***
Energy demand [TWh]				
Industry	2974.76	2802.61	1819.47	1557.84
rel to EU-Ref [%]		-	-35	-44
Transport	4278.93	3799.16	1704.94	1183.64
rel to EU-Ref [%]		-	-55	-69
Buildings	3133.11	2689.67	1074.42	820.68
rel to EU-Ref [%]		-	-60	-69
Total	**10386.80**	**9291.44**	**4598.83**	**3562.16**
rel to EU-Ref [%]		**-**	**-51**	**-62**

In total, the energy demands of the technology & fuels scenario and the behaviour & tech scenario are by 51 % (T&F) and 62 % (B&T) lower than in the EU-Reference scenario.

3.3 Costs

It is important for the reader to understand the scope of each of the sectors considered in this chapter[5]. In general, in the technology and fuels scenario as well as in the behaviour and tech scenario the cumulated costs from 2020 to 2050 of all the considered sectors exceed those in the EU-Reference scenario, except for the transport sector, where the highest cumulative costs arise in the EU-Reference scenario.

The cumulative capital expenditures (CAPEX) from 2020 to 2050 of the electricity sector are significantly higher in the T&F (332 %) and in the B&T (352 %) scenario than they are in the EU-Ref scenario with a value of about 1,450 billion Euros. The operational expenditures (OPEX) of the T&F (2,375 bn EUR) and the B&T (2,401 bn EUR) scenario are of similar height and exceed the value of the EU-Ref scenario by about 160 %.

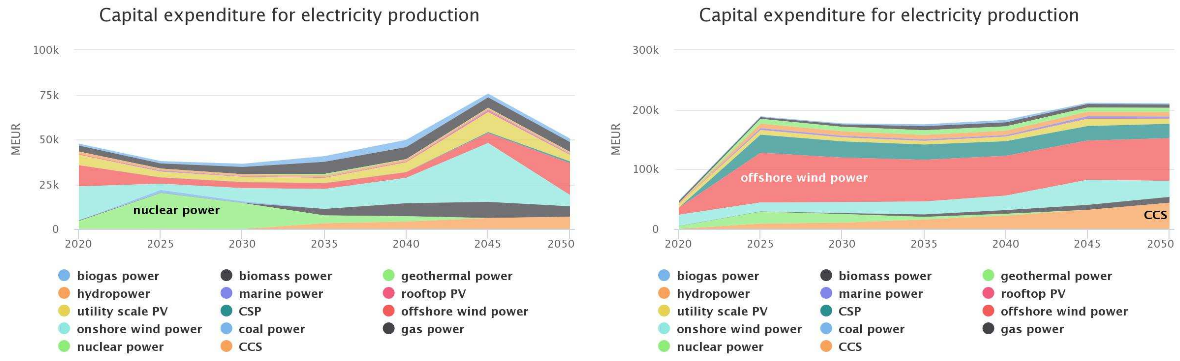


Figure 12: CAPEX for electricity production in the EU-Reference scenario (left) and in the behaviour & tech scenario (right)

The cumulative CAPEX from 2020 to 2050 of the transport sector decreases in the technology and fuels scenario (-17 %) as well as in the behaviour and tech scenario (-28 %) compared to the EU-Ref of about 29,952 bn EUR. This can be explained by a massive shift from the use of private (owned) cars to public transport as well as a reduced travel demand. Especially in cities, substantial efforts to stem the shift from cars, incentives for walking, cycling and public transport are made. Additional factors having a significant impact on lower total costs are the higher "occupancy rate" (62% higher than today) and a radical change in terms of car ownership and intensification of car sharing. The fuel costs can be reduced by 59 % in the T&F scenario and by 64 % in the B&T scenario compared to the EU-Ref scenario, where cumulated fuel costs amount to 9,807 bn EUR. Currently, no costs for transport infrastructure are considered in EUCalc.

[5] Refer to the scientific documentation on underlying assumptions and scope definition for each sector at http://www.european-calculator.eu/documentation/ (as for buildings, transport, supply = electricity production, and carbon capture, use and storage = CCUS)

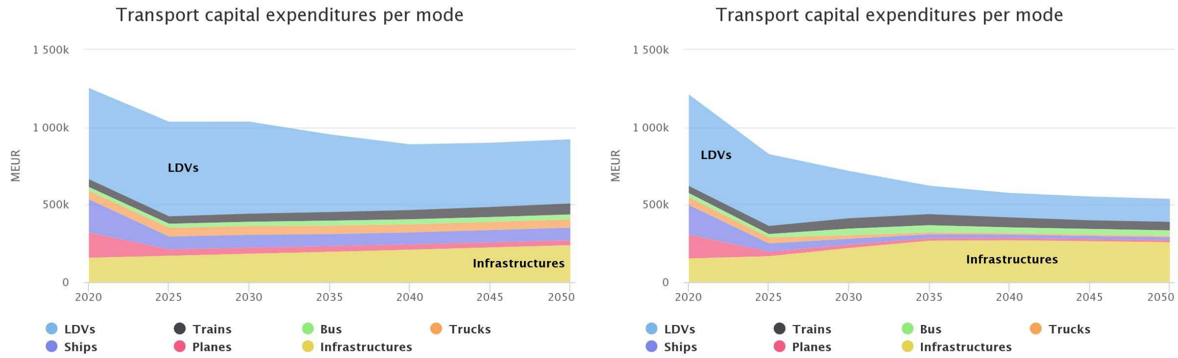


Figure 13: CAPEX of the transport sector per mode in the EU-Reference scenario (left) and in the behaviour & tech scenario (right)

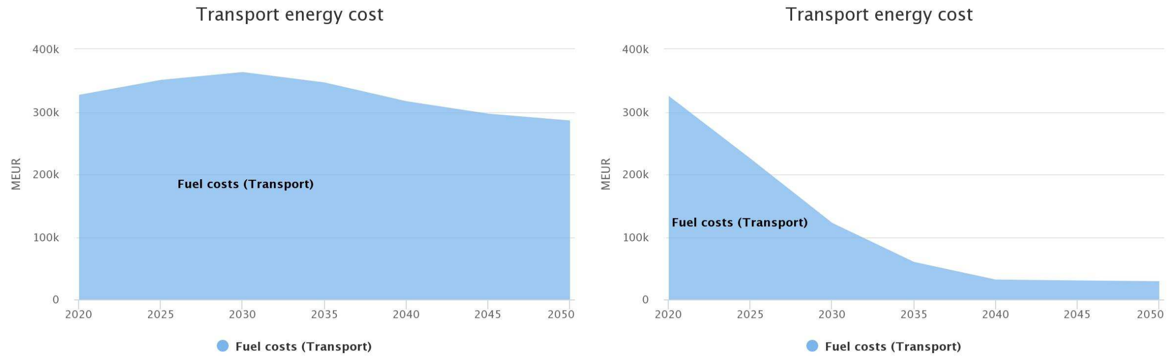


Figure 14: Fuel costs in the EU-Reference scenario (left) and in the behaviour & tech scenario (right)

The building sector shows higher cumulated investment costs for renovation in the T&F (288 %) and in the B&T (264 %) scenario compared to an EU-Reference scenario, where approximately 1,943 billion Euros are invested from 2020 to 2050. The higher investment costs primarily result from a greater depth (and quality) of renovation in these scenarios. An annual renovation rate of 3 % is considered, with 30 % medium and 70 % deep renovation depth. 70 % of all new buildings are highly energy efficient, meaning a specific energy need of 50 kWh/m^2.a or lower.

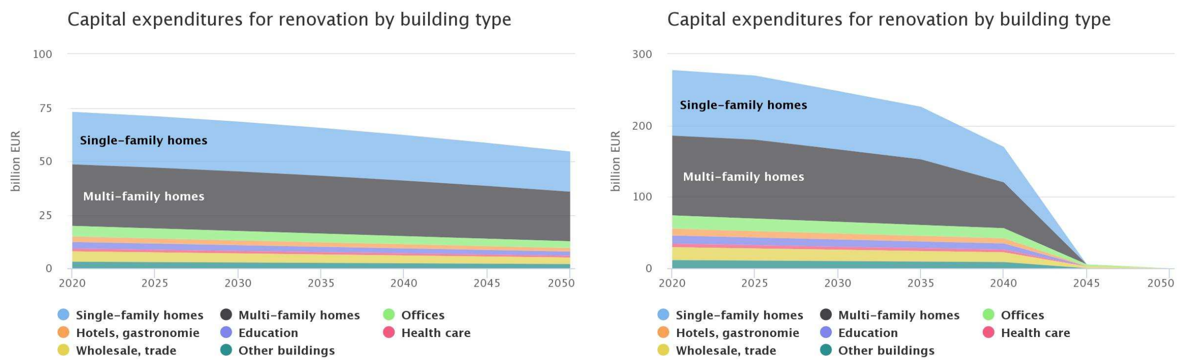


Figure 15: CAPEX of the buildings sector in the EU-Reference scenario (left) and in the behaviour & tech scenario (right)

The carbon capture and usage sector has significantly increased values of cumulated CAPEX in the T&F (91.5 bn EUR) and in the B&T (114 bn EUR) scenario compared to the EU-Ref scenario (5 bn EUR). In the EU-Reference scenario only small shares of carbon emissions are captured, while in the T&F and in the B&T scenarios the share of emissions captured goes up to 70 %.

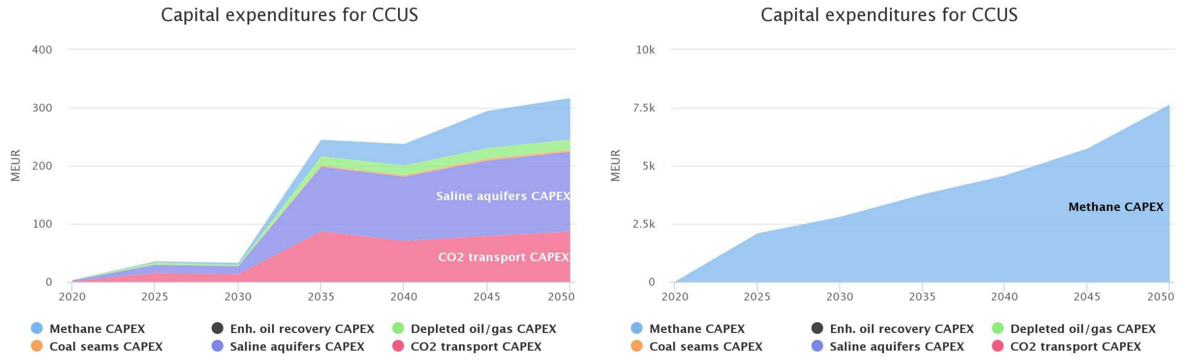


Figure 16: CAPEX of the CCUS sector in the EU-Reference scenario (left) and in the behaviour & tech scenario (right)

4 Policy recommendations

To achieve the decarbonisation in the energy sector and reach net-zero emissions, ambitious and urgent action is required:

- **Nurture technology development and innovation.** The emergence of breakthrough technologies in the manufacturing and production sector is vital for achieving a deep decarbonisation. From a technological point of view an increased share of novel technologies, i.e. the switch to renewable energy carriers, the electrification of processes in the heavy industry, as well as the further increase of energy efficiency in industrial processes could lead to a 33 % reduction of energy consumption in 2050 (compared to 1990). In terms of GHG emissions the decrease would be 74 %.
- **Time and speed of technological transitions.** A wide range of technological configurations are available in EUCalc. These need to be adapted to the different geographical, social, economic, institutional environments which characterize the different EU member countries (diet management; building envelopes; power generation). The availability of low carbon technologies at relatively low cost does not guarantee technology diffusion.
- **Better understand sectoral requirements.** Aviation, shipping, iron and steel, and chemical sectors, and to some degree cement, are globalised sectors and require global collaboration, standard-setting and/or agreements for deployment of innovative technology solutions. As a solution, industrial R&D and piloting of net-zero technologies would also ideally be pooled across technology/project portfolios and amongst firms and government entities to allow global collective learning and risk and cost diversification.
- **A wide range of technologies and sectors need to contribute**. Sectors with the little innovation progress toward decarbonisation are those where policy incentives and long-term perspectives are lacking. This includes heavy industry as well as freight transportation and aviation. A full decarbonisation of some industry sectors (and power/electricity) may not be achievable without the implementation of Carbon Capture Use and Storage (CCUS) technologies. For example, the electricity production will require gas power plants in most scenarios to guarantee the balancing between demand and supply due to the intermittency of renewables. In EUCalc, CCUS provides a higher granularity compared to existing models by offering insights on various carbon sources within industrial and power sectors with corresponding carbon capture technologies. It further points out possible carbon flow pathways via sequestration (both onshore and offshore) or utilization according to country-specific analysis based upon geological and geographical information, including the carbon transport and associated cost.
- **Learning curves and technology diffusion**. The goal of innovation is the large-scale deployment of low-carbon technologies. After some initial support, their scale-up should be without direct governmental financial support and incentives, irrespective of fossil fuel prices volatility. Learning curves operate on complex econometric models and assumptions based on the most reliable data available. The accuracy of cost curves depends on

many factors, among others, on ambition of decarbonisation policy (e.g. coal phase-out), emerging of breakthrough technologies (e.g. Carbon Capture Use and Storage), learning rates (as used for all RES in power generation) or future energy prices.

- **Establishing a systematic monitoring of innovation and technology development**. To better identify gaps and opportunities in low-carbon transitions, a rigorous tracking of investment on energy technology innovation is recommended. Measurement of key performance indicators (such as efficiency, deployment and cost reduction by learning rates) need to go beyond investments.
- **Stringent policy setting and research priorities**. Finally, while there are many emerging technologies under development, they are insufficiently represented in existing modelling frameworks and, consequently, in policy discussion. To transition these technologies to commercial usability in time to meet the objectives of the Paris Agreement we need a broad range of stringent innovation and market up-take policies from production to end-use. In addition, prioritised research into supporting institution, actors and their roles, and business models, integrated in a comprehensive policy framework.

5 References

Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. Climate Risk Management, 16, 183–194

Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S, Solano-Rodriquez B, Denis-Ryan A, Steiber S, Waisman H, Sartor O, Rahbar S, (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement, Journal of Cleaner Production, doi: 10.1016/j.jclepro.2018.03.107

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., et al. (2016). EU Reference Scenario 2016 – Energy, transport and GHG emissions - Trends to 2050, Publications Office of the European Union, Luxembourg: Publications Office of the European Union

Christensen, C., M. Raynor, and R. McDonald, (2015). What is Disruptive Innovation? Harvard Business Review, December, 44–53

Christensen, C. (1997). The Innovator's Dilemma, Harper Business, New York

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Kypreos, S. (2010). The economics of low stabilization: Model comparison of mitigation strategies and costs. The Energy Journal, 31(1), 11–48

Eurostat (2012). Eurostat-OECD Methodological Manual on Purchasing Power Parities, OECD, ISBN 978-92-64-18923-2

Geels, F.W., F. Berkhout, and D.P. van Vuuren, 2016a: Bridging analytical approaches for low-carbon transitions. Nature Climate Change, 6(6), 576–583

Green, J. and P. Newman, 2017b: Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy. Journal of Sustainable Finance & Investment, 7(2), 169–187

Grubb, M., Hourcade, J.-C., & Neuhoff, K. (2014). Planetary economics. Abingdon: Routledge

IEA (2012). IEA 2012. World Energy Outlook. In: AGENCY, I. E. (ed.).

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 [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press

IPCC. (2014b). Mitigation of climate change. Contribution of Working group III to the Fifth assessment report of the Intergovernmental Panel on climate change. Cambridge: Cambridge University Press

Jamasb, T, (2007). Technical Change Theory and Learning Curves: Patterns of Progress in Electricity Generation Technologies. The Energy Journal 28, 51–71

Kouvaritakis, N., Soria, A., & Isoard, S. (2000). Endogenous learning in world post-Kyoto scenarios: Applications of the POLES model under adaptive expectations. International Journal of Global Energy Issues, 14, 222–248

Kriegler, E., Weyant, J. P., Blanford, G. J., Krey, V., Clarke, L., Edmonds, J, Richels, R. (2014). The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change, 123(3-4), 353–367

MacKay, D.J.C., 2013: Could energy-intensive industries be powered by carbon-free electricity? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371

McDonald A, Schrattenholzer L. (2001). Learning rates for energy technologies. Energy policy, 29(4):255-261

Mercure, J.-F., Pollitt, H., Bassi, A. M., Viñuales, J. E., & Edwards, N. R. (2016b). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. Global Environmental Change, 37, 102–115

Nemet GF (2006). Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy policy, 34(17):3218-3232

Nijs W, Politis S, Castello PR, Sgobbi A, Thiel C, Zappon F, et al. (2015). Supporting the deployment of selected low-carbon technologies in Europe. Implications of techno-economic assumptions. An energy system perspective with the JRC-EU-TIMES model. Publication Office of the European Union

Nordhaus, W. D. (2010). Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences, 107(26), 11721–11726

Pindyck, R.S., 2017: The Use and Misuse of Models for Climate Policy. Review of Environmental Economics and Policy, 11(1), 100–114

Pollitt, H., & Mercure, J.-F. (2018). The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. Climate Policy, 18(2), 184–197

Poux, X., Aubert, P.-M., 2018. An agroecological Europe in 2050: multifunctional agriculture for healthy eating. IDDRI, Paris.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 C. Nature Climate Change, 5(6), 519–527

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change, 8, 325–332

Rubin, E.S., Azevedo, I., Jaramillo, P., Yeh, S., (2015). A review of learning rates for electricity supply technologies. Energy Policy 38, 198-218

Söderholm P, Sundqvist T. (2007). Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. Renewable energy, 32(15):2559-2578

Wilson, Charlie (2018). Disruptive low-carbon innovations, Energy Research & Social Science 37 (2018) 216-223

Wilson, C., Grubler, A., Bauer, N., Krey, V., & Riahi, K. (2013). Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? Climatic Change, 118(2), 381–395

Yeh, S., Rubin, E.S., (2012). A review of uncertainties in technology experience curves. Energy Econ, 34,762–771

Yu, W. and Clora, F. (2018). Deliverable 7.1: Formulation of baseline projections and documentation on modeling approach review – Public deliverable of the EUCalc project.