Industrial Innovation: Pathways to deep decarbonisation of Industry.

Part 2: Scenario analysis and pathways to deep decarbonisation

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A report submitted by ICF Consulting Services Limited and Fraunhofer Institute for Systems and Innovation Research (ISI)

to the European Commission, DG Climate Action

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Document Control

Document Title	Industrial Innovation | Part 2: Scenario analysis and pathways to deep decarbonisation
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Checked by	Ravi Kantamaneni
Date	20 March 2019

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Executive Summary

Achieving a carbon-neutral economy by the middle of this century in Europe requires a fundamental transformation of every economic sector including industry, which today is responsible for about 20% of total EU greenhouse gas (GHG) emissions. While the carbon-neutral target has been set, it is still being debated which pathway industry should take to achieve it and what contribution different technologies can make. In particular, the role of low-carbon process innovations that enable CO_2-neutral or low-carbon production has not been systematically researched within energy system models.

This report contains a detailed modelling analysis of transition pathways for energy-intensive industry sectors towards 80% and 95% reduction targets by 2050 compared to 1990. The bottom-up model FORECAST is used for the analysis. This model has a high technology and process resolution and can track technical change on a sub-sector and process level. At the same time, it contains the complete energy demand and GHG emissions of EU industry on a country level.

In order to make a comprehensive evaluation of the potential of so-called low-carbon process innovations, the FORECAST model is updated with technology data from the technology review in task 1[1]. These include innovations across all sectors and across the entire value chain proven to be feasible at pilot scale (technology readiness level 5).

In order to analyse alternative technology pathways, eight scenarios were defined as shown in the table below. The scenarios are distinguished with regard to level of ambition and mitigation options considered.

Table 0-1 General set-up of scenarios

	Scenario name	Main scenario philosophy
no innovations	1) REF	**Existing technologies** and **incremental improvements** in **energy efficiency** and **fuel switch** towards natural gas and some biomass. Slow continuation of past trends regarding recycling.
	2) BAT	Like scenario 1, but with complete diffusion of **today's best available technologies** with regard to energy efficiency where technically applicable. Fast development of recycling.
GHG reduction >80%. (ref. 1990) Including innovations with TRL >4	3a) CCS	**~80% Decarbonisation, focus on CCS**, but also use of other mitigation options (energy efficiency innovations & BAT).
	3b) Clean gas	**~80% Decarbonisation, focus on renewable hydrogen and synthetic methane**, but also use of other mitigation options (low-carbon process innovations & BAT).
	3c) Bioeconomy & circular economy	**~80% Decarbonisation, focus on biomass as fuel and feedstock.** Comprehensive implementation of **circular economy** beyond today's practices and downstream **material efficiency.** Also use of other mitigation options (low-carbon process innovations & BAT).
	3d) Electric	**~80% Decarbonisation, focus on direct use of electricity**, but also use of other mitigation options (low-carbon process innovations & BAT).
	4a) Mix 80%	**Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -80%, on a track towards deeper decarbonisation beyond 2050. No use of CCS and limited biomass.
	4b) Mix 95%	**Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -95%, CCS allowed, but limited biomass use.

The individual scenarios contain detailed assumptions on technology options by industry sub-sector including process efficiency improvement, fuel switching, CCS, Recycling & re-use and material efficiency & substitution. The assumptions are summarised in the following table.

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[1] See seperate report: Chan, Petithuguenin, Fleiter, Herbst, Arens, Stevenson (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis, ICF and Fraunhofer

Table 0-2 Overview of scenario definition by mitigation option

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	Carbon capture and storage (CCS)	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices, higher discount rate	No CCS	Current trends	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices		More recycled steel, glass, paper, aluminium	= 1) + clinker share reduction
3a) CCS	BAT + innovations > TRL4, e.g. • Near Net shape casting of steel • Oxygen depolarized cathode (chlorine) • Low-carbon cement types (excl. in 3a) • Re-carbonating cement/concrete • Innovative paper drying • Inert anodes & wettable cathodes for primary al.	Fuel switch driven by prices	CCS in steel, chem., cement, refineries	= 2)	= 2) + reduced demand for diesel/gasoline and heating oil due to transformation in buildings and transport
3b) Clean gas		clean gas, H-DR (80%), H2 feedstocks	No CCS		
3c) BioCycle (Bioeconomy & circular economy)		Biomass for energy and feedstock		=2) + More Recycling in steel, plastics, concrete, paper, glass plus more „re-use"	Strong increase in material efficiency along value chain in all sectors
3d) Electric		Electrolysis steel, H2 feedstock, electric furnaces, boilers, heat pumps (80%)		= 3a)	= 3a)
4a) Mix 80%		= 3d) + H-DR and plasma steel (80%)		= 3c) + less plastics recycling	= 3c), little less ambitious plus deep decarbonisation in buildings and transport
4b) Mix 95%		= 4a) + clean gas, 100% diffusion of innovations	CCS in cement, lime, refineries		

The results show that the greenhouse gas emissions of industry could be reduced by 80 to 95% by 2050 compared to 1990 (potential reduction beyond 95% was not analysed). The analysis also shows that today's policies and trends clearly fail to achieve a substantial reduction by 2050 (Scenario Ref: -45% by 2050 compared to 1990). Applying the best available technology (BAT) in energy efficiency and fuel switching without fundamental process switching does not achieve the required reduction either (-59% GHG reduction in BAT scenario).

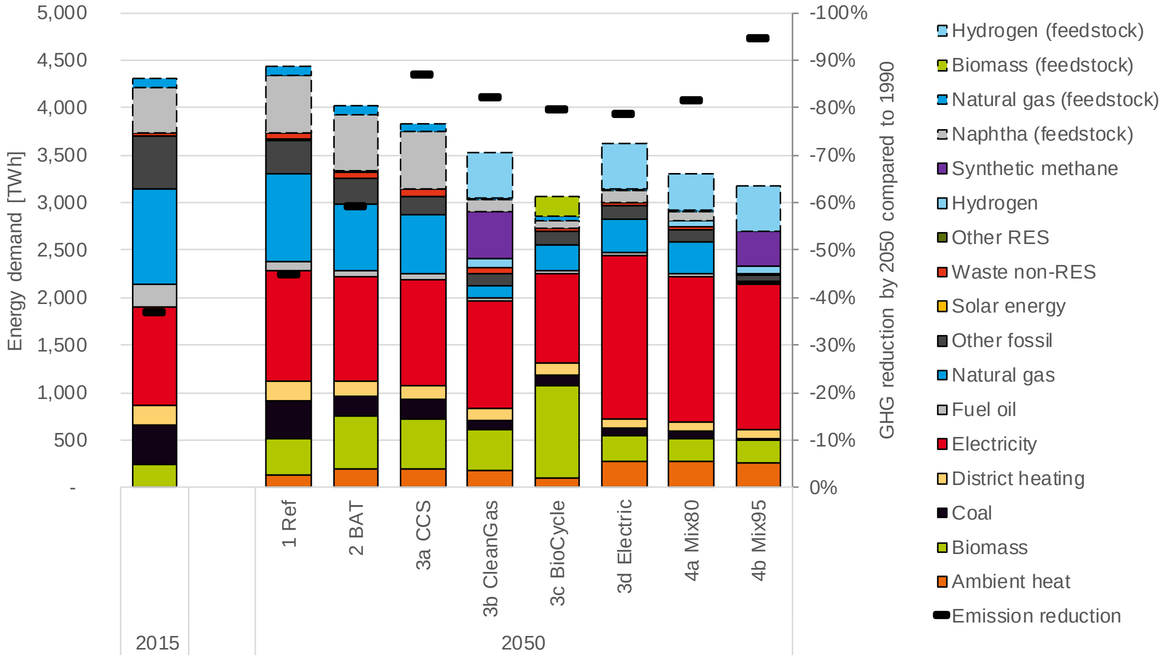
Four scenarios do achieve a GHG reduction of about 80% compared to 1990. These include additional mitigation options like innovative low-carbon production technologies (e.g. low-carbon cement, hydrogen-based chemicals, electricity-based steelmaking), a comprehensive circular economy, material efficiency along the value chain, CO_2-free secondary energy carriers (electricity, synthetic methane and hydrogen) and more biomass or CCS.

The results of the four technology-focused scenarios are as follows. A pathway focussing on clean gas (3b CleanGas) has high energy expenditures. Biomass (3c BioCycle) might be cheaper, but is simply not available in sufficient quantities. CCS (3a CCS) has reasonable costs but high uncertainty regarding market introduction and a high risk of lock-ins if the rest of the system does not change. Direct use of electricity requires substantial changes in the production system (e.g. electric kilns in all sectors) and leads to a high burden on the electricity sector (4d electric). These technology-focused scenarios might result in substantial lock-ins if additional GHG reduction is needed in the evolution towards CO_2 neutrality.

Combining several of the above mitigation options (hydrogen in chemicals and steel, innovative low-carbon cements, electrification, material efficiency and circular economy) achieves a reduction of about 82% (scenario 4a Mix80), excluding CCS and synthetic methane and limiting biomass consumption to today's levels. Such a pathway achieves the desired reductions and allows deeper decarbonisation beyond 2050 without substantial lock-ins and at lower costs than any of the four decarbonisation scenarios with a strong technology focus.

Adding additional mitigation options (CCS for the remaining process emissions, synthetic methane in the gas grid, early replacement of fossil-based steam generation and 100% process innovations) can achieve a 95% reduction by 2050 (scenario 4b Mix95). Compared to the 80% reduction, only relatively low additional investments are required, but the annual energy expenditures increase substantially, driven mainly by a stronger switch to synthetic methane, hydrogen and electricity. While we conclude that a reduction of 95% is possible using CCS and clean gas (and other options), the opposite conclusion "CCS and clean gas are both needed to achieve a reduction of at least 95%" cannot be drawn. Indeed, more analyses would be necessary to explore this statement.

Table 0-3 Total industrial energy demand by scenario and energy carrier incl. feedstocks and final energy for 2050 (EU-28)



Across all scenarios, the following conclusions can be drawn:

- In all scenarios, the additional costs compared to the reference scenario are dominated by energy expenditures and range widely across the scenarios. While scenarios using synthetic methane and hydrogen (3b CleanGas and 4b Mix95) show higher annual energy expenditures than the reference scenario, other scenarios show substantially lower energy expenditures, mainly due to material efficiency gains and comparatively low biomass prices (3c BioCycle).
- Energy efficiency is important in each transition pathway and a strong factor in reducing overall energy system costs as well as other impacts.
- A crucial factor is the rapid deployment of renewable energies to produce carbon-free electricity. This is critical because industry’s electricity consumption could increase strongly up to 2050 – doubling or even tripling depending on the scenario (if biomass and CCS are excluded as large-scale options).
- A GHG reduction of 80% and beyond compared to 1990 requires innovative technologies (TRL > 4).

To conclude, it is possible to achieve CO2 neutrality in industry by the middle of the century using technologies proven on a pilot and demo scale. However, this transformation will require a fundamental technology change that needs to be accompanied by a similar change in the policy and regulatory framework.

These changes include supporting the R&D and market introduction of innovative technologies (both directly and indirectly, e.g. by generating niche markets), revising economic incentives (CO2 price, taxing secondary energy carriers like electricity), introducing new incentives for sustainable value chains down to the final consumer and developing infrastructure (transport of CO2, electricity grid). In addition, changes are required in the construction industry to move it away from its reliance on GHG-intensive products. At the same time, it must be ensured that industrial production in Europe remains competitive.

As a result, policy makers will also need to look more closely at the demand side. This is necessary to unlock the remaining (high) potentials for material efficiency and circularity, and to design markets that generate demand for innovative products using low-carbon basic materials. This demand will allow companies to make large-scale investments in production plants, particularly in first-of-a-kind and subsequent plants.

Conclusions can also be drawn about the timing of actions. It was assumed that most low-carbon process innovations enter the market between 2025 and 2030, and diffuse rapidly and comprehensively thereafter. This implies that innovative technologies must be ready for the market between 2020 and 2030, infrastructure constructed and the regulatory framework adapted.

Finally, it should be noted that the analysis includes a set of assumptions that are by definition uncertain. These include, among others, assumptions regarding the future development of the economy, energy prices, and the future availability, cost and performance of new technologies. Data on (future) investments and costs are particularly very uncertain and challenging to collect for a broad set of technologies.

Introduction

The Paris Agreement[2] on climate change has the objective to keep global temperature increase to below 2°C and to pursue efforts to limit the increase to 1.5°C above pre-industrial levels. To achieve these targets, energy-intensive sectors will need to contribute significant emission reductions. The extent to which key EU industrial sectors can benefit and contribute to a climate-neutral future will depend on their ability to implement existing technologies, and the continued development and commercialisation of new products and breakthrough technologies.

This report is a deliverable of the service contract *Industrial Innovation and Decarbonising the EU Industry: a 2050 and beyond horizon*, it was undertaken by ICF, Fraunhofer ISI and DIW.

The purpose of this report is to use the findings from the report Industrial Innovations Part 1: Technology Analysis and conduct modelling scenarios for technology uptake pathways through 2050.

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[2] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

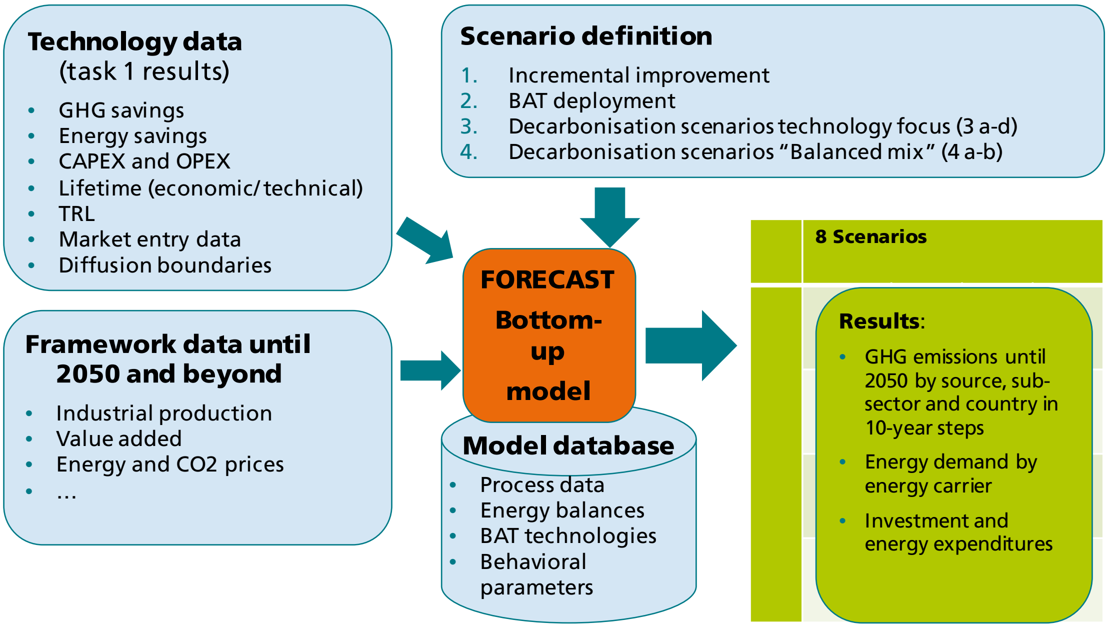
1 Model set-up and scenario definition

1.1 Overview of modelling approach

Scenarios have been developed for the future evolution of energy demand and greenhouse gas emissions of the EU's industry sector under varying assumptions with regards to technology innovation and diffusion. The scenarios show possible pathways to a low-carbon EU industrial sector. The scenarios are calculated using the bottom-up simulation model FORECAST.

Figure 1.1 provides an overview of the data and process flow for the scenario-based analysis. The underlying model simulations require a broad set of input data including technology assumptions (see *Part 1: Technology Analysis* report) and economic framework data like e.g. energy prices and industrial production. Additional data is contained in the FORECAST model database.

Figure 1.1 Overview of FORECAST model



Source: Fraunhofer ISI

For the analysis, four groups of scenarios are defined based on alternative assumptions regarding technology diffusion. These range from reference scenarios to deep decarbonisation scenarios.

The main result of the scenarios are the annual GHG emissions, broken down by the following dimensions:

- sub-sector (e.g. iron and steel) / total industry,
- source of GHG emissions: energy carrier and process emissions,
- country / EU-28,
- time points: 2015, 2020, 2030, 2040, 2050,
- scenario.

1.2 Methodology: The FORECAST model

The FORECAST model was developed by Fraunhofer ISI as a tool that can be used to support strategic decisions. Its main objective is to develop scenarios for the long-term development of energy demand and greenhouse gas emissions for the industry, services and household sectors of entire countries. The industry sector module of FORECAST considers a broad range of mitigation options combined with a high level of technological detail. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways and speed. The model further aims to integrate policies and considers changes in the socio-economic framework.

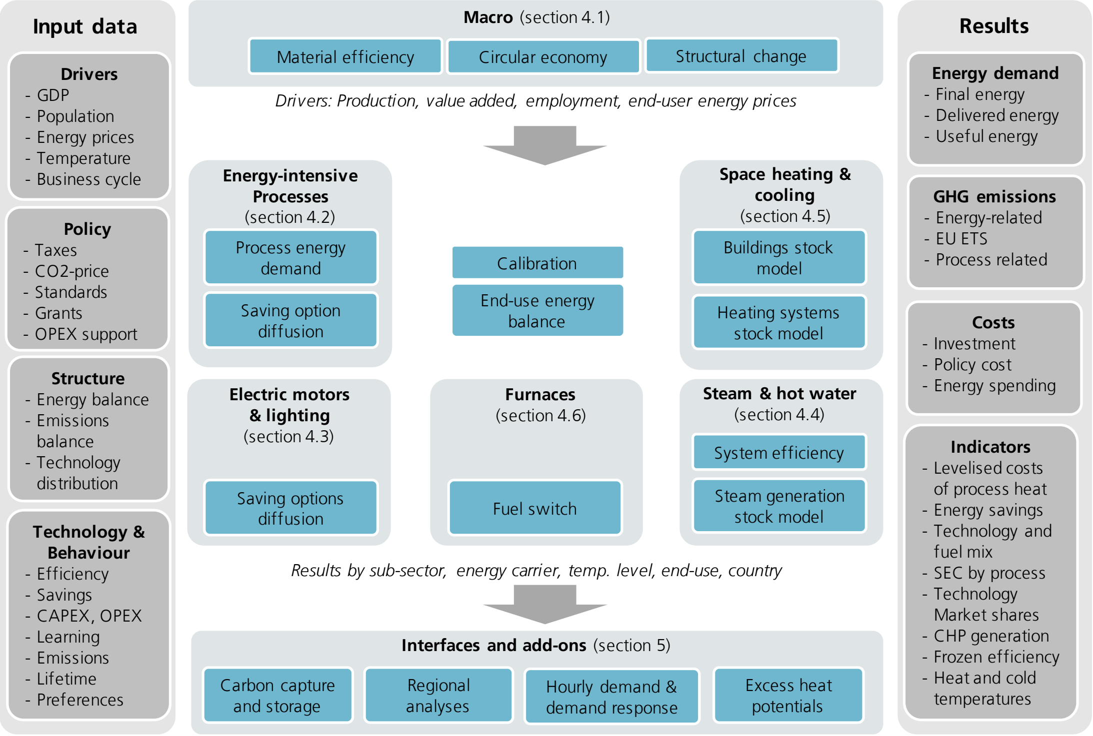
Scope

The model is designed to cover the entire industry sector including major energy-intensive processes with a high level of detail, but also many less energy-intensive sub-sectors and applications. The complete simulation is conducted on the level of individual sub-sectors like iron and steel. The scope of the model is defined by the energy balances and focuses on final energy, but also includes useful energy.

Structure

The structure of FORECAST also reflects the heterogeneity and data availability in the industry sector. Energy-intensive processes are considered explicitly, while other technologies and energy-using equipment are considered in the form of cross-cutting technologies modelled similarly across all sub-sectors. Accordingly, the model is divided into sub-models.

Figure 1.2 Overview of the FORECAST model: Input data, methods and sub-models (Fleiter et al. 2018)



t: tonnes, CAPEX: capital expenditures, OPEX: operating expenditures, ETS: Emissions Trading Scheme

Figure 1.2 shows the structure of FORECAST. Six sub-models are distinguished: *macro, energy-intensive processes, space heating and cooling, electric motors and lighting, furnaces, and steam and hot water*. Add-ons are also defined that can be applied after the calculation of the core model. Different approaches to simulate technology change are used in the various sub-models. These range from exogenous assumptions, diffusion curves to vintage stock models and discrete choice simulation.

Input parameters

Input data comprise the main drivers, policy parameters, structural information and a huge set of technology parameters including behavioural assumptions (see Figure 1.2). Most of these input parameters are long-term drivers of energy demand and GHG emissions, but business cycles and temperature (heating degree days) are included as well since these can affect energy demand in a one-year timeframe.

Database

The model requires a broad set of input data, which combines a variety of data sources. The model database was first developed in 2008 and since then has been continuously extended and improved.

Energy balances, employment, value added, and energy prices were calibrated to most recent EUROSTAT statistics whenever possible. When such data was not available (prices for certain energy carriers) IEA data was used to fill the gaps.

Industrial production on country and process level (e.g. electric steel production in Italy) is a major input. It was collected and annually updated via a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.).

Technology data (costs, efficiencies, age distribution etc.) are mostly not available from public data sources but need to be collected from literature or estimated via discussion with industry representatives.

The technology database is continuously being improved via individual research projects.

Policies and investment decisions

FORECAST allows the simulation of policy impacts. This includes price-based policies like subsidies or taxes, market-based instruments like the EU's Emissions Trading Scheme, but also standards like minimum energy performance standards for individual products. In a more aggregated form, policy instruments such as energy management or audits schemes are also considered by adjusting behaviour parameters.

The need to simulate the impact of policies also requires detailed representation of investment decisions in the model, because these are the main anchor for policy intervention. They include investments in new steam generation technology, energy efficiency improvements in existing installations, new electric motors but also investments in radically new production plants. Investment decisions in energy efficiency are modelled according to the real-life behaviour of companies, which often deviates from cost-optimal decisions under perfect knowledge and faces manifold barriers. Instead, investment decisions are myopic (based on costs and prices in a specific year) and simplified decision rules are applied (like payback time threshold).

Mitigation options and technology detail

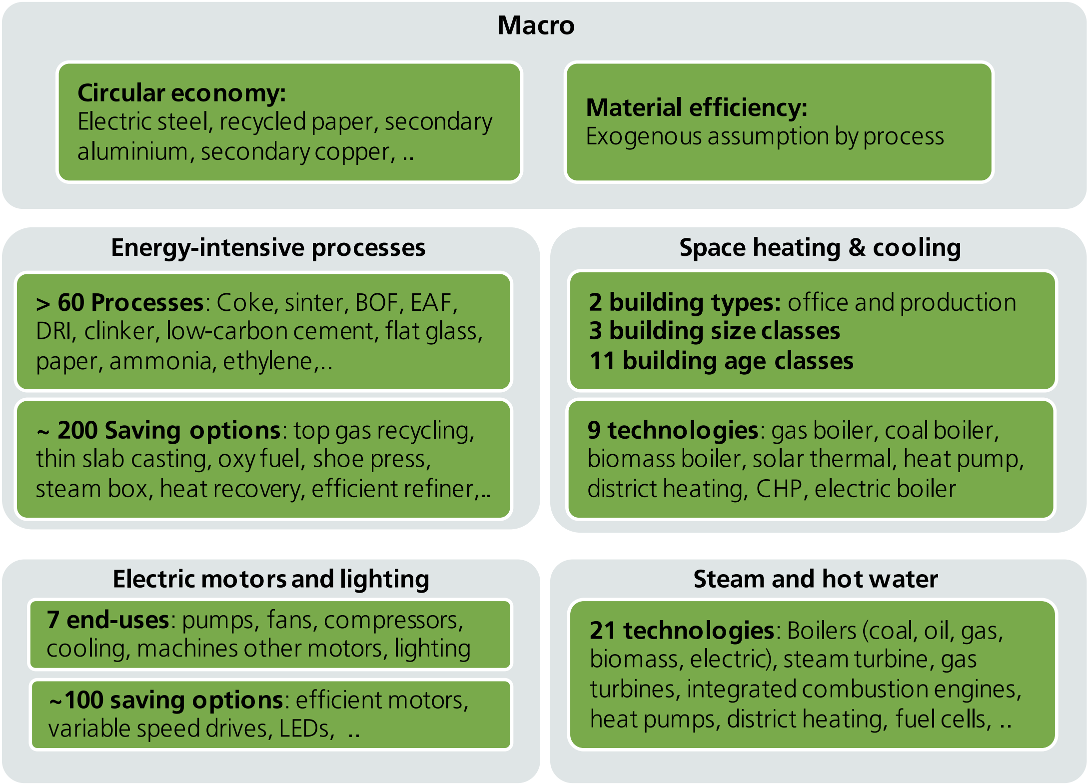
Achieving deep decarbonisation in 2050 requires a broad range of mitigation options. FORECAST considers the following mitigation options:

- energy efficiency (incremental and radical change),
- fuel switching (to renewable and low-carbon energy carriers),
- carbon capture and storage (CCS),
- circular economy and recycling,
- material efficiency and substitution down the value chain.

These mitigation options are included with a varying level of detail in the individual sub-models. Energy efficiency improvements and fuel switching are modelled endogenously on a technology level in a number of individual sub-models. Mitigation options like material efficiency and recycling are considered via exogenous assumptions that need to be incorporated in the scenario definition.

Figure 1.3 presents an overview of the technology detail included in FORECAST. For a complete list of all the technologies included in FORECAST, we refer to the supplementary online material.

Figure 1.3 Overview of technology detail in FORECAST by sub-model (Fleiter et al. 2018)



A more detailed description of the FORECAST model is attached in the annex and available in Fleiter et al. (2018).

1.3 Definition of scenarios

1.3.1 Overview

Long-term quantitative scenarios always contain a huge uncertainty and may not be taken as forecasts. The main conclusions can, however, be drawn by comparing alternative scenarios, which requires a structured and well-defined scenario set-up.

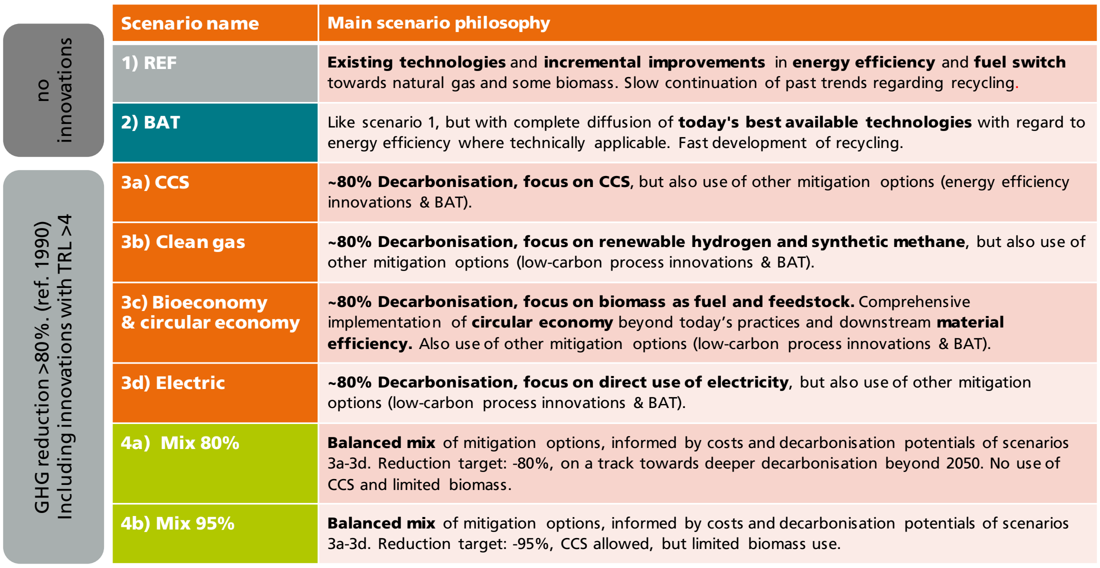
We explore 8 scenarios in 4 scenario groups differentiated by the type of mitigation options and the level of ambition in GHG mitigation:

- Scenario 1 Ref: incremental improvement as reference,
- Scenario 2 BAT: best available technologies,
- Scenarios 3a-d: decarbonisation scenarios with varying technology focuses including innovations (Technology Readiness level (TRL) > 4):
    a. CCS: focus on CCS,
    b. CleanGas: focus on clean gas (renewable hydrogen and synthetic methane),
    c. BioCycle: focus on bioeconomy & circular economy,
    d. Electric: focus on electrification.
- Scenarios 4a-b: “Balanced mix”/”Mix” of the above-mentioned supply/mitigation options with varying levels of ambition (~80%/~95%).

The decarbonisation scenarios by 2050 will achieve about 80% reduction in GHG emissions compared to 1990.

Table 1.1 shows a qualitative scenario philosophy as well as the main research question addressed by the scenario. *Scenarios 1 and 2* illustrate possible GHG emission pathways and mitigation potentials including only technologies that are available today. *Scenario 1* is the reference scenario to which the results of *scenarios 2-4* can be compared. In terms of diffusion of today's best available technologies (BAT), *scenario 2* is ambitious; still, it does not allow new technologies (i.e., TRL<9) to enter the market. *Scenarios 3a-d and 4a* aim for a GHG reduction of about 80% compared to 1990. *Scenario 4b* aims for almost CO2-neutrality by decreasing emissions by about 95% by 2050. Scenarios 1 and 2 are explorative. The GHG reduction is a result of available BAT technology potentials (scenario 2) and past trends (scenario 1).

Table 1.1 Proposal for general set-up of scenarios



	Scenario name	**Main scenario philosophy**
no innovations	**1) REF**	**Existing technologies** and **incremental improvements** in **energy efficiency** and **fuel switch** towards natural gas and some biomass. Slow continuation of past trends regarding recycling.
	2) BAT	Like scenario 1, but with complete diffusion of **today's best available technologies** with regard to energy efficiency where technically applicable. Fast development of recycling.
GHG reduction >80%. (ref. 1990) Including innovations with TRL >4	**3a) CCS**	**~80% Decarbonisation, focus on CCS**, but also use of other mitigation options (energy efficiency innovations & BAT).
	3b) Clean gas	**~80% Decarbonisation, focus on renewable hydrogen and synthetic methane**, but also use of other mitigation options (low-carbon process innovations & BAT).
	3c) Bioeconomy & circular economy	**~80% Decarbonisation, focus on biomass as fuel and feedstock.** Comprehensive implementation of **circular economy** beyond today’s practices and downstream **material efficiency.** Also use of other mitigation options (low-carbon process innovations & BAT).
	3d) Electric	**~80% Decarbonisation, focus on direct use of electricity**, but also use of other mitigation options (low-carbon process innovations & BAT).
	4a) Mix 80%	**Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -80%, on a track towards deeper decarbonisation beyond 2050. No use of CCS and limited biomass.
	4b) Mix 95%	**Balanced mix** of mitigation options, informed by costs and decarbonisation potentials of scenarios 3a-3d. Reduction target: -95%, CCS allowed, but limited biomass use.

The decarbonisation scenarios focusing on individual technology options represent a radical shift compared to today. They also require substantial changes in the regulatory and economic framework, built up of infrastructure or public perception.

Table 1.2 summarises some of these key underlying assumptions by scenario. These are, however, outside the system boundary of this analysis.

Table 1.2 Main underlying assumptions by scenario

Scenario	Major underlying assumptions / requirements
3a) CCS	Transport and storage infrastructure is constructed on a large-scale in Europe. Public and political acceptance of CCS is improved Economic and political framework allows implementation of CCS while maintaining international competitiveness for industries.
3b) CleanGas	Hydrogen and methane are produced on a large scale based on electrolysis and renewable electricity, The economic and political framework ensures competitiveness of H2 and other synthetic fuels compared to natural gas, large-scale deployment of RES-E technologies.
3c) BioCycle	Import of sustainable biomass as available, Cascading use of biomass (from product to fuel).
3d) Electric	Large-scale deployment of RES-E technologies, Market design allows extensive demand response and electricity prices are competitive compared to other fuels.

1.3.2 Definition by sub-sector

The following figures present key technology assumptions by sub-sector and type of mitigation option. The detailed characteristics of individual mitigation options and technologies are summarised in the *Part 1: Technology Analysis* report. For the discussion we distinguish five types of mitigation options:

- Integrated process improvement: Mainly energy efficiency improvement of existing production processes
- Fuel switch: Switching to low-carbon or carbon-free fuels
- CCS: Carbon capture and storage
- Recycling and re-use: Introduction of circular economy along the entire value chain
- Material efficiency and substitution: Efficient use of materials along the value chain and in the end-use sectors like the construction industry as well as substitution of CO2-intensive materials.

Figure 1.4 Technology assumptions for the iron and steel sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	No CCS	Slow increase according to current trends	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	No CCS	Faster increase EAF: Used for construction steel, others	= 1)
3a) CCS	Energy efficiency innovations > TRL4 • Near Net shape casting • Top-gas recycling	Fuel switch driven by prices	Post-combustion CCS	= 2)	=1)
3b) CleanGas		Hydrogen based direct reduction (H-DR) (80%), clean gas	No CCS		
3c) BioCycle (Bioeconomy & circular economy)		Biomass co-firing	No CCS	High quality EAF allows higher shares for e.g. flat steel products	Steel substitution by biomass-based products; Higher material efficiency, Reinforced steel
3d) Electric		Electrolysis steel (80%)	No CCS	= 2)	=1)
4a) Mix 80%		H-DR, plasma, electrolysis steel (80%)	No CCS	= 3c	= 3c
4b) Mix 95%		H-DR, plasma, electrolysis steel (100%)	No CCS	= 3c	= 3c

**80% and 100% refer to the overall crude steel production capacity of the primary route*

Figure 1.5 Technology assumptions for the chemical industry sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel/feedstock switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	-	Slow increase in plastics recycling	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	-	= 1)	= 1)
3a) CCS	Energy efficiency innovations > TRL4 • Chlorine: Oxygene depolarized cathode • Catalytic cracking of naphtha • Selective membranes	Fuel switch driven by prices	CCS for ammonia, ethylene, methanol	=1)	=1)
3b) CleanGas		Clean gas for fuel Feedstock: H_2 for ethylene, ammonia, methanol (80%)	CCU: H_2+CO_2 for methanol -> ethylene		
3c) BioCycle (Bioeconomy & circular economy)		Stronger switch to biomass and biogas; Feedstock: Methanol to ethylene from biomass (80%)	-	Ambitious plastics recycling;	Plastics replaced by bio products; bio-based plastics; reduce fertiliser demand; material efficiency
3d) Electric		Electric boilers Feedstock: H_2 for ethylene, ammonia, methanol (80%)	-	=3a)	=3a)
4a) Mix 80%				=3c, but less ambitious	=3c, but less ambitious
4b) Mix 95%		Electric boilers, clean gas Feedstock: H_2 for ethylene, ammonia, methanol (100%)			

**80% and 100% refer to the overall production capacity of ethylene, ammonia and methanol*

Figure 1.6 Technology assumptions for the cement and lime sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	No CCS	Concrete recycling only for low-grade use	Slow reduction in clinker share
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	No CCS	= 1)	Ambitious reduction in clinker share
3a) CCS	= 2)	Fuel switch driven by prices	Post-combustion CCS; lime direct seperation	= 1)	= 2)
3b) CleanGas	Process innovations > TRL4 • Low-carbon cement types • Re-carbonating cement/concrete	Fuel switch driven by prices; clean gas	No CCS		
3c) BioCycle (Bioeconomy & circular economy)		Focus biomass and RES-waste	No CCS	Concrete recycling for use in new cement and re-use	Efficient concrete use; Concrete substitutes based on biomass; carbon reinforced concrete
3d) Electric		Electric clinker kiln	No CCS	= 1)	= 2)
4a) Mix 80%		Fuel switch driven by prices	No CCS	=3c	=3c
4b) Mix 95%		Clean gas	CCS for lime and conventional clinker	=3c	=3c

Figure 1.7 Technology assumptions for the glass and ceramics sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	-	Slow increase in recycling	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	-	Faster increase in container glass recycling	= 1)
3a) CCS	Energy efficiency innovations > TRL4 • Oxy-fuel • Excess heat use	Fuel switch driven by prices	Ceramics: No CCS Glass: late post-combustion CCS	= 2) + Increase in flat glass recycling	= 1)
3b) CleanGas		Clean gas to replace natural gas	-		
3c) BioCycle (Bioeconomy & circular economy)		Switch to biomass and biogas	-	Re-use of glass	More efficient glass use
3d) Electric		Electric furnaces to replace gas	-	= 2) +Increase in flat glass recycling	= 1)
4a) Mix 80%		Electric furnaces	-	=3c	=3c
4b) Mix 95%		Electric furnaces, Clean gas	-	=3c	=3c

Figure 1.8 Technology assumptions for the pulp and paper sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	-	Slow improvement in recycling	Slow improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	-	Ambitious recycling	= 1)
3a) CCS	Energy efficiency innovations > TRL4 • Enzymatic pre-treatment • Innovative paper drying • Black liquor gasification	Fuel switch driven by prices	Late CCS by big emitters	= 2)	= 1)
3b) CleanGas		Fuel switch driven by prices; clean gas	-		
3c) BioCycle **(Bioeconomy & circular economy)**		Biomass focus	-	Maximum paper recycling and more re-use	Wood fibre products replace plastics Improved material efficiency
3d) Electric		Focus electric boilers and heat pumps	-	= 2)	= 1)
4a) Mix 80%			-	=3c	=3c
4b) Mix 95%		Electricity, clean gas	-	=3c	=3c

Figure 1.9 Technology assumptions for the non-ferrous metals sub-sector

Mitigation option / Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	-	Slow increase according to current trends	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	-	Faster increase in recycling	= 1)
3a) CCS	Energy efficiency innovations > TRL4 • Hal4E • Inert anodes & wettable cathodes • Magnetic billet heating	Fuel switch driven by prices	-	= 1)	=1)
3b) CleanGas		Clean gas	-		
3c) BioCycle (Bioeconomy & circular economy)		Biomass and biogas	-	Increased recycling by higher quality in sorting	=1)
3d) Electric		Induction heating in foundries; electric furnaces	-	= 1)	=1)
4a) Mix 80%		Focus electricity	-	=3c	=3c
4b) Mix 95%		Focus electricity, clean gas	-	=3c	=3c

Figure 1.10 Technology assumptions for the refineries sub-sector

Mitigation option Scenario name	Integrated process improvement	Fuel switch	CCS	Recycling and re-use	Material efficiency and substitution
1) REF	Incremental efficiency improvements	Fuel switch driven by prices	-	No substantial improvement	No substantial improvement
2) BAT	Fast deployment of BAT efficiency	Fuel switch driven by prices	-	= 1)	= 1)
3a) CCS	Energy efficiency innovations > TRL4	Faster switch to natural gas	Post-combustion CCS Oxy-fuel CCS	= 1)	Electric vehicles reduce demand for diesel/gasoline
3b) CleanGas		Clean gas	-		= 3a) but Blue Fuel synthesis to capture CO2 (CCU) instead of EVs
3c) BioCycle (Bioeconomy & circular economy)		Columns heated by biofuels Feedstock: biomass Biocrude	-		=3a) but biofuels instead of electric vehicles
3d) Electric		Column heated through electricity	-		= 3a)
4a) Mix 80%		Focus electricity	-		= 3a)
4b) Mix 95%		Electricity, clean gas	CCS		Faster demand-side transformation

2 Assumptions and input data

2.1 Economic development

The macroeconomic framework data for the model-based analysis stem from the European Reference Scenario 2016 (European Commission 2016) and remain the same across all scenarios. The reason for this assumption is the better comparability of changes in policy parameters and assumptions between scenarios. The same applies to the assumptions on the wholesale price development of fossil fuels (coal, gas, oil), which are also based on the European Reference Scenario 2016 and are kept constant between the scenarios. Other important assumptions like the development of industrial production or CO2-prices are the results of the project team's assumptions, analyses and estimates.

The macroeconomic framework data shown in Table 2.1 indicate that industry is expected to continue growing until 2050. However, energy-intensive industries like the iron and steel industry and non-ferrous metals grow below the industrial average (<1% p.a.) in the scenarios. An exception is the chemical industry - which is growing at a slightly above average rate - and the non-metallic minerals sector (including cement production). Stronger growth is to be expected in non-energy-intensive sectors like engineering (including vehicle construction) and the food industry, which reflects a structural change in industry towards less-energy-intensive sub-sectors.

Table 2.1 Macroeconomic framework assumptions based on EU Ref 2016

EU-28	CAGR '15-'50
Population (in million)	0.1 %
Gross domestic product (GDP) (in 000 m€13)	1.5 %
Gross value added (GVA) industry (in 000 m€13):	1.0 %
Iron and steel	0.3 %
Non-ferrous metals	0.5 %
Chemicals	1.1 %
Non-metallic minerals	0.9 %
Pulp and paper	0.8 %
Food, drink, tobacco	1.1 %
Engineering	1.3 %
Other	0.9 %

Source: European Commission 2016

2.2 Overview of policy assumptions

Policy instruments are required to make the transformation from the reference scenario to the decarbonisation scenarios. These instruments are additional to the instruments implemented in today's policy mix. Some of the needed policy instruments are modeled endogenously (e.g. CO2 price effect on steam generation) while others are integrated into the scenarios more exogenously (e.g. introduction of low-carbon process innovations). The policies considered in the individual scenarios include the following:

- **Overcoming barriers to energy efficiency**: Energy efficiency investments are made on the basis of payback period, which reflects real investment decisions in this field. Today, often thresholds of 2-3 years payback time are required by companies to invest in energy-efficiency measures - if the potential measures are identified. This high level of barriers to investment is reflected in the assumptions of scenario 1 Ref. In the scenarios 2-4b it is assumed that barriers are overcome and also long payback times of up to 10 years are accepted for investment.
- **CO2 price**: A CO2 price is assumed for the ETS sector in line with the EU Reference Scenario 2016 for scenario 1 Ref. It is increased to 200 euros/t CO2 in scenarios 2-4a by 2050. An even 10 years earlier increase is assumed for scenario 4a Mix95, which arrives at 200 euros/t CO2 in 2040 and then remain on that level (see section 2.4.4). In addition to the EU ETS allowance price, the decarbonisation scenarios 3a to 4b assume that the ETS price is also included for the industries in the non-ETS sector, which introduces incentives for fuel switching.
- **Reducing (implicit) discount rates**: Discount rates are less important in this modeling framework than they are in optimisation models. Even more, energy efficiency investments are decided on the basis of payback period (see above) and radically new production processes are introduced exogenously. However, discount rates are important for investments in steam and hot water supply. Here the scenario 1 Ref assumes 20%, while scenarios 2-4b assume a low discount rate of 5% reflecting only costs of finance and no remaining barriers.
  In addition to discount rates, it is also assumed in the scenario 1 Ref that in 30% of all re-investment cases, companies choose the same technology again that is replaced. In scenarios 2-4b a rational investment decision based on total cost of ownership is assumed for 100% of re-investment decisions.
- **Financial support for renewable heat supply**: Scenarios 3c to 4b use additional financial support to increase the share of renewable-based heating solutions starting in 2020. Scenario 3c BioCycle supports biomass and district heating for process heat generation with about 20 euros/MWh produced. In scenarios 3d Electric, 4a Mix80 and 4b Mix95 only power-to-heat is financially supported including about 20 euros/MWh for heat pumps and about 100 euros/MWh for direct use of electricity in electric steam boilers. Financial support for hydrogen and synthetic methane is not separately modelled, because the introduction of both energy carriers is assumed exogenously. However, if it were to be modelled endogenously, the support would need to be at least as high as for electricity.
- **Early replacement of fossil technologies**: Across all scenarios and technologies we assume that the turnover rate of the technology stock is not altered and that technologies are not replacement before the end of their technical lifetime, with one exception: Steam generation in the scenario 4b Mix95. Here, old fossil technologies are replaced in the time period 2040-50, because else a small but important share of coal-fired boilers and steam turbines would still persist in 2050. An alternative to "early replacement" would be the introduction of a ban on fossil generation technologies by 2040 in the scenario 4b Mix95 in order to arrive at close to CO2 neutrality in 2050.

- **R&D and market introduction of new low-carbon production processes**: Market introduction of e.g. low-carbon cement or hydrogen-based steelmaking are assumed exogenously via the production output by process (see section 2.3).
- **Material efficiency and circular economy policies**: Due to the huge diversity in this sector, policies are not endogenously modelled but improvements in material efficiency and circular economy are assumed exogenously via means of lower production output on process level and switch to recycling-based production routes (see section 2.3).

2.3 Industrial production: material efficiency, circular economy and process innovations

The future development of production by process (in physical units) is a central driver of energy consumption and GHG emissions in the (basic materials) industry, in particular as production is much more closely related to energy demand than more general economic drivers such as the value added. The model considers more than 80 individual processes and their respective products and semi-finished products measured in tonnes of output. The future physical production projections discussed below enter the simulation model as exogenous inputs based on historic production trends as well as assumptions on the future developments of material efficiency improvements, material substitution, possible circular economy developments, as well as assumptions on the future downstream demand for products, saturation effects and structural changes within industrial sub-sectors. The switch to low-carbon process innovations like low-carbon cement or hydrogen-based steelmaking is also exogenously assumed on the basis of production output by process and described in this chapter by sub-sector.

2.3.1 Iron and steel industry

In the Ref scenario crude steel production is expected to more or less stagnate in the EU-28 (see Table 2.2), which also means there are no additional improvements in material efficiency and material substitution. However, according to past trends, a slow increase of the secondary production route takes place. In scenario 2 BAT a faster increase of electric arc furnace (EAF) steel production (which is much less energy-intensive than basic oxygen furnace BOF production) is expected. The overall EU-28 EAF share in crude steel production increases from 40% in 2015 to 42% in 2050 in the Ref scenario and to 67% in 2050 in the scenarios 2 BAT, 3a CCS, 3b CleanGas and 3d Electric. In these scenarios, remaining EAF potentials will be exploited among the different EU Member States, considering future scrap availability as well as first improvements in scrap collection/quality (e.g. disassembling with more care to avoid alloy mixing and to maintain larger components), which lead to a broader range of applications for EAF steel compared to today (Allwood 2016).

In scenario 3c BioCycle, future demand for steel decreases due to:

- reduced losses (e.g. near-net-shape casting),
- material efficiency improvements (e.g. high-performance steel, less over-dimensioning in construction),
- material substitution (e.g. use of aluminium, carbon fibre in the automotive sector, steel substitution by biomass-based products in construction) and

- changes in use behaviour (e.g. more-intense-use (e.g. car sharing), increasing average time of usage) and
- re-use (e.g. re-use of large I-beams in construction) (Allwood 2013; Herbst 2017).

Compared to the Ref scenario future crude steel production decreases by 10% in 2050 from 169 Mt (1 Ref) to 153 Mt (3c BioCycle). In addition, it is assumed that production of high quality EAF steel has reached industrial scale and can be used in high-performance steel segments (e.g. aviation and automotive) resulting in a share of 77% EAF steel of total steel production in 2050. This is supported by assumptions on scrap availability, which is expected to increase further in the future, taking into account the steel consumption of recent decades and assuming that there will be no significant changes in foreign trade in scrap. Combined with innovative collection and sorting technologies (e.g. robotic cutting and handling or laser induced breakdown spectroscopy to allow automated sifting of mixed waste streams; Allwood (2016)) a further increase in the share of electric steel production also to substitute higher-quality steelmaking appears possible. Other options supporting this assumption would be: purification of molten scrap steel (e.g. sulphide matte, chloride slagging, preferential melting), new processes (e.g. belt casting), new product design reducing the use of unwanted elements or enabling easier separation (Allwood 2016).

In the CleanGas and the Electric scenario two innovative production technologies substituting conventional primary production enter the market: hydrogen-based direct reduction (DR RES H2+EAF) and purely electricity-based direct reduction (DR electrolysis) (see Figure 2.1). In both scenarios it is assumed that 80% of conventional blast furnace production in 2050 is substituted with the respective technology (DR RES H2+EAF or DR electrolysis; see *Part 1: Technology Analysis* report for decarbonisation technology descriptions). In the Balanced mix scenarios (4a and 4b) all categories of mitigation options for the steel industry are used, resulting in lower production compared to the Ref scenario, a high share of EAF steel production as well as the use of innovative production technologies (see Figure 2.1).

Figure 2.1 EU-28 crude steel production by scenario and process in 2050

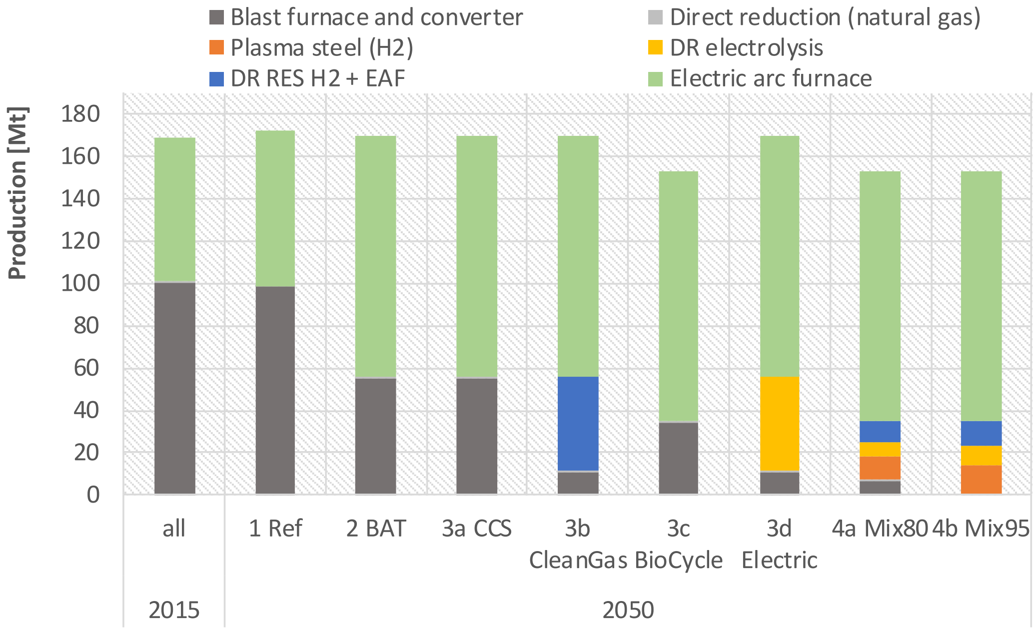


Table 2.2 EU-28 crude steel production by scenario in Mt (2015-2050); absolute %-change compared 2015

	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref	169	174	178	177	172	2%
2 BAT	167	172	175	174	170	2%
3a CCS	167	172	175	174	170	2%
3b CleanGas	167	172	175	174	170	2%
3c BioCycle	167	169	168	162	153	-8%
3d Electric	167	172	175	174	170	2%
4a Mix80	167	169	168	162	153	-8%
4b Mix95	167	169	168	162	153	-8%

2.3.2 Non-metallic minerals industry

The non-metallic minerals sector consists of a variety of different products (e.g. glass, ceramics, cement, bricks, lime, and gypsum).

Cement

Industrial CO2 emissions in this sector are dominated by the production of cement clinker (0.52 tonnes of process-related CO2-emissions per tonne of clinker). In the 1 Ref, 2 BAT, 3a CCS, 3b CleanGas and 3d Electric scenario total cement production increase by 23% until 2050 compared to 2015 (see Table 2.3). This increase mainly takes place in the period from 2015 to 2030 driven by developments in the construction sector (e.g. renovation activities and investments in infrastructure; European Commission 2016). Consequently, clinker production also increases in these scenarios. However, clinker shares vary between scenarios. Having a more or less constant clinker share in the reference case, the clinker share decreases in the 2 BAT and 3a CCS scenario: e.g. for the case of Germany from 0.7 in 2015 to 0.6 (-14%) in 2050.

In the 3b CleanGas and the 3d Electric scenario it is assumed that new cements – less-carbon cements -30%, low-carbon cements -50% to -70% as well as re-carbonating cement products – enter the market this also leads to reduced clinker production. Such new binders reduce both process-related (less/no decarbonation) and energy-related emissions (lower process temperatures, lower demand for thermal energy) compared to conventional Portland cement production. In the two scenarios innovative cement types substitute 50% of total cement production by 2050, which is about the entire Portland cement production (see Table 2.3).

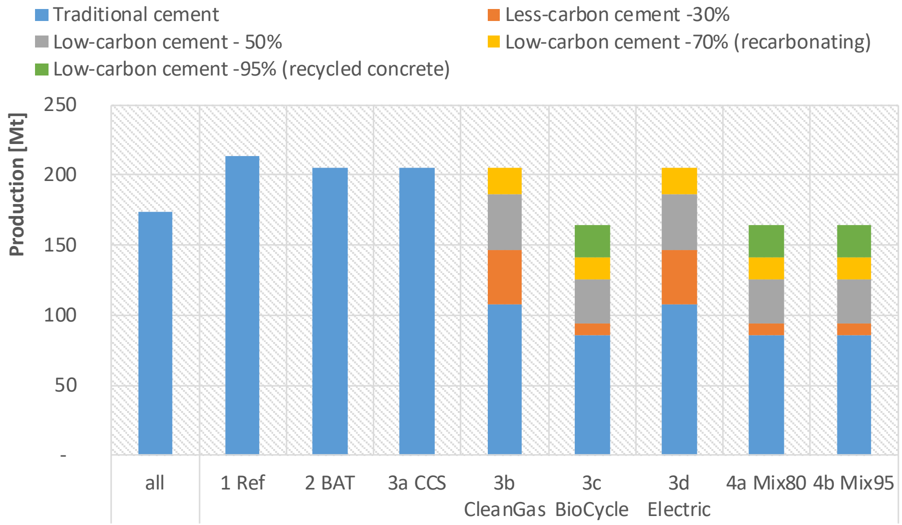
In the 3c BioCycle scenario total cement production more or less stagnates (-2% in 2050 compared to 2015). Translating to -23% compared to the 1 Ref scenario due to increasing efforts in material efficiency (e.g. efficient concrete use/types (Müller et al. 2014) and less over-dimensioning in construction) and material substitution (e.g. concrete substitutes based on biomass). In addition to the above mentioned innovative cement types, another process enters the market: recycled concrete, which is expected to make cement production nearly CO2-neutral by completely replacing limestone as raw-material. Its share is assumed to be around 14% of total cement production in 2050.

In scenarios 4a to 4b all innovative cement varieties/products enter the market and substitute around 50% of cement production (mainly Portland cement) (see Figure 2.2). The remaining conventional cement production mainly consists of cements with low clinker shares.

Table 2.3 EU-28 cement production by scenario in Mt (2015-2050)

Cement	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref	174	190	208	214	213	23%
2 BAT	167	183	201	206	206	23%
3a CCS	167	183	201	206	206	23%
3b CleanGas	167	183	201	206	206	23%
3c BioCycle	167	177	184	177	165	-2%
3d Electric	167	183	201	206	206	23%
4a Mix80	167	177	184	177	165	-2%
4b Mix95	167	177	184	177	165	-2%
4b Mix90	167	177	184	177	165	-2%

Figure 2.2 EU-28 cement production by scenario and process in 2050



Glass

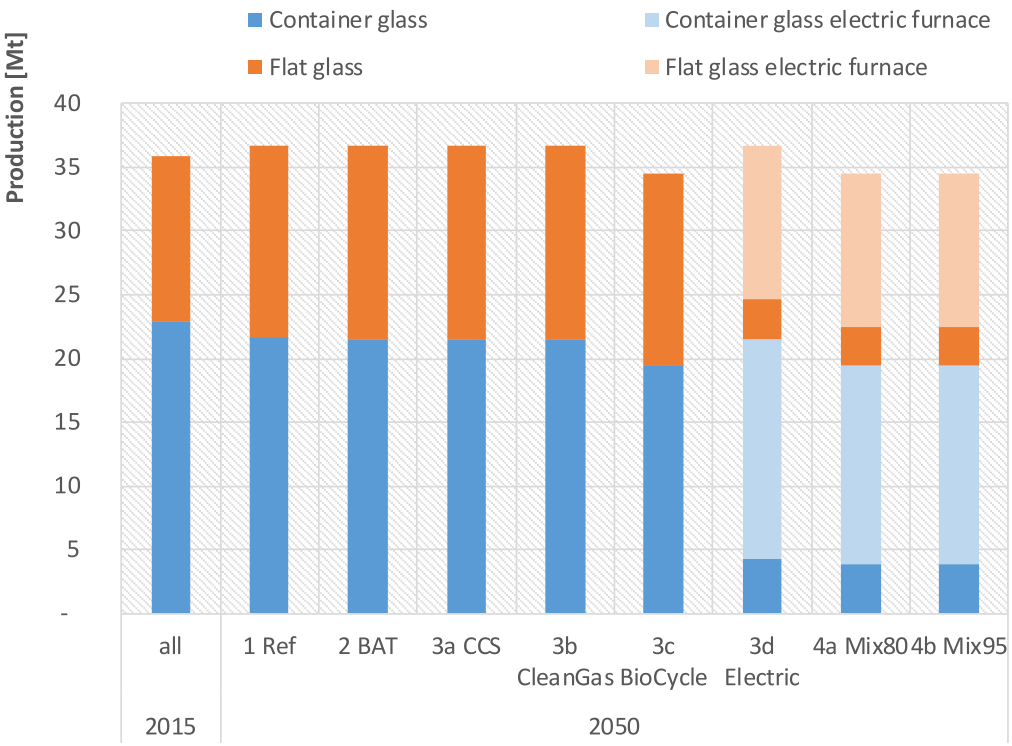
In the 1 Ref, 2 BAT, 3a CCS and 3d Electric scenario the European glass industry production of container and flat glass has only slightly increased by 2% in 2050 compared to 2015. Two contrary trends are assumed here: EU-28 container glass production is expected to further decline until 2050 due to material substitution by plastics and other forms of packaging, while the production of flat glass with its many application possibilities (e.g. triple-glazing for insulation, solar equipment, flat screens) is expected to increase until 2050 compared to 2015. In all other scenarios a slight decrease in overall glass production is assumed due to higher efforts in material efficiency improvements as well as material substitution (e.g. use of bio fibres) and re-use of glass products.

In the 2 BAT scenario a faster increase in container glass recycling is assumed until 2050 compared to the 1 Ref scenario. In the 3a CCS, 3b CleanGas, the 3d Electric and the 3c BioCycle scenario the amount of flat glass recycled also increases (e.g. due to lower standards in the building industry). In the 3d Electric and the 4a&b Mix scenarios new processes enter the glass industry: 80% of the conventional glass production will be substituted by electric melting processes in the 4a&b Mix scenarios, 85% in the 3d Electric scenario.

Table 2.4 EU-28 container and flat glass production by scenario in Mt (2015-2050)

Scenarios	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref	36	37	38	37	37	2%
2 BAT	36	37	38	37	37	2%
3a CCS	36	37	38	37	37	2%
3c BioCycle	36	37	37	36	35	-4%
3d Electric	36	37	38	37	37	2%
4a Mix80	36	37	37	36	35	-4%
4b Mix95	36	37	37	36	35	-4%

Figure 2.3 EU-28 container and flat glass production by scenario and process in 2050



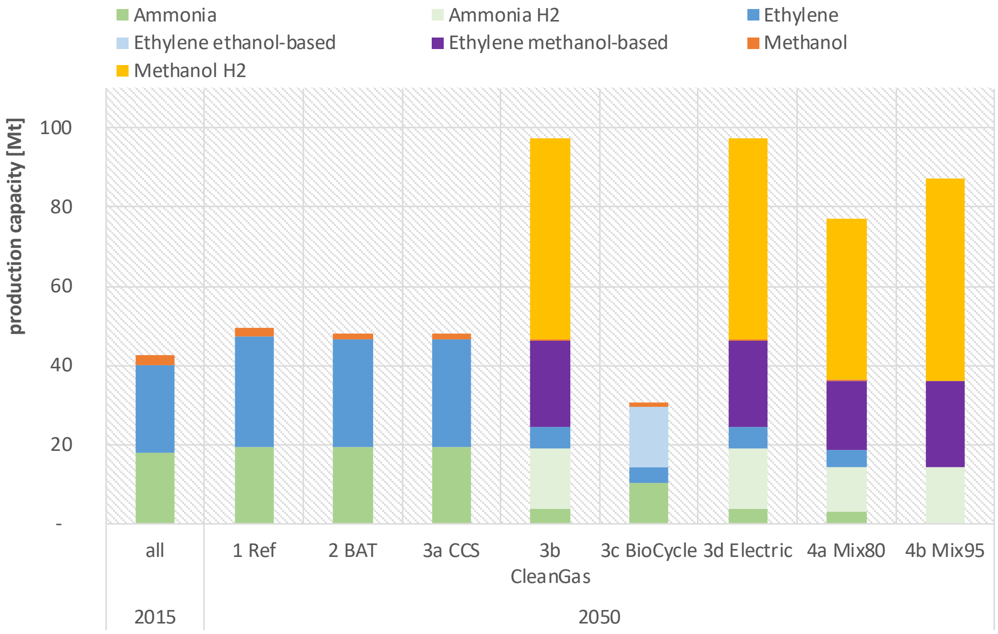
2.3.3 Chemical industry

For the chemical industry three main products have been selected for further discussion: ammonia, ethylene (and other olefines), and methanol. In the 1 Ref, 2 BAT, and 3a CCS, scenarios the European ethylene production has still increased significantly by around 25% in 2050 compared to 2015. In the 3b CleanGas and the 3d Electric scenario a similar increase in ethylene production is assumed, however, new technologies like ethanol- and methanol-based ethylene production enter the market leading to a significantly higher demand for methanol in these scenarios (1.3 Mt in 2015 compared to 51 Mt in 2050). In addition, conventional methanol production is substituted using hydrogen-based production routes. All hydrogen is produced from electrolysis using renewable energy.

In the chemical industry, significant improvements in plastic recycling (e.g. by reducing the variety of plastics to simplify recycling) and substitution by bio-based products (e.g. wood fibre products replace plastic) as well as re-use and lifetime extensions for disposable and non-disposable plastic goods are assumed in the scenario 3c BioCycle (Allwood et al. 2012) leading to a decrease in ethylene production by 12% by 2050 compared to 2015. In addition, further material efficiency improvements due to 3D-printing will take place in this scenario. Reduced demand for synthetic fertilisers results in a decrease in ammonia production by about 40% by 2050 compared to 2015.[3]

In the 4b Mix95 scenario all ammonia, ethylene and methanol production is converted to ethanol-, methanol, and hydrogen-based production. While ethylene production remains constant in this scenario (compared to a 25% increase in the 1 Ref scenario), ammonia production is expected to decrease by around 20% by 2050 compared to 2015.

Figure 2.4 EU-28 ethylene, ammonia, and methanol production in Mt by scenario and process in 2050



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[3] Reducing synthetic fertilizer use by 40% involves a fundamental change in the agricultural system. However, a case study for the Netherlands for example found that a 40% reduction of ammonia use by shifting to sustainable extensive agriculture is possible and even beneficial for society (van Grinsven et al. 2015). A large scale EU-wide shift to sustainable extensive farming will not need additional land if accompanied by a shift in diets according to WHO recommendations and substantially reduce the environmental impact of the agricultural sector (Westhoek et al. 2014).

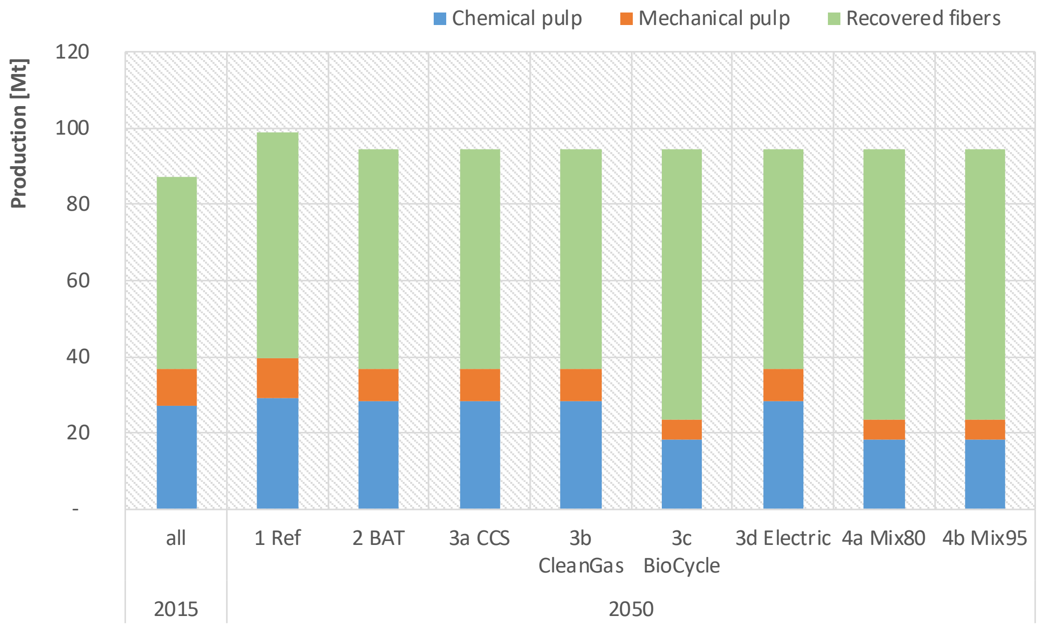
2.3.4 Paper industry

EU-28 paper production increases in all scenarios by 10% from 2015 to 2050. In the 3c BioCycle and scenarios 4a and 4b the share of recovered fibres in paper production increases assuming steady improvements in paper recycling by increasing the rate of collected waste-paper and yield improvement of recycled fibres by improving the separation of contaminants (Allwood et al. 2012).

Table 2.5 EU-28 paper production in Mt by scenario (2015-2050)

Scenarios	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref	95.6	98.1	103.1	104.9	105.6	10%
2 BAT	93.2	95.3	100.1	101.8	102.5	10%
3a CCS	93.2	95.3	100.1	101.8	102.5	10%
3b CleanGas	93.2	95.3	100.1	101.8	102.5	10%
3c BioCycle	93.2	95.3	100.1	101.8	102.5	10%
3d Electric	93.2	95.3	100.1	101.8	102.5	10%
4a Mix80	93.2	95.3	100.1	101.8	102.5	10%
4b Mix95	93.2	95.3	100.1	101.8	102.5	10%

Figure 2.5 EU-28 pulp and recovered fibres production Mt by scenario and process in 2050



2.3.5 Non-ferrous metals industry

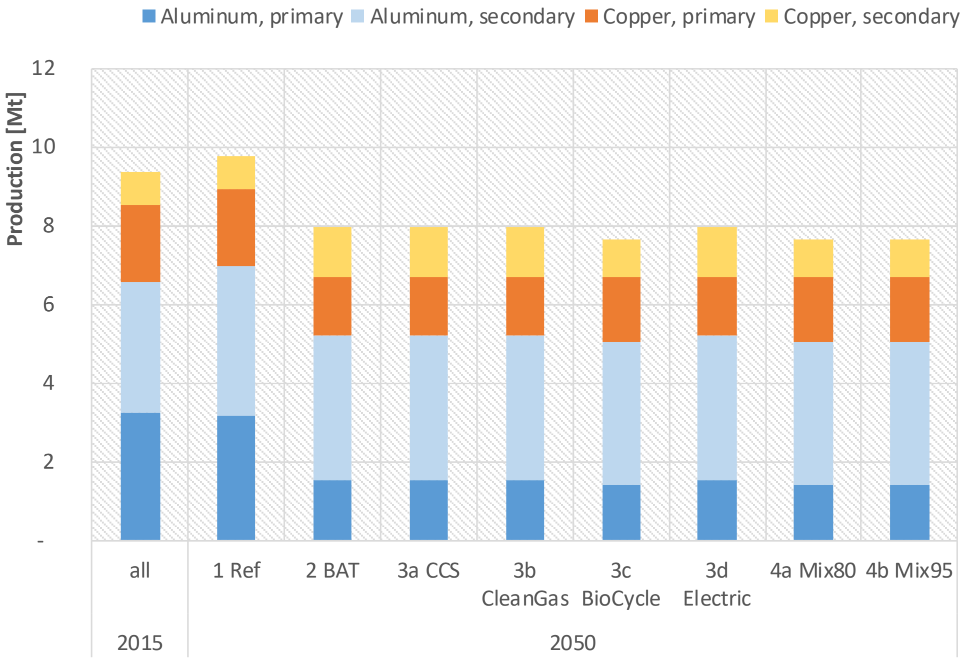
Aluminium

In the 1 Ref scenario the European aluminium industry production has increased by approximately 6% in 2050 compared to 2015. Cooper production is assumed to stay constant in this scenario. In all other scenarios a slower increase in aluminium production is assumed due to material efficiency improvements (e.g. using less metal by design or reducing yield losses), re-use of components and longer product lifetimes (Allwood et al. 2012). These effects outweigh potential demand increases due to substitution of steel with aluminium. In addition, a faster increase in aluminium production due to improved collection and sorting techniques are assumed up to 2050 in all ambitious scenarios compared to the 1 Ref scenario.

Table 2.6 EU-28 aluminium and copper production in Mt by scenario (2015-2050)

Scenarios	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref						
Aluminium	7	7	7	7	7	6%
Copper	3	3	3	3	3	0%
2 BAT, 3a CCS, 3bCleanGas, 3c BioCycle, 3d Electric, 4a Mix80, 4b Mix95						
Aluminium	5	5	5	5	5	4%
Copper	3	3	3	3	3	0%

Figure 2.6 EU-28 aluminium and copper production by scenario and process in 2050



2.3.6 Refinery industry

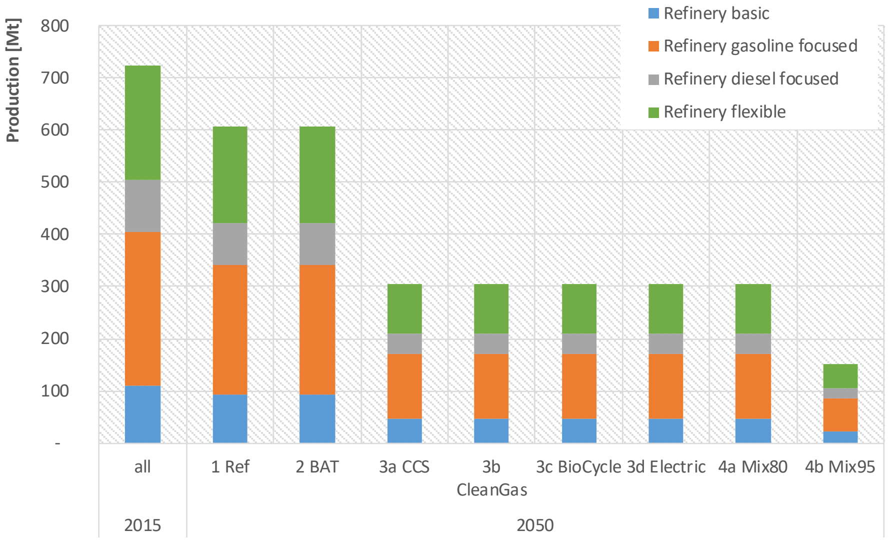
Refinery products are mainly consumed in transport, industry and the heating sector. In all scenarios a decrease in EU-28 refinery production is assumed up until 2050, due to a switch towards renewable heating as well as alternative fuels such as biofuels but also to electricity and hydrogen in the demand sectors in all decarbonisation scenarios (-16% compared to 2015: scenarios 1 and 2; ~-60%

compared to 2015: scenarios 3a to 4a; ~-90% compared to 2015). Another important consumer of refinery products is the chemical industry using, for example, naphtha as feedstock in ethylene production. Switching fossil feedstock production in refineries to renewable hydrogen produced methanol will lead to a significant drop in EU-28 demand for refinery products under the assumption that trade flows do not change significantly in the scenarios.

Table 2.7 EU-28 refinery production in Mt by scenario (2015-2050)

Scenario	2015	2020	2030	2040	2050	Δ% 2015-2050
1 Ref	723	678	628	617	608	-16%
2 BAT	723	678	628	617	608	-16%
3a CCS	723	663	544	424	304	-58%
3b CleanGas	723	663	544	424	304	-58%
3c BioCycle	723	663	544	424	304	-58%
3d Electric	723	663	544	424	304	-58%
4a Mix80	723	663	544	424	304	-58%
4b Mix95	723	663	513	333	152	-79%

Figure 2.7 EU-28 refinery production by scenario and process in 2050



2.4 Energy and CO2 prices

Energy and CO2 prices are important input as they influence investment decisions and respective technology choice in the scenarios as well as the overall cost assessment. In the following we give an overview on the assumptions. Energy carrier prices are similar across the scenarios, while CO2 prices vary. Biomass as well as hydrogen and synthetic methane are discussed separately, because the assumptions are strongly dominating the overall cost results.

2.4.1 Biomass prices

Biomass is a limited resource and all economic sectors request it as a potentially cheap measure in an emission reduction portfolio. At the same time, biomass resources and energy carriers are very heterogeneous and prices depend on the type of biomass as well as on the overall biomass use.

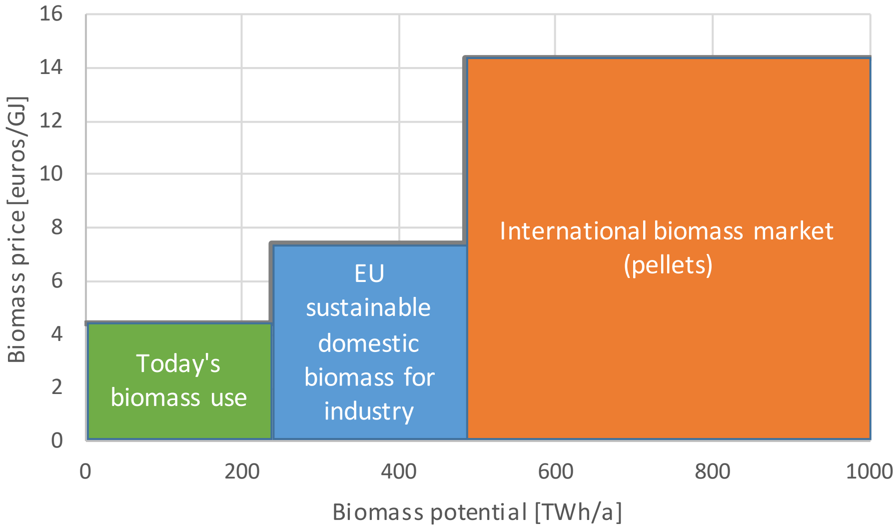
In order to take the limitation of biomass resources into account, we use a cost-potential curve to determine the biomass price. To do so, we derive three potentials for biomass supply in industry, each with different prices (Figure 2.8).

The first potential depicts the biomass already in use in 2015 (238 TWh (Eurostat), equivalent to almost 50 Mt of wood pellets[4]) and is assumed to consist mostly of locally available and cheap (4 EUR/GJ assumed) production residues (e.g. in the paper and food industry).

The second potential considers the entire potentially sustainable domestic biomass supply in Europe. Estimates of the additional sustainable potential in the EU-28 range from roughly 240 to 1950 TWh (or equivalently 20.6 to 168 Mtoe) (Sikkema et al. 2011; Fraunhofer ISI et al. 2017). We assume an additional potential of 1,450 TWh (125 Mtoe) (Fraunhofer ISI et al. 2017), resulting in a total domestic potential of 2,560 TWh (220 Mtoe) including today's biomass use. Here we assume that the share of the additional sustainable domestic biomass potential used for industry remains as in 2015 biomass use (21.4%). This results in an additional domestic potential of around 250 TWh (21 Mtoe) available for the EU-28 industry sector (equivalent to slightly over 50 Mt of wood pellets). Due to the higher effort of production (oriented at wood pellets), the price increases to 7.4 EUR/GJ[5]. With this potential, the domestic biomass available to industry in EU-28 is exhausted.

Additional demand must be satisfied by imports (e.g. from Canada, USA, Russia), which is the third step of the biomass cost-potential curve. The price increases to 14.4 EUR/GJ and the quantity for this third potential is not limited.

Figure 2.8 Biomass cost-potential curve assumed for EU-28 industry



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[4] With 17.5 GJ/t heating value.

[5] https://www.pellet.org/wpac-news/global-pellet-market-outlook-in-2017 (access: October 2018)

The actual price of the biomass in each scenario is calculated as a weighted average of the use[6], cheaper sources of biomass are used first.

2.4.2 Hydrogen and synthetic methane

Hydrogen and synthetic methane are used for feedstocks and other process heat supply. As an assumption, both are assumed to be produced exclusively via electrolysis using electricity from renewable energy sources.

According to the system boundary defined, both hydrogen and synthetic methane are accounted for as energy carriers, which are produced outside the industry system we are looking at. Consequently, CAPEX for e.g. electrolysers is not included, however, it is considered via the price of hydrogen and synthetic methane.

The future price of hydrogen and synthetic methane depends on a number of factors including CAPEX, electricity prices, annual full load hours, transportation costs, etc. The available literature shows a huge range of future price estimates with varying degrees of optimism regarding technology learning and cost decrease (Götz et al. 2016). For example, the expected CAPEX of electrolysers ranges between 350 and 900 euros/kWel for 2050.

We assume costs that reflect an average expectation from the literature. For hydrogen this results in 160 and 140 euros/MWh in 2030 and 2050, respectively. Such costs assume electrolyser CAPEX of about 700 and 500 euros/kWel, about 4,000 annual full load hours and electricity prices of about 100 euros/MWh. No costs for hydrogen transportation are assumed. Instead electricity transmission is included in electricity price assuming that hydrogen production is close to industrial sites.

For synthetic methane we assume higher prices of 240 and 220 euros/MWh for 2030 and 2050, respectively. The higher price is explained by the additional process step in the methanation of the hydrogen. Note that uncertainty as concerns the CO2-source is very high. If air-capture CO2 would be needed, instead of CO2 captured from burning biomass for power or heat generation or remaining process CO2 sources, the costs of synthetic methane might be substantially higher. However, there are still some emission sources from distributed process emissions that might be used (lime, bricks, ceramics, ammonia). Figure 2.9 provides an overview on the assumptions taken.

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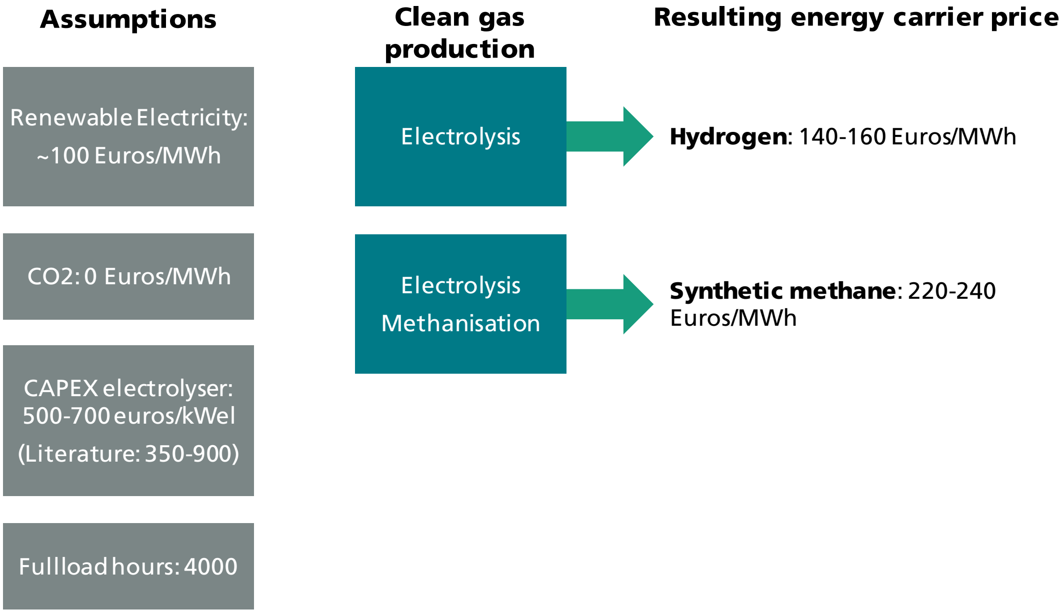
[6] For example, if the second potential is used fully, the price would be at 4.40 euros/GJ for the first 238 TWh and at 7.00 euros/GJ for additional 247 TWh, yielding an average price of 6.40 EUR/GJ for the entire biomass use.

Figure 2.9 Overview of assumptions and costs for hydrogen and synthetic methane

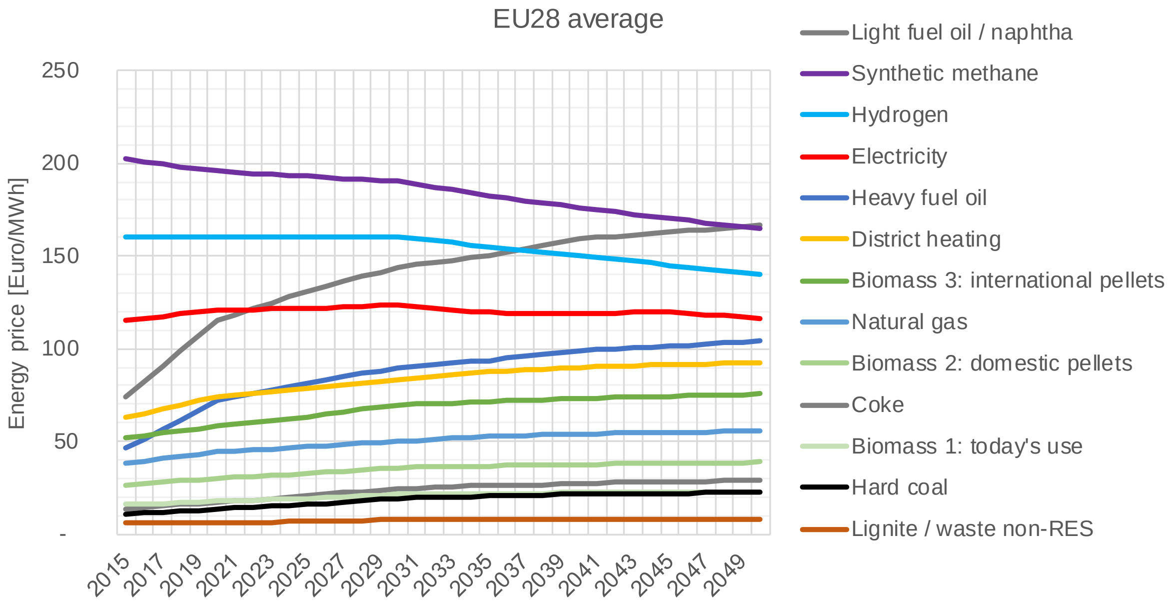


Costs for both hydrogen and synthetic methane are regarded as assumptions in this study in order to calculate the overall costs of the individual scenarios. The focus of the study is neither the assessment of the infrastructure issues nor the assessment of the entire energy system in this regard. The costs are assumptions, not predictions and contain a high degree of uncertainty.

2.4.3 Energy carrier prices EU28 summary

Energy carrier prices including existing taxes and levies for industrial consumers is a major exogenous input to the model. The assumptions on energy prices are similar across all scenarios. Figure 2.10 shows the evolution of industrial energy prices over time for individual energy carriers in comparison. Prices include taxes and levies as applied to industrial companies on average. CO2-prices (ETS and non-ETS) as assumed in the individual scenarios are not included. The future evolution of energy prices follows the overall trends of the EU Reference Scenario 2016 (European Commission 2016). It can be observed that the spread across energy carriers is huge with very low prices for waste products, lignite and also types of biomass (e.g. production residues) used today and on the other side expensive secondary energy carriers like electricity, hydrogen and synthetic methane (both latter being produced via electrolysis based on renewable energy). Towards 2050 most energy carriers show an increasing trend. E.g. natural gas and biomass increase by about 45% from 2015 to 2050. Fuel oil shows the highest increase with about 125% over the same time period. The same development is assumed for naphtha as used in chemical feedstocks, which has historically been at similar price levels as light fuel oil. Electricity remains relatively constant and hydrogen and synthetic methane show even falling costs due to technical learning of 12% and 18%, respectively.

Figure 2.10 Evolution of industry sector energy carrier prices as EU28 average (non-weighted) for all scenarios (incl. taxes and levies, excluding CO2 allowance price)



Source: 2015 based on Eurostat, IEA, projection own assumption raking into account the EU Reference Scenario 2016 (European Commission 2016)

2.4.4 CO2 price

The CO2 price is an exogenous assumptions, which affects the speed of fuel switching and energy efficiency improvement. The reference scenario assumes a CO2 price for the ETS sector that is equal to the EU Reference Scenario 2016 *(25€/tCO2-eq in 2030, 50€/tCO2-eq in 2040 and 85€/tCO2-eq in 2050)*. The decarbonisation scenarios 3a-4a assume a higher CO2 price for the EU ETS, (around 50€/tCO2-eq in 2030, 100€/tCO2-eq in 2040 and 200€/tCO2-eq in 2050) and in addition also a CO2 price for the non-ETS sector following the same price path. This is necessary for the industry to decarbonise, as it needs higher CO2 prices than power generation in order to drive emission reductions. The faster CO2 prices increase, the faster and to a greater extent the industry will decarbonise. For this reason, the more ambitious scenario Mix 95 (4b) assumes an increase in the CO2 price for both ETS and non-ETS taking place about 10 years earlier.

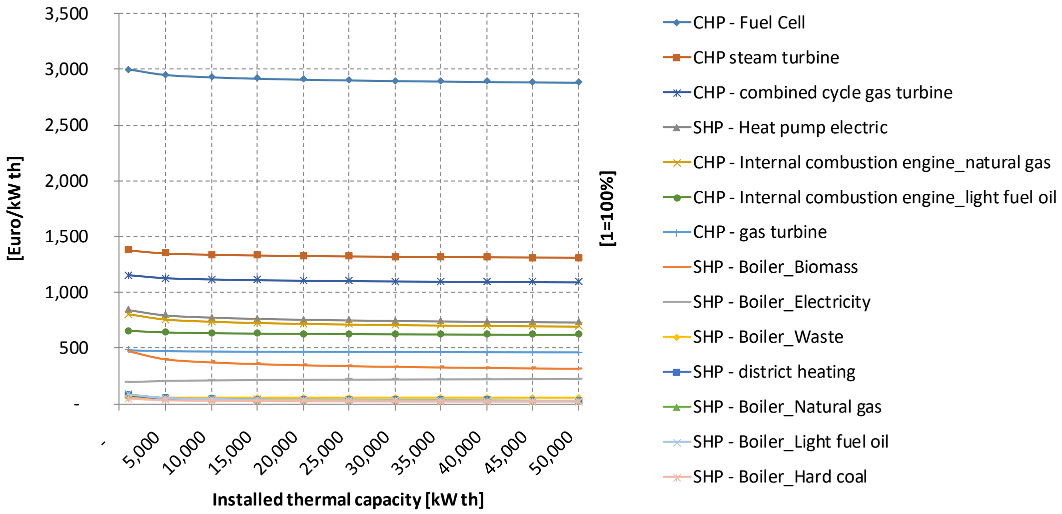
2.5 Technology costs

The FORECAST model contains many technology assumptions. In the following section assumptions on costs for selected technology groups are presented.

2.5.1 Steam generation

The techno-economic data considered for steam generation technologies includes CAPEX, OPEX, efficiency (thermal and electric), and lifetime. The specific efficiency and costs vary by technology size, country and year. As an example, the costs of individual steam generation technologies are presented for the year 2015 for Poland in Figure 2.11. The variation across technologies is huge with fuel cells having the highest specific capital costs in 2015 and individual gas and coal boilers the lowest. With increasing size, the specific costs fall. Costs also decrease over time, particularly for innovative technologies with remaining potential for technology learning.

Figure 2.11 Assumed specific CAPEX for steam generation technologies for Poland for 2015 by technology and size

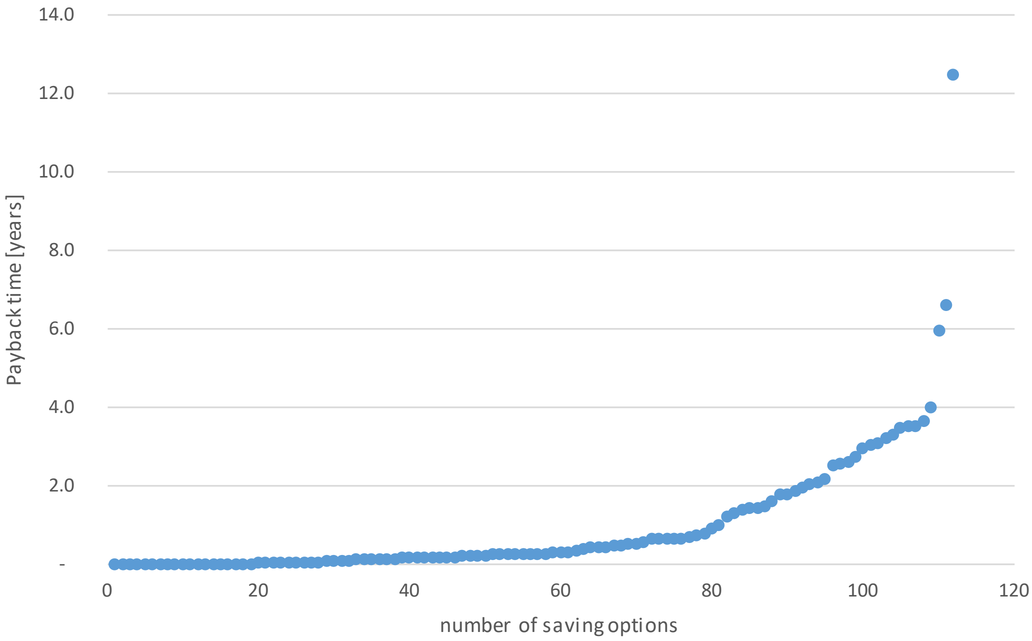


2.5.2 Energy efficiency improvement

Energy efficiency improvement is included in the model via explicit saving options that are either related to a process or to a cross-cutting technology (e.g. compressed air). Saving options improve the energy efficiency of the process or the cross-cutting technology by diffusing through the market. Market diffusion depends on their cost-effectiveness. As investment decisions in energy efficiency are typically decided on the basis of their payback period, this criterion is also used in the FORECAST model for the investment simulation.

Figure 2.12 shows the distribution of the payback time for 112 individual saving options related to energy efficiency in cross-cutting technologies for the year 2015 for Germany. It can be observed that for most saving options the payback time is very short with only few options being longer than 2 years.

Figure 2.12 Payback time of saving options in cross-cutting technologies in 2015 in Germany



2.5.3 Radical process innovations

The diffusion of new production processes is an exogenous assumption in FORECAST. However, the related investments will affect the overall results on investment needs and costs. Table 2.8 summarises the specific investment assumed by process per t production capacity. Costs are given as additional costs compared to the reference technology. That is, it is assumed that a production plant using a new process technology is only constructed if a conventional plant would have been replaced anyway. The production of hydrogen via electrolysis, which is needed as input for several of the new processes, is outside the system boundary chosen in this study. Accordingly, investments in electrolyser capacity are not included in Table 2.8. However, these costs are translated into energy prices and revealed in the analysis of energy expenditures via the price of hydrogen or clean gas.

It shall further be noted that data availability regarding such investment needs is very scarce and uncertain. This is true in particular as these innovative processes are not yet on the market and future technology development might substantially change the current cost expectations.

Table 2.8 Assumed costs for new production processes. Costs are related to annual capacity and provided as additional costs of the innovative process compared to the reference process

Sector	Process	Reference process	CAPEX [euro/t product] compared to reference process			
			2020	2030	2040	2050
Iron and steel	Plasma steel (H2)*	BOF route	438	377	324	278
	DR electrolysis	BOF route	198	170	146	126
	DR RES H2 + EAF*	BOF route	0	0	0	0
Chemicals	Methanol H2*	Methanol	-14	-14	-14	-14
	Ammonia H2*	Ammonia	-222	-222	-222	-222
	Ethylene methanol-based*	Ethylene naphtha based	0	0	0	0
	Ethylene ethanol-based	Ethylene naphtha based	0	0	0	0
Non-metallic minerals	Less-carbon cement - 30%	Ordinary Portland Cement	20	17	15	13
	Low-carbon cement - 70% (recarbonating)	Ordinary Portland Cement	50	43	37	32
	Low-carbon cement - 50%	Ordinary Portland Cement	80	69	59	51
	Low-carbon cement -95% (recycled concrete)	Ordinary Portland Cement	150	129	111	95
	Clinker electric kiln	Clinker conventional rotary kiln	50	43	37	32
	Container glass electric furnace	Container glass gas furnace	129	111	95	82
	Flat glass electric furnace	Flat glass gas furnace	129	111	95	82

Excluding investment for electrolyser, DRI RES H2 + EAF assumes similar costs as BOF new plant (Wortler et al. 2013; Vogl et al. 2018); ammonia and methanol based on (Bazzanella und Ausfelder 2017) but corrected for electrolyser CAPEX; negative costs for ammonia H2 reflect replaced synthesis gas generation; low-carbon cement: own assumption based on generic cement type and no cost data was available;

2.5.4 Carbon capture and storage

Costs for CCS are distinguished in costs for capture, transport and storage. Due to the system boundaries of our analysis, transport and storage of CO2 are not modelled in detail. Still, assumptions on the average costs based on literature are included in order to provide a complete picture. For example, Saygin et al. (2013) presented a range of transport and storage costs of 2 to 16 euro/t CO2 for 100 km pipeline and assumed 10 euro/t CO2 as average for the Netherlands. Budinis et al. (2018) reported a range of about 2 to 5 euros/t CO2 for transportation costs using a 250 km pipeline with 10 Mt CO2/a capacity. Storage costs depend heavily on the site. For storage in saline formations, Budinis et al. (2018) estimate a range of about 9.4 to 31.4 euros/t CO2.

The capture costs are rather specific to the respective process/sub-sector and depend on the practical integration into the process, the purity of the flue gas and the CO2 concentration. for example, Garðarsdóttir et al. (2018) report CAPEX capture costs of 10-20 euro/ t CO2 captured for steel and cement plants in Sweden based on a detailed process analysis and assuming mature capture technology.

Table 2.9 summarises the assumptions used and provides the relevant references to the literature. Costs for capture, storage and transport are included per tonne of CO2 capacity in the year the capture equipment is installed. Using this approach, such costs are assumed to be investment and accounted as CAPEX. Different literature also alternatively reports transport and storage costs as operating costs over the entire life of the equipment, which gives the CAPEX cited above smaller values. While the total costs are not changed, the time allocation of the costs is strongly affected.

Table 2.9 Assumed costs for CCS by process/sub-sector. Costs are related to annual capacity

Process	Sector	Capture CAPEX [euro/t CO2 a]		Transport & storage [euro/ t CO2 a]		OPEX [% of CAPEX]
		2030	**2050**	**2030**	**2050**	
Ammonia	Chemicals	40	30	140	113	7%
Methanol		60	44	140	113	7%
Ethylene		180	133	140	113	10%
Integrated steelworks	Iron and steel	90	67	140	113	5%
Clinker	Non-metallic minerals	150	111	140	113	12%
Lime		150	111	140	113	5%
Container glass		400	296	140	113	7%
Flat glass		400	296	140	113	7%
Fibreglass		400	296	140	113	7%
Other glass		400	296	140	113	7%
Integrated paper mill	Pulp and paper	400	296	140	113	7%
Refinery basic	Refineries	200	148	140	113	10%
Refinery gasoline focused		200	148	140	113	10%
Refinery diesel focused		200	148	140	113	10%
Refinery flexible		200	148	140	113	10%

Own assumptions based on: (Saygin et al. 2013; Kuramochi et al. 2012; Budinis et al. 2018; van Ruijven et al. 2016; The European Chemical Industry Council (cefic) und Ecofys 2013)

3 Results

3.1 Definitions

- **GHG** include all direct GHG emissions and process-related emissions. The accounting is based on energy demand statistics from Eurostat and process emission factors related to production by process. Indirect emissions via the consumption of electricity or district heating are not accounted for (if not stated otherwise). GHG emissions are accounted as CO2-equivalents (CO2-equ) throughout the entire report. Energy consumption from feedstock is not reported in GHG emissions, because these occur after the product use e.g. in waste incineration outside the industry sector system boundary.
- **Energy demand** follows Eurostat's definition of final energy (see annex) and is reported in TWh with the following exceptions:
    1. Energy consumption of coke ovens and refineries is included within the industrial final energy demand scope of the study.
    2. Feedstock energy demand is reported separately and not included in final energy.
    3. Ambient heat (for heat pumps) is included under final energy.
- **Sub-sectors**: industry includes all sub-sectors according to final energy demand plus coking in the steel industry and refineries.
- **Supply-side**: all scenarios exclusively focus on the demand side. They explore the potential demand for e.g. biomass or electricity but do not assess the supply of such energy carriers.
- **Clean gas** includes synthetic methane produced from hydrogen. In all scenarios, if hydrogen is used, it is assumed to be produced from renewable electricity via electrolysis. Electricity consumption for the production of clean gas is not included in final energy, however, it is separately reported.
- **Ambition**: all decarbonisation scenarios represent an ambitious and radical change of the industrial energy system. However, the scenarios include restrictions like age and stock-turnover of steam generation technologies. The applications of innovative low-carbon process technologies are exogenous assumptions.
- **Beyond 2050**: the quantitative model-based analysis develops scenarios up to 2050. However, the perspective beyond 2050 is taken in the discussion of scenario results.

In the following section, results are first briefly summarised by scenario, before a comparison across the eight scenarios is conducted. Finally, technology specific analyses and sector summaries are presented.

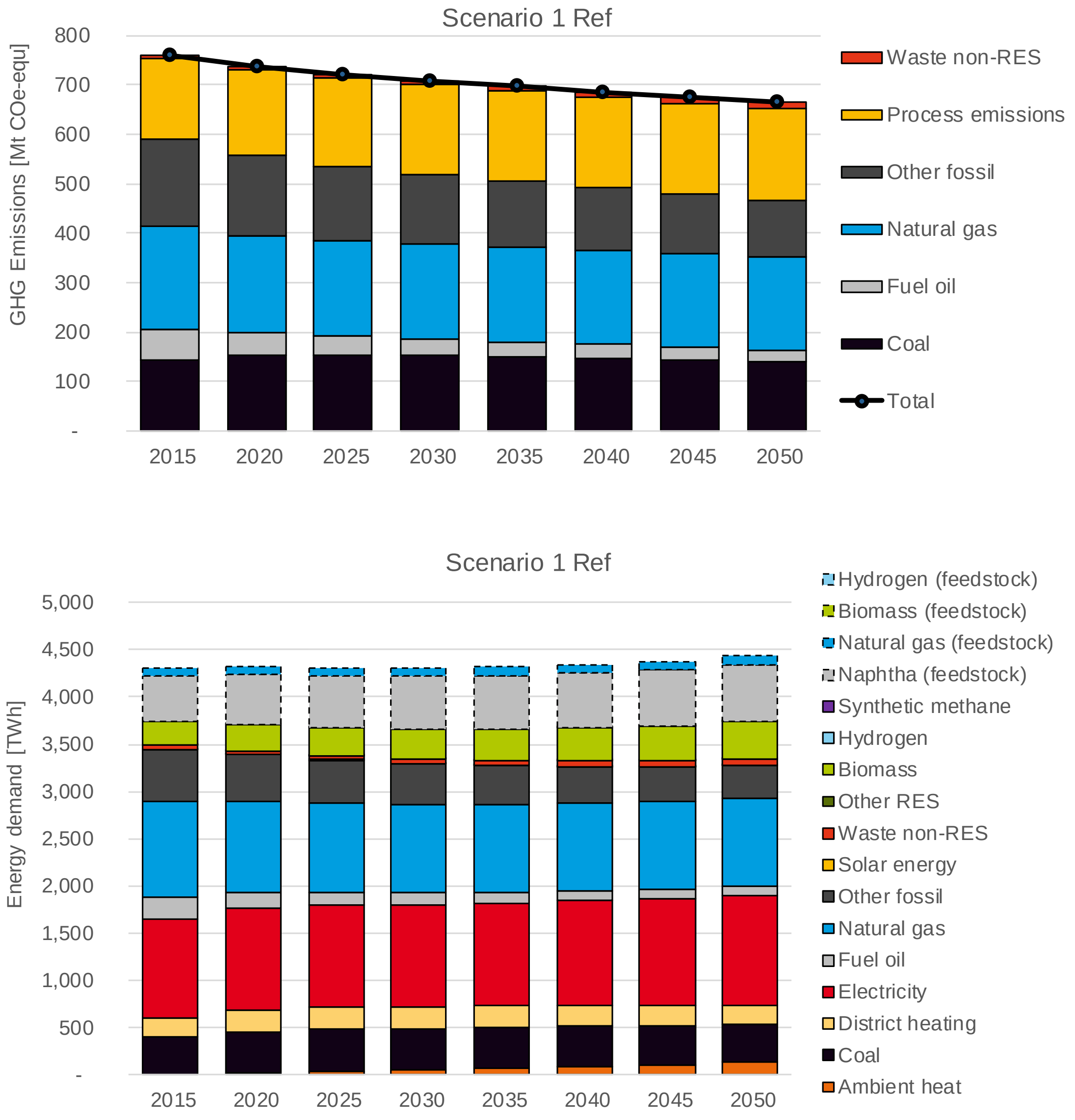
3.2 Results by scenario

3.2.1 Scenario 1 Ref

The *Reference scenario (1 Ref)* reflects the effects of current policies on the future energy system and serves as a benchmark to compare the decarbonisation scenarios. Its economic and demographic developments are based on the assumptions of the European Reference Scenario 2016. In terms of industrial production, it shows a slow continuation of past trends. Material recycling also follows past trends, but no additional efforts in terms of material efficiency and substitution occur. Energy efficiency measures continue to diffuse through the technology stock, while innovations (i.e. new technologies) are not considered.

Under the given assumptions, results of *scenario 1 Ref* show a slow and continuous GHG reduction towards 2050 by 12% compared to 2015. Compared to 1990, the GHG reduction equals about 45%. At the same time final energy demand remains more or less constant but experiences a slow fuel switch towards biomass and some ambient heat (heat pumps). In particular, fuel oil shows a reduction towards 2050. Energy efficiency gains are offset by economic growth and increasing industrial production, while electricity and natural gas remain the most important energy carriers. Feedstock use continues to be based on fossil fuels.

Figure 3.1 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 1 Ref by energy carrier (EU-28)



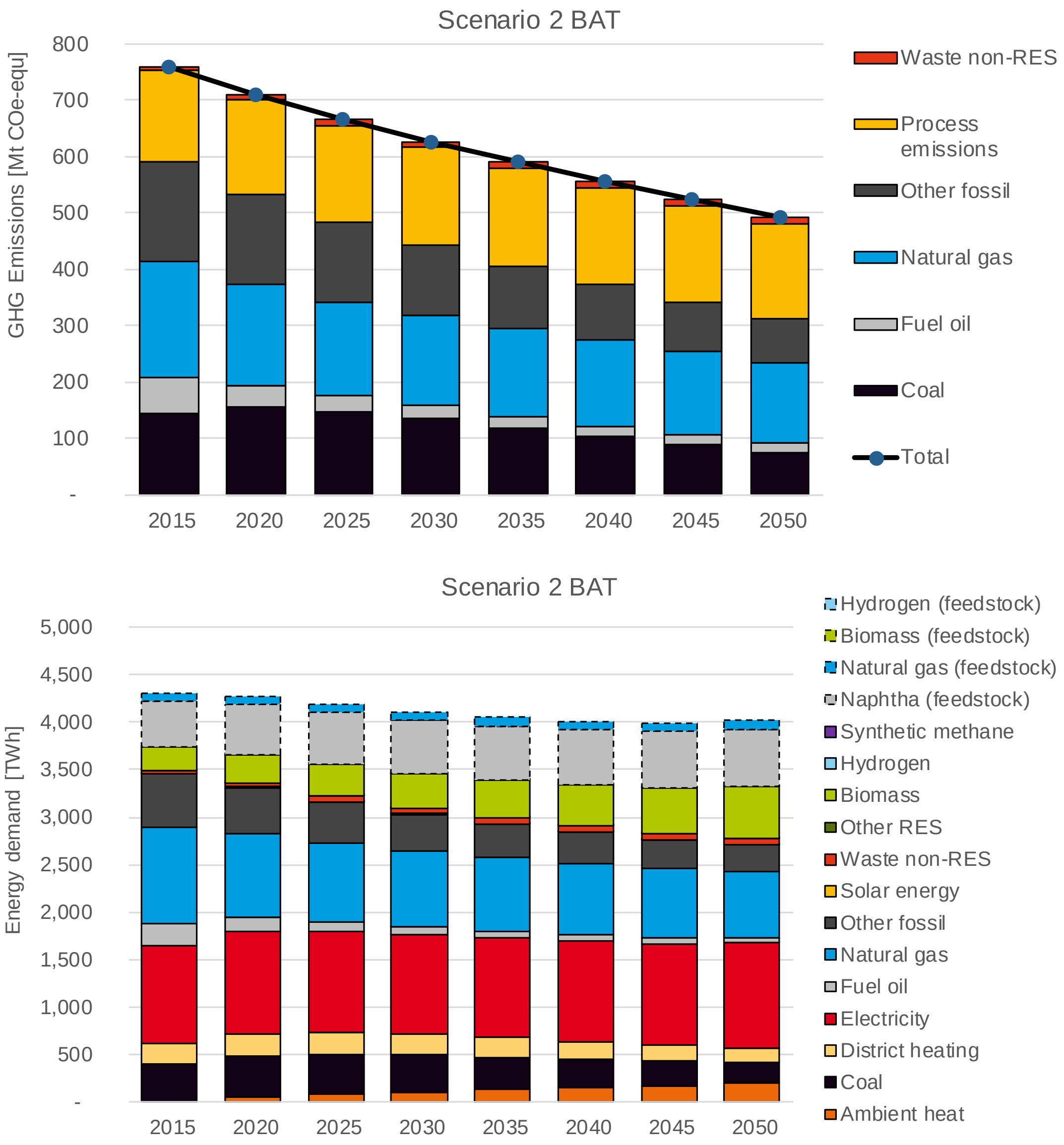
3.2.2 Scenario 2 BAT

The *BAT scenario* applies today's best available energy efficiency technologies. Innovations are not considered. As in the Ref scenario, economic and demographic developments are based on the assumptions of the European Reference Scenario

2016. In terms of physical production, the BAT scenario is more ambitious concerning recycling and assumes higher shares of secondary production compared to the *scenario 1 Ref*. However, no additional efforts in terms of material efficiency and substitution are carried out in this scenario except for a higher clinker share in cement production.

Results show a substantial decrease of GHG emissions by about 35% in 2050 compared to 2015 (59% compared to 1990). This is driven by energy efficiency improvements (final energy demand decreases by 11% towards 2050) fuel switch towards renewable energy and electricity as well as higher recycling rates particularly for steel. Biomass and ambient heat are assumed to gain market share while the use of coal and other fossil fuels fall substantially. Fuel oil is nearly completely phased out by 2050. Feedstock use is equivalent to the scenario 1 Ref and is based on fossil fuels.

Figure 3.2 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 2 BAT by energy carrier (EU-28)

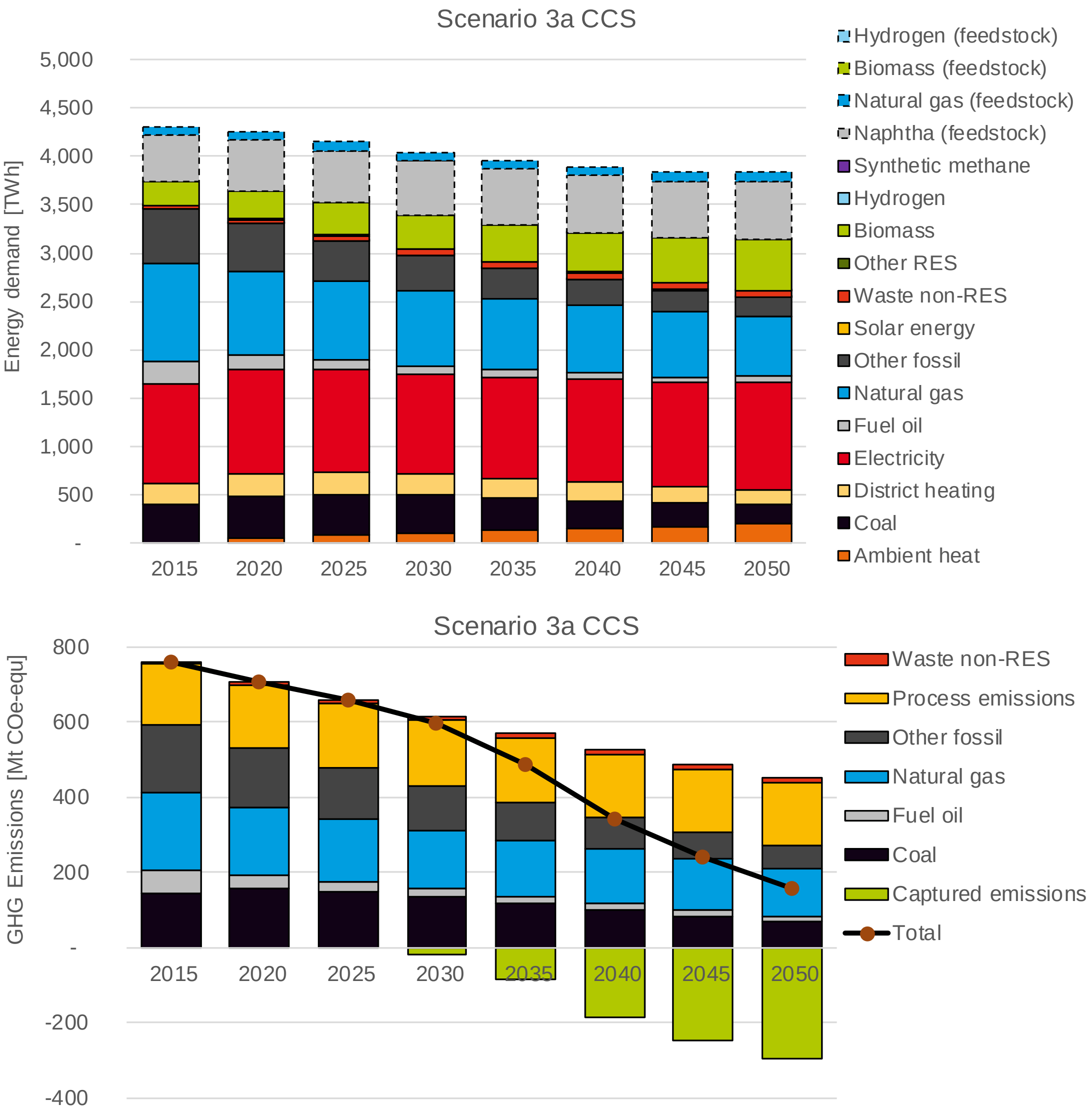


3.2.3 Scenario 3a CCS

Compared to the scenario 2 BAT, the scenario 3a CCS adds innovative energy efficiency measures and large-scale diffusion of CCS. The assumptions on physical production, recycling, material efficiency and substitution are the same as in scenario 2 BAT.

Results show a rapid decline of GHG emissions particularly after 2030 when CCS diffusion accelerates. In 2050 net GHG emissions are 79% below 2015 emissions. Compared to 1990 the reduction in GHGs equals 87%. In 2050 about 294 Mt CO2 are captured per year, of which most comes from cement and lime production, the chemical and the iron and steel sectors. Glass production and the paper industry contribute lower amounts. In 2050, the diffusion of CCS has reached its limit in most industries, and a larger reduction is not envisioned via CCS alone. Driven by energy-efficiency innovations, energy demand falls by 16% until 2050. This includes 65 TWh/a electricity use for CCS, which equals about 6% of industry's 2015 electricity demand. Feedstock use is based on fossil fuels as in scenarios 1 and 2.

Figure 3.3 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 3a CCS by energy carrier (EU-28)



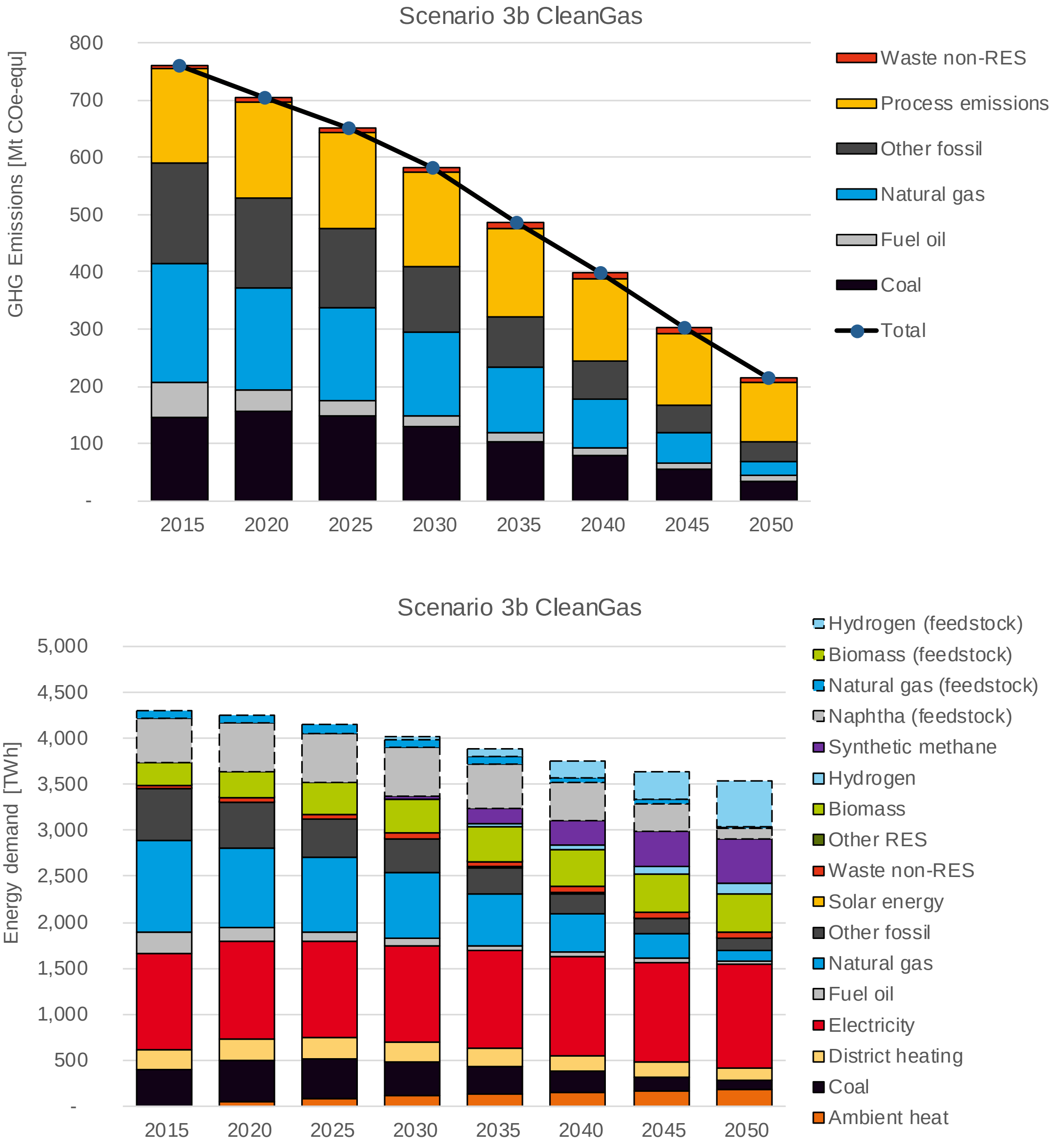
3.2.4 Scenario 3b CleanGas

In the scenario 3b CleanGas, hydrogen-based production technologies enter the market in the steel and chemical industry. Synthetic methane based on renewable energy is fed into the gas grid from 2030 onwards replacing 80% of conventional natural gas by 2050. Also, innovative energy efficiency technologies diffuse rapidly. Other assumptions remain the same as in *scenario 2 BAT*.

Results show a decrease of GHG emissions by 72% by 2050 compared to 2015 and a reduction of 82% compared to 1990. Remaining emissions in 2050 mainly come from process emissions. Emissions from natural gas use decrease due to two reasons. First, demand for gas decreases and second, synthetic methane based on renewable electricity is fed into the grid and lowers the average emission factor by 80% towards 2050. The reduction of gas demand is among others driven by a switch towards (renewable) hydrogen-based production of ethylene, methanol and ammonia as well as energy efficiency improvements.

Further, coal use decreases as the steel industry changes largely from oxygen steel to steel based on direct reduced iron. The reducing agent is hydrogen, which is assumed to be produced via electrolysis using renewable electricity. Additional mitigation efforts will need to focus on the reduction of process-related emissions and the remaining distributed amounts of fossil fuels used across all sub-sectors.

Figure 3.4 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 3b CleanGas by energy carrier (EU-28)



3.2.5 Scenario 3c BioCycle

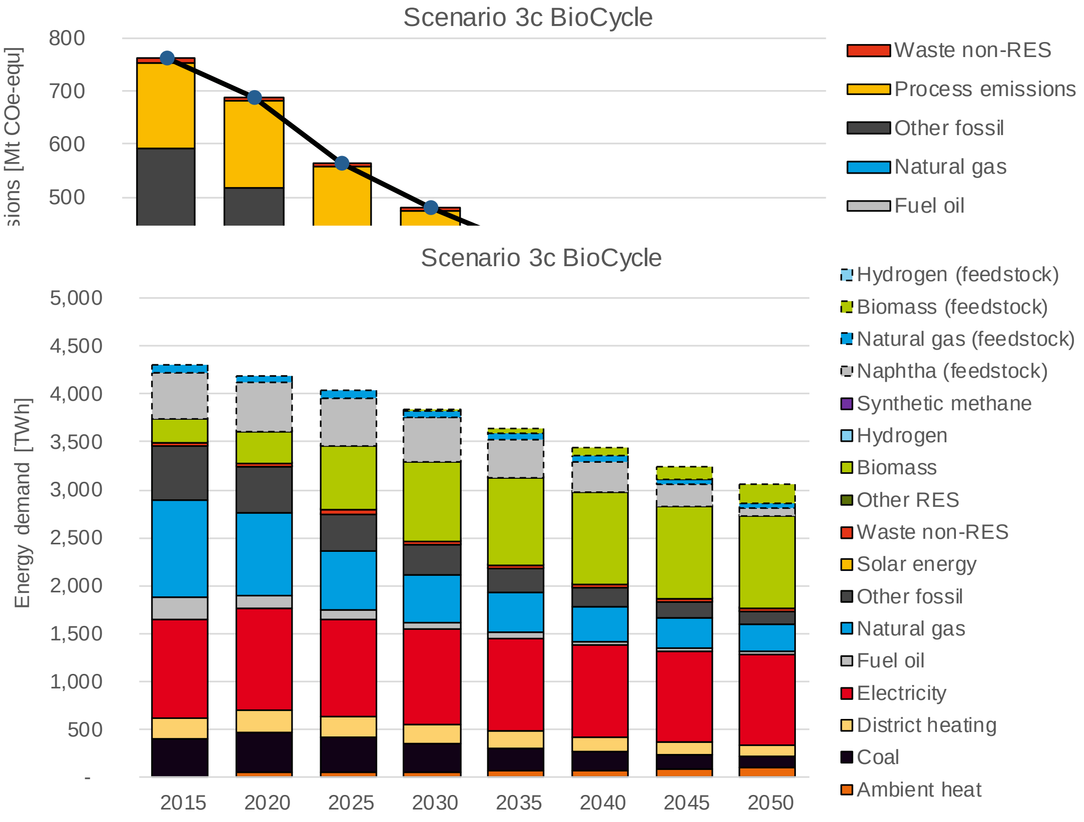
Scenario 3c BioCycle achieves substantial decarbonisation by a strong shift to biomass as fuel and feedstock, innovative energy-efficiency and low-carbon production technologies, implementation of a comprehensive circular economy beyond today’s practices and downstream material efficiency and substitution taking place along the entire value chain.

Possible (domestic and international) limitations to biomass supply are not considered. The scenario explores the potential biomass demand required to decarbonise the industrial sector by 2050.

In the BioCycle scenario, the future demand for steel decreases, due to reduced losses, material efficiency improvements, material substitution and changes in use behaviour. Electric steel production reaches a share of 77% of total steel production in 2050 due to higher scrap availability and the production of high-performance scrap-based steels. The remaining steel production capacity uses the blast furnace route with biomass co-firing. H2 or electricity-based steel production routes are not considered. Total cement production decreases by 20% in 2050 compared to the *scenario 1 Ref* due to efficient concrete use and less over dimensioning in construction, as well as the increased use of concrete substitutes based on wood and concrete recycling. This involves radical changes in the construction sector. Recycling rates also increase faster in the non-ferrous metals, the glass and the paper industry. In the chemical industry significant changes in plastic recycling (shift from downgrading to chemical re-use) and substitution by bio-based products as well as material efficiency are assumed.

Results show a rapid decarbonisation achieving a 68% reduction of GHG emissions by 2050 compared to 2015 and by 80% compared to 1990. Due to comprehensive changes in production and consumption structures process emissions fall substantially, however, their relative importance in the overall GHG emissions still increases. Final energy demand decreases by 27% compared to 2015. Besides energy efficiency, material efficiency and recycling also contribute to this reduction. The use of biomass in final energy increases from 250 TWh in 2015 to 970 TWh in 2050, making biomass the single most important energy carrier. Feedstock switch from naphtha to biomass adds an additional 197 TWh of biomass (bio-ethanol) use in 2050, resulting in a total of 1,167 TWh of biomass use in 2050. At the same time, natural gas demand as well as electricity demand decreases by 2050. Additional mitigation potential through the reduction of the remaining coal and gas consumption (e.g. via process switches in the steel industry) is still available.

Figure 3.5 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 3c BioCycle by energy carrier (EU-28)

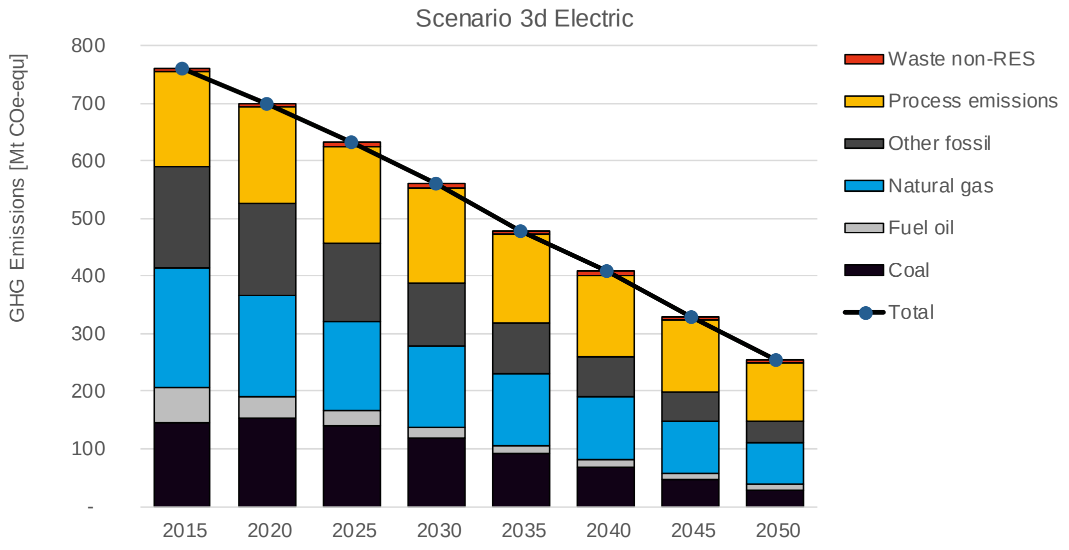


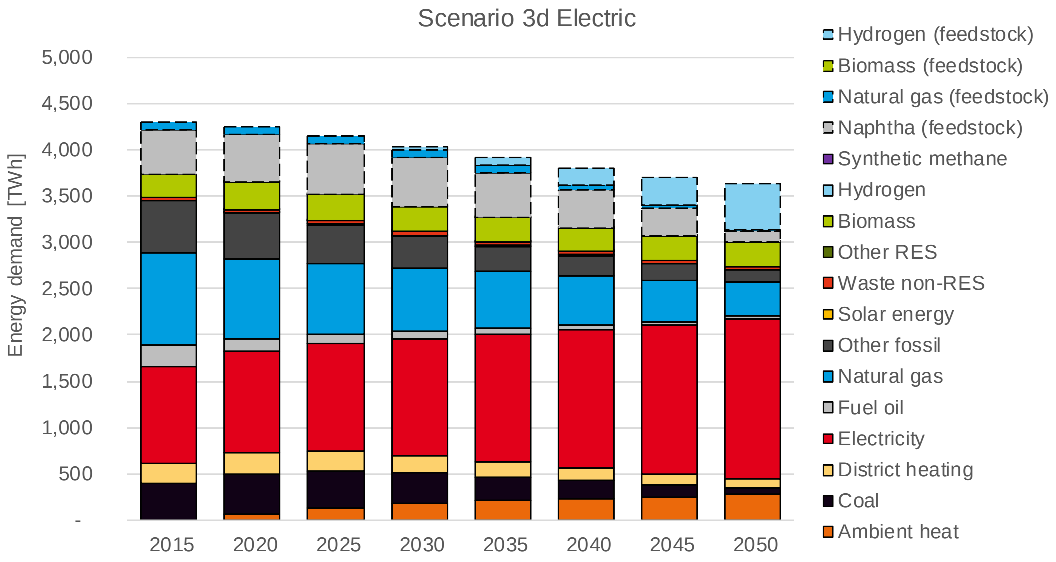
3.2.6 Scenario 3d Electric

In the *scenario 3d Electric* the assumptions on physical production, recycling, material efficiency and substitution stay the same as in the scenarios CCS, BAT, and CleanGas. In the *scenario 4d Electric*, innovative energy-efficiency technologies enter the market as well as process technologies using electricity directly (e.g. DR electrolysis in the steel industry) and indirectly (e.g. production of ethylene via methanol). The steel industry shifts from blast furnace steel to direct reduction of iron based on electrolysis, the chemical industry uses H2 as feedstock for ethylene, methanol and ammonia production stemming from renewable-based electrolysis, the cement and glass production shift to electric kilns and furnaces and the paper industry and other steam using industries use high temperature heat pumps where applicable as well as electric steam boilers. The scenario assesses the potential demand for electricity in an electricity-focused industrial energy system, while it did not explore the possibility of supplying the required amounts of electricity.

The resulting GHG emissions fall by 66% by 2050 compared to 2015 and 79% compared to 1990. Final energy demand decreases by about 20% towards 2050 compared to 2015. Results show a comprehensive shift towards electricity as the dominant energy carrier in all sectors, accelerating particularly after 2030, when the economic and regulatory framework is in favour of electricity and innovative electricity-based production technologies are available at an industrial scale (e.g. electrolysis steel, electric clinker kiln). The resulting electricity final energy consumption increases from about 1,040 TWh in 2015 to more than 1,718 TWh in 2050. The demand for hydrogen (feedstock) produced via electrolysis adds another 693 TWh, resulting in a total electricity demand of 2,412 TWh in 2050. Remaining mitigation efforts will need to focus on replacing the natural gas and other fossil fuels left over in 2050 as well as addressing process-related emissions.

Figure 3.6 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 3d Electric by energy carrier (EU-28)



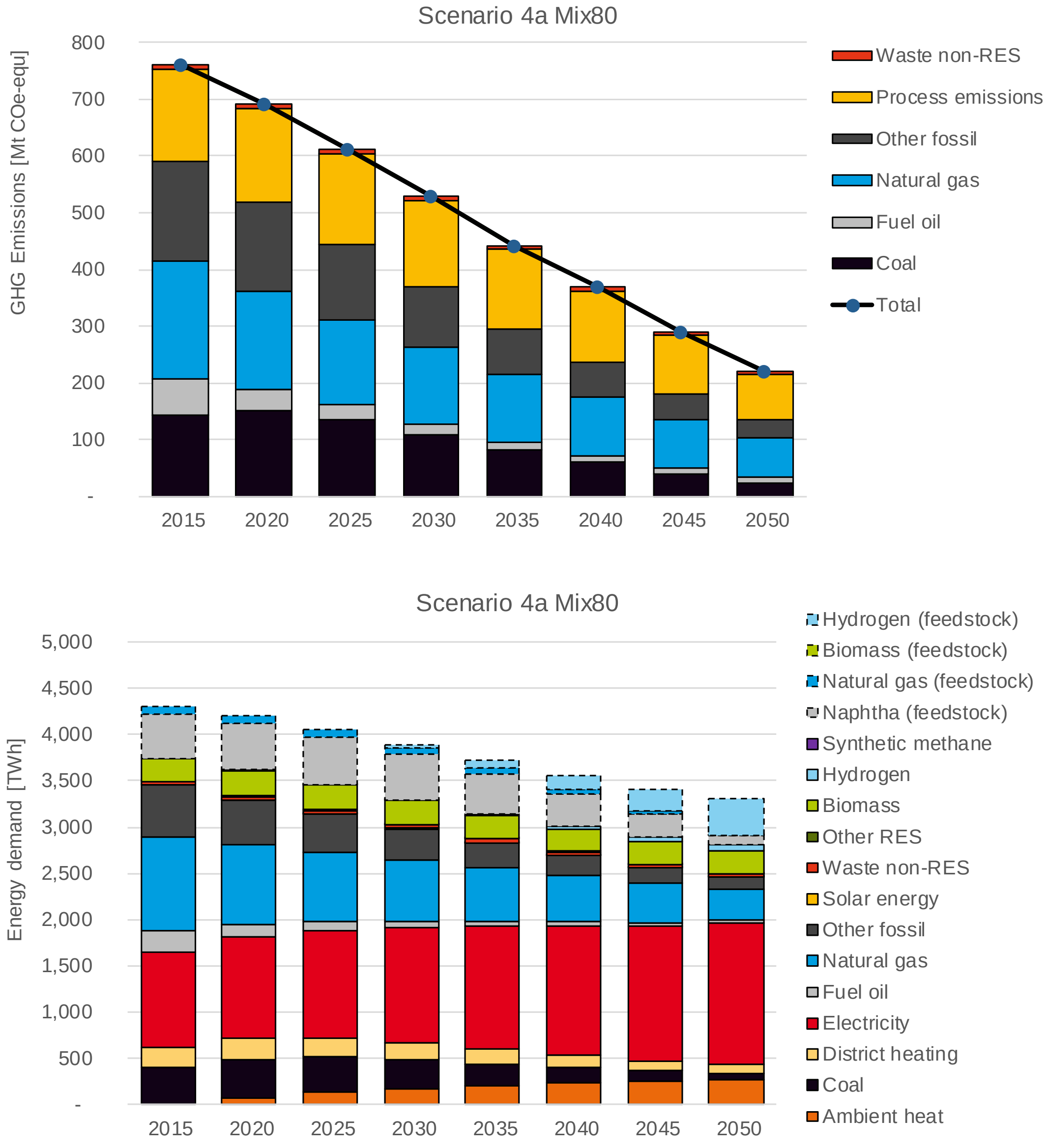


3.2.7 Scenario 4a Mix80

The scenario 4a uses mitigation options of various types explored in the scenarios 3a to 3d including energy-efficient and low-carbon production innovations, renewable-based electricity and hydrogen, a comprehensive circular economy and material efficiency improvements. The latter are, however, a little less ambitious than in the scenario 3c BioCycle. The scenario 4a Mix80 excludes the use of CCS and reduces the need of biomass to more or less the same level of use as in 2015. Also, the feed-in of synthetic gas in the natural gas grid is not considered.

Results show a reduction of 71% of GHG emissions by 2050 compared to 2015, which equals an 82% reduction when compared to 1990 levels. Driven by energy and material efficiency improvements, final energy demand decreases by about 25% towards 2050. H2 feedstock use is assumed to take place at a large scale (80% of ethylene, ammonia and methanol). While natural gas, biomass and ambient heat also play an important role, electricity is clearly the major energy carrier in 2050. Where possible, the direct use of electricity is preferred over the indirect use; for example, electrolysis-based hydrogen. The resulting total electricity demand increases from 1,041 TWh in 2015 to about 2,162 TWh in 2050 including 632 TWh for hydrogen production. Remaining mitigation efforts need to focus on replacing the left-over gas demand or the process-related emissions.

Figure 3.7 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 4a Mix80 by energy carrier (EU-28)



3.2.8 Scenario 4b Mix95

The scenario 4b Mix95 builds on the assumptions of the scenario 4a Mix80 and adds:

- CCS for the major remaining process emissions in lime, remaining cement clinker kilns and refineries,
- replacement of natural gas by synthetic methane in the gas grid (95% of natural gas replaced),
- "early replacement" of steam generation technologies before their end-of-life,
- increased market diffusion of innovative CO2-free production technologies in steel, chemicals and cement to 100%,

- and faster transformation of the buildings and transport sectors reducing the demand for conventional refinery products.

Results show a reduction of GHG emissions by 92% by 2050 compared to 2015, which equals about 95% compared to 1990.

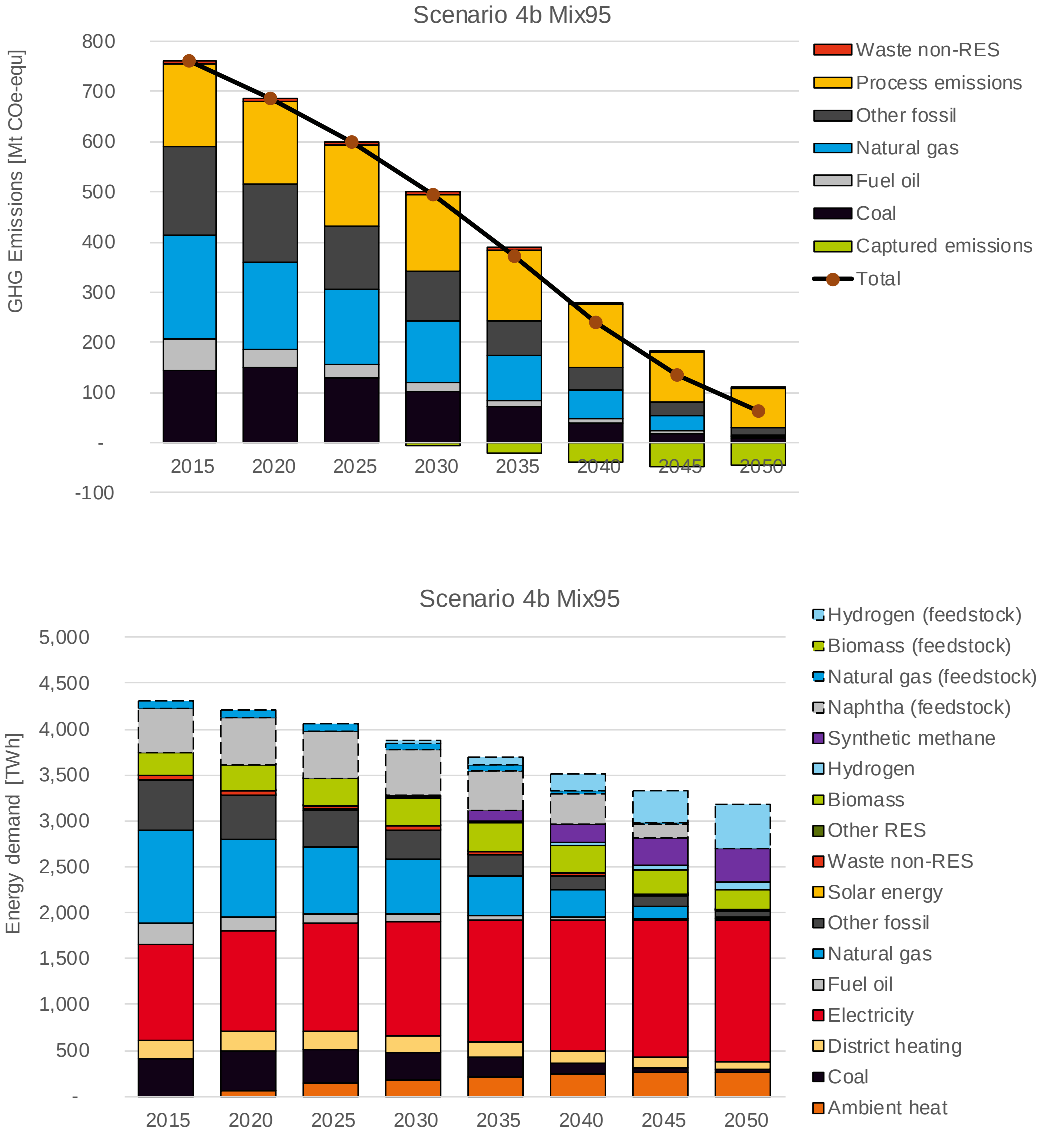
Electricity is the most important energy carrier in 2050 followed by hydrogen (mainly for feedstock use), synthetic methane, biomass and ambient heat. District heating falls substantially. However, from a systems perspective it might be more cost-efficient to use heat grids. Only minor shares of fossil fuels remain in 2050. In total, electricity demand increases from 1,041 TWh in 2015 to 2,946 TWh in 2050 of which 1,539 TWh are directly used and 1,407 TWh are needed for the production of hydrogen and synthetic methane via electrolysis.

CCS is used substantially less than in the scenario 3a CCS reflecting the radical transition taking place in all sub-sectors. Only emission sources which seem - from today's perspective - very difficult to decarbonise by other means use CCS (e.g. lime and clinker). In total 46 Mt CO2 are captured and stored in 2050.

The scenarios include ambitious changes in the entire industrial production system. The speed of change is rapid and targets a nearly 100% transition by 2050. In some cases, this requires early replacement of technologies before they reach their ordinary end-of-life, which increases overall investment needs and costs.

More ambitious mitigation efforts towards full CO2-neutrality need to address remaining smaller (distributed) sources of process emissions or focus on negative emissions like biomass in combination with CCS e.g. in the clinker kilns to compensate for smaller more distributed sources of process emissions that would be costlier (or impossible) to address via CCS.

Figure 3.8 Total industrial GHG emissions (top) and final energy demand (bottom) scenario 4b Mix95 by energy carrier (EU-28)



3.3 Comparison of scenarios

3.3.1 GHG emissions

The GHG emissions covered in the FORECAST model amount to about 761 Mt CO2-equ in 2015 for the EU industry sector including refineries. The major sources are process-related emissions, coal, natural gas and other fossil fuels. Towards 2050, all six scenarios show a decreasing GHG emissions trend. Even in the reference scenario, a reduction of 12% is observed by 2050 compared to 2015. The BAT scenario achieves a reduction of 35% and all four decarbonisation scenarios achieve substantially larger reductions. These range from 92% (4b Mix95) to 66% (3d Electric), as shown in Table 3.1. Compared to 1990, these emission reductions are even larger, as industry reduced emissions by about 37% in the period from 1990 to 2015 (source: EEA). Consequently, the decarbonisation scenarios range between 95% and 79% reductions by 2050 compared to 1990. As such, all decarbonisation scenarios are in line with a reduction of at least about 80% GHG by 2050 compared to 1990. The scenario 4b Mix95 achieves an even larger reduction of about 95%.

Table 3.1 Overview of emission reduction by scenario in 2050 compared to 2015 and 1990 [Mt CO_2-equ]

Scenario	2015	2050	Change 2050/2015	Estimated change 2050/1990*
1 Ref	761	665	-12%	-45%
2 BAT	761	493	-35%	-59%
3a CCS	761	157	-79%	-87%
3b CleanGas	761	216	-72%	-82%
3c BioCycle	761	245	-68%	-80%
3d Electric	761	255	-66%	-79%
4a Mix80	761	221	-71%	-82%
4b Mix95	761	63	-92%	-95%

** The change compared to 1990 is calculated by taking the change compared to 2015 and adding the relative reduction of 37% achieved from 1990 to 2015 according to the EEA.*

As observed in Figure 3.9, GHG reduction is relatively continuous over time towards 2050 in all scenarios and all emission sources contribute to the reduction. However, the relative importance of process-related emissions increases towards 2050, while other emission sources like coal, other fossils or natural gas decrease rapidly in scenarios 3b to 4b.

The main drivers of GHG emissions as well as major mitigation options differ across the scenarios. In *scenario 1 Ref* the continuation of past trends like slow and continuous fuel switch away from coal and fuel oil drive emissions slowly downwards. In *scenario 2 BAT a* more ambitious fuel switch and energy efficiency play important roles and achieve substantial additional emission reductions compared to the reference scenario. In the *scenario 3a CCS,* CCS is the main factor for decreasing emissions beyond what is achieved in *scenario 2 BAT*. In *scenario 3b CleanGas* the main GHG reductions are driven by feeding synthetic methane into the gas grid and by introducing new hydrogen-based production routes in steel and chemicals as well as additional process innovations such as new cement types. *Scenario 3c BioCycle* achieves emission reductions via a comprehensive transition to a circular and material efficient economy combined with a strong use of biomass as an energy carrier and feedstock and innovative energy-efficient production technologies. *Scenario 3d Electric* achieves major emission cuts via fuel-switching to electricity for process heating and indirect use of electricity using hydrogen in steel production and chemical feedstocks as well as low-carbon production innovations in other sub-sectors. The *scenario 4a Mix80* uses a combination of mitigation options including a fuel switch to electricity, low-carbon production innovations, hydrogen, a circular economy and material efficiency. *Scenario 4b Mix95* adds to this clean gas, CCS, a more ambitious fuel switch, faster diffusion of low-carbon production technologies in steel, cement, chemicals and others.

In most decarbonisation scenarios, fossil fuels are still used in 2050, while only the scenario 4b Mix95 achieves a nearly complete phase-out of fossil fuels. The reasons for remaining use of fossil fuels are: long capital lifetime, inertia in the technology stock replacement and remaining niches (e.g. a natural gas boiler installed in 2030 is likely to still be in operation in 2050). The nearly complete phase-out of fossil fuels for process heating in 2050 is - among others - achieved by a faster increase in CO2 prices, providing needed cost incentives early and replacement of fossil-based steam generation technologies before they reach their end-of-life.

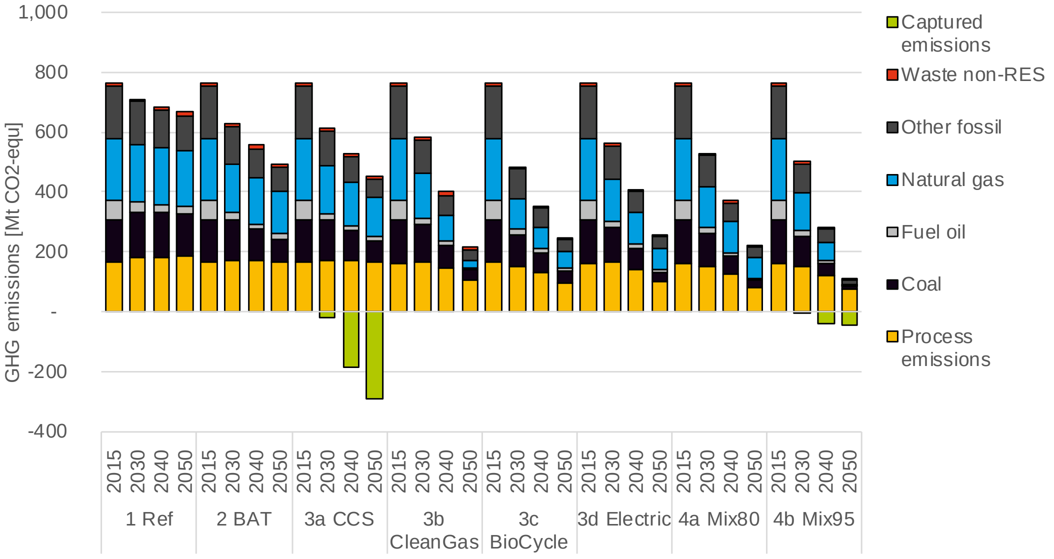
CCS is included in two scenarios. *Scenario 3a CCS* shows a technology development relatively similar to *scenario 2 BAT* (including, however, innovative energy-efficient technologies), but adds CCS. In 2050 about 293 Mt CO2 are captured and stored across many industries, including iron and steel, cement, lime, glass, chemicals, paper production and refineries. The *scenario 4b Mix95 also* includes CCS, however, due to an ambitious diffusion of other mitigation options, less large point sources remain, and its application is limited to the clinker and lime production as well as refineries.

Process emissions are reduced in *scenarios 3b to 4b* via the use of innovative low-carbon cement types as well as a more ambitious material efficiency and circular economy. The latter is particularly pronounced in scenarios 3c, 4a and 4b. New cement types also include concrete that absorbs CO2 during curing, representing a form of carbon capture and use (CCU).

Other forms of CCU are not included in the scenarios on a large scale. Mainly because short product lifetimes would not result in net long-term emission reductions or require additional carbon capture at the end of the product use chain (e.g. waste incineration). However, CCU might play a role in providing the needed carbon to produce synthetic methane from hydrogen. If this is not extracted from the atmosphere, but instead re-used from industrial point sources this increases the economy of synthetic methane. However, it will not mitigate additional CO2 emissions, because the CO2 is released into the atmosphere again when the methane is burned.

In the *scenario 3b CleanGas*, natural gas is replaced by renewable synthetic methane using the existing grid infrastructure, which results in drastically falling natural gas emissions towards 2050. The scenario 4b Mix95 uses all measures including CCS and synthetic methane feed-in.

Figure 3.9 Total industrial GHG emissions by scenario and energy carrier (EU-28)



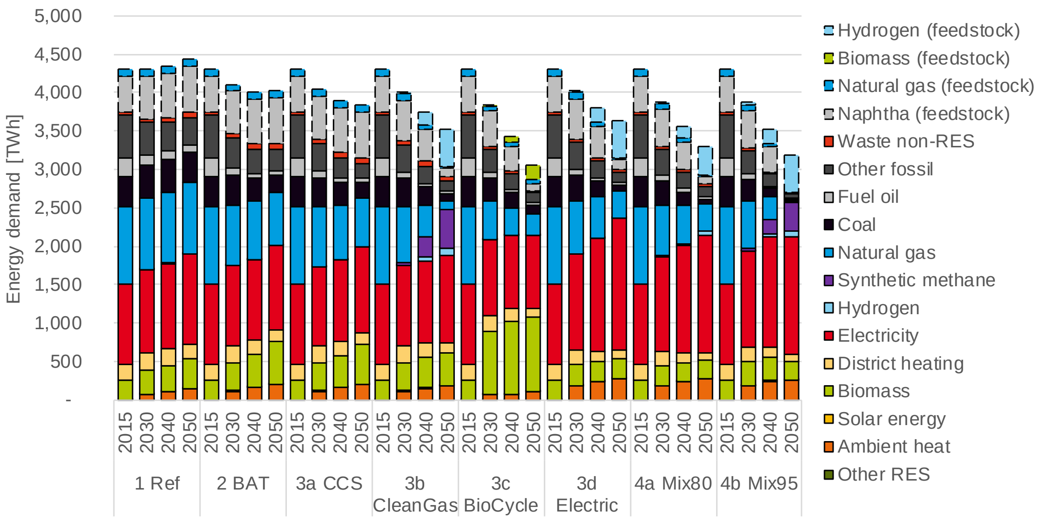
3.3.2 Energy demand and feedstocks

An overview of total energy demand is provided in Figure 3.10 and Table A3.1 including both final energy demand (FED) and feedstock use. Industrial FED remains stable in the reference scenario from 2015 to 2050. Applying the best available technologies (scenario 2 BAT) achieves a reduction of 11% compared to 2015 or about 410 TWh energy savings compared to the reference scenario. All decarbonisation scenarios show a lower FED in 2050 than in 2015 ranging from -16% (3a CCS) to -27% (3c BioCycle).

Feedstock demand for ethylene (olefines), ammonia and methanol production does not undergo major changes in scenarios 1 to 3a, while scenarios 3b to 4b show a radical change from fossil-based feedstocks (natural gas and naphtha) to renewable energy (hydrogen or bio-ethanol). In scenarios 3b, 3d and 4a, 80% of naphtha and natural gas feedstock use are replaced by hydrogen in 2050, while scenario 4b assumes a 100% replacement. In scenario 3b BioCycle, 80% of naphtha use for ethylene production is replaced by biomass.

Synthetic methane is fed into the gas grid in the scenarios 3b CleanGas and 4b Mix95 and amounts to 490 and 367 TWh in 2050, respectively.

Figure 3.10 Total industrial energy demand by scenario and energy carrier incl. feedstocks and final energy (EU-28)



Dotted bars relate to feedstock demand. Hydrogen is split up into feedstock and energetic use. Electricity consumption does not include demand for hydrogen electrolysis. Natural gas demand and synthetic methane are separated. Biomass feedstock demand equals methanol.

Regarding energy carrier developments, it can be observed that ambient heat (via heat pumps for low temperature process and space heating) gains market share rapidly but reaches saturation at about 4 to 10% of FED reflecting technical limitations related to temperature levels.

Biomass grows by more than 100% in scenarios 2 BAT and 3a CCS. A particularly strong growth of 287% to a total of 970 TWh in 2050 is shown in scenario 3c BioCycle. In the remaining scenarios, biomass competes with direct electricity use and clean gas. It does not grow substantially beyond today's level. In scenario 4b Mix95 a small decrease of 9% is even observed, while its use remains constant in scenario 4a Mix80. This does not take into account any biomass used to supply CO2 feedstock in the production of clean gas.

While coal use is relatively constant in the reference scenario (due to a steady demand from the steel industry), it falls in all other scenarios with varying speeds. The reduction is mainly driven by changes in the steel industry including an ambitious shift towards electric steel (2-4b), replacement by H2 and electrolysis direct reduction steel (3b and 3d, 4a and 4b) and decreasing steel demand due to increased material efficiency (3c, 4a and 4b).

Natural gas demand falls in all scenarios, but also manages to retain some market share in 2050 even in the decarbonisation scenarios 3a to 4a. Only the scenario 4b Mix95 phases out natural gas nearly completely. The scenario 3b CleanGas converts 80% of natural gas demand to (renewable) synthetic methane by 2050. In the scenario 4b Mix95 this is the case for 95%.

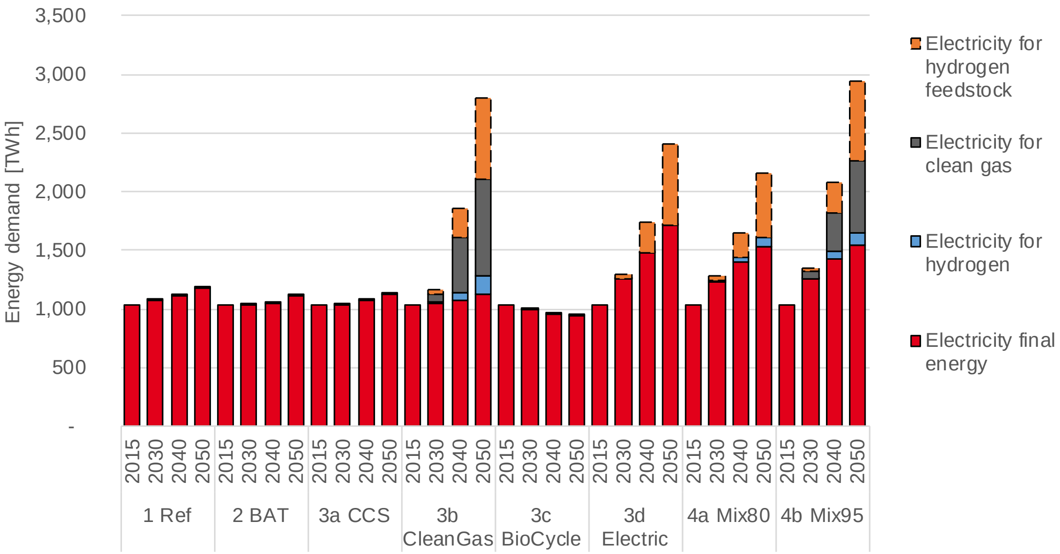
Two types of **electricity demand** are distinguished in this study. One is the direct use of electricity as final energy mainly for mechanical energy and heating. The second is the indirect use via electrolysis-based secondary energy carrier's hydrogen and synthetic methane. A comparison of the electricity demand for both types in Figure 3.11 and Figure 3.12 shows a diverse picture across scenarios. The reference scenario experiences an increased electricity demand of about 13% where economic growth overcompensates energy efficiency gains. The BAT scenario nearly achieves a stabilisation of electricity demand (+6% compared to 2015) due to the implementation of the best available energy efficiency technologies. Only scenario 3c BioCycle shows a small reduction (-9%), driven by material efficiency gains along the product value chain as well as a strong focus on biomass instead of electricity for process heat generation.

Scenarios 3b, 3d, 4a and 4b show a drastic increase in electricity demand driven by the large-scale use for process heating as well as the use of hydrogen and synthetic methane: +169% (3b CleanGas), +132% (3d Electric), +108% (4a Mix80) and +183% (4b Mix80). In the scenario 3b CleanGas, the increase in electricity is driven by three main factors. First, a switch in the steel industry from oxygen steel to direct reduced steel based on H2, second, a shift to H2-based feedstocks in the chemical industry (ammonia, methanol and ethylene) and, third, the feed-in of synthetic methane in the gas grid. Hydrogen is assumed to be produced onsite via electrolysis. In the place of clean gas, scenario 3d Electric explores a broad shift towards the direct use of electricity in process heat generation. This includes heat pumps where applicable, but also electric boilers for industrial steam generation and electric furnaces e.g. in glass melting or even electric clinker kilns. As a consequence, electricity demand including electrolysis increases to 2,797 TWh (3b CleanGas) and 2,412 TWh (3d Electric) by 2050.

The scenario 4a Mix80 shows a slightly smaller increase to 2,162 TWh in 2050. Compared to the scenario 4d Electric, this is slightly smaller due to additional recycling and material efficiency gains, but it also includes H2 in the steel industry, H2 for chemical feedstocks and electricity as process heat supply. The step from 82% to 95% decarbonisation by 2050 adds additional demand for electricity in the form of more hydrogen as well as synthetic methane, resulting in a total of 2,946 TWh in 2050, which is nearly threefold compared to 2015.

Regarding the diffusion pathway, the rapid increase of electricity demand takes place after 2030.

Figure 3.11 Industrial electricity demand in final energy by scenario (EU-28) incl. production of feedstocks, clean gas and hydrogen



A sectoral breakdown of electricity demand for final energy use including process heating, but not accounting for indirect use via clean gases is shown in Figure 3.12. The increase in scenarios 3d, 4a and 4b is driven by electricity use for process heating. Here, all sub-sectors show an increase, resulting in a very diverse picture in 2050.

Figure 3.12 Industrial electricity demand in final energy by scenario and sub-sector (EU-28) excluding production of feedstocks, clean gas and hydrogen

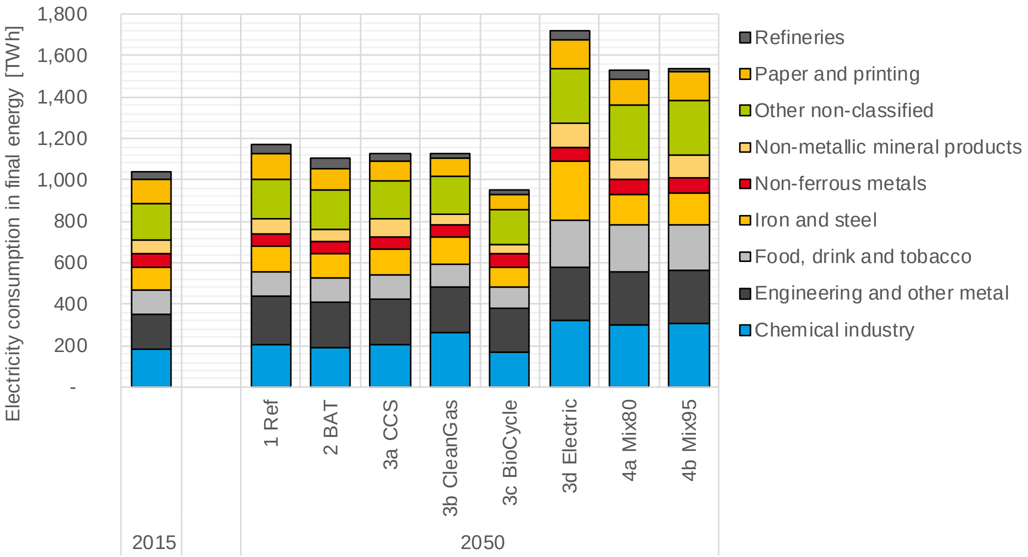


Figure 3.13 shows the total biomass demand of the industry sector by scenario. It can be observed that biomass demand increases in scenarios 1 to 3c until 2050 compared to 2015. A specifically high biomass demand is observed in scenario 3c BioCycle, which reflects a broad shift towards biomass for process heat generation, but also as a feedstock for the production of ethylene via ethanol. In this scenario,

biomass demand grows from 251 TWh in 2015 to about 1,167 TWh in 2050 including a feedstock biomass demand for ethylene production of 197 TWh in 2050 (see chemical industry chapter for more specific definitions).

The scenarios 3d to 4b show a constant or decreasing biomass demand, as it is replaced by the large-scale use of electricity for process heating (low and high temperature).

Figure 3.13 Industrial biomass demand by scenario (EU-28) including feedstock demand

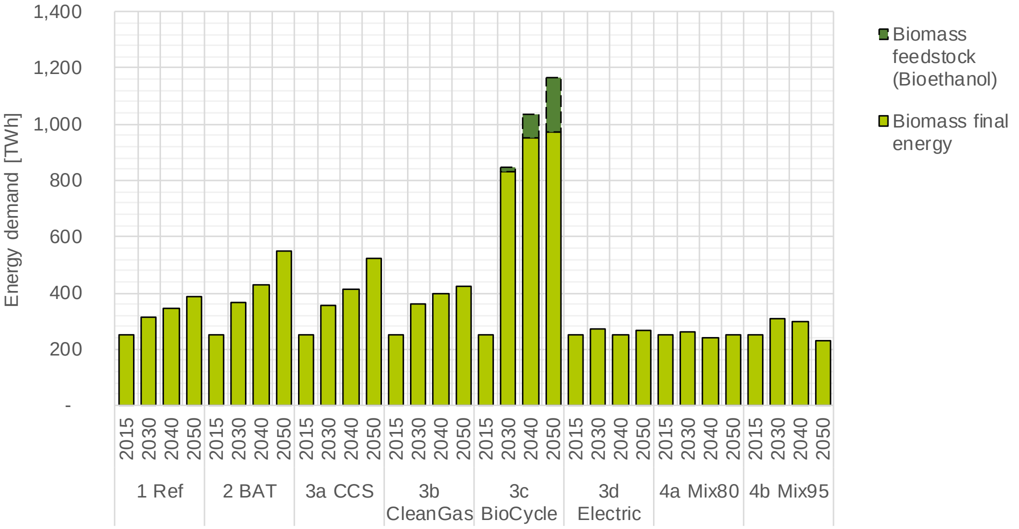
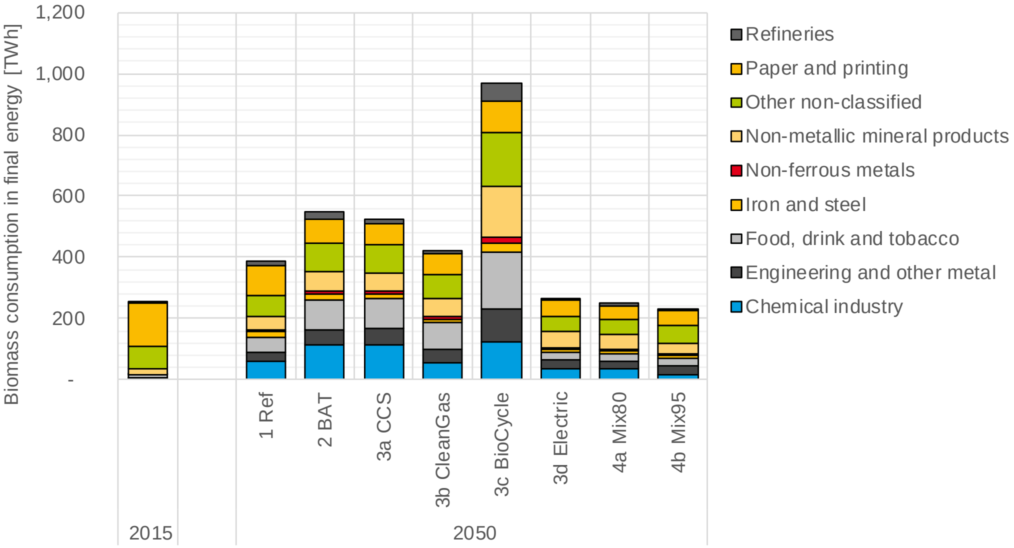


Figure 3.14 Industrial biomass demand in final energy by scenario and sub-sector (EU-28) excluding feedstock demand

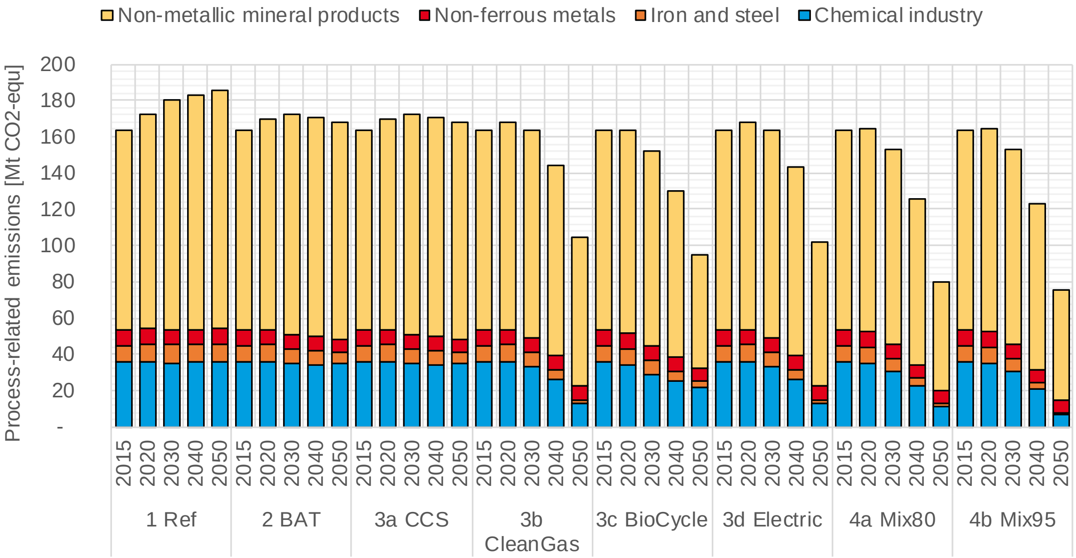


3.3.3 Process-related emissions

Process-related emissions exhibit a specific challenge to industry sector decarbonisation as in most cases, technical options for mitigation are not available. CCS is often the only option in discussion. Furthermore, with increasing levels of ambition and increasing RES-deployment, the relative importance of process emissions increases. In 2015, process emissions are dominated by the non-metallic minerals industry and the chemical industry.

While the process-related emissions remain more or less stable in scenarios 1 to 3a CCS, they fall substantially in the remaining scenarios as shown in Figure 3.15. Note that the process emissions shown for scenarios 4a CCS and 4b Mix95 are gross emissions, not yet corrected for CCS. The substantial decrease of (gross) process emissions is driven by two factors: one of them is the diffusion of innovative process technologies including low-carbon cement types and hydrogen-based chemicals, the other factor are changes along the product value chain. These changes include material efficiency and recycling in the construction industry as well as organic agriculture reducing the demand for ammonia fertilisers.

Figure 3.15 (gross) Process emissions by sector before possible CO2 capture (EU-28)



As a consequence, the scenario 4b Mix95 reduces (gross) process emissions by 54% compared to 2015. Figure 3.16 breaks down the remaining (gross) process emissions in 2050 by process and scenarios. It becomes evident that major sources are reduced substantially in the ambitious decarbonisation scenarios compared to the scenario 1 Ref. The large emission sources are briefly discussed by comparing the scenario 4b Mix95 with the scenario 1 Ref for 2050:

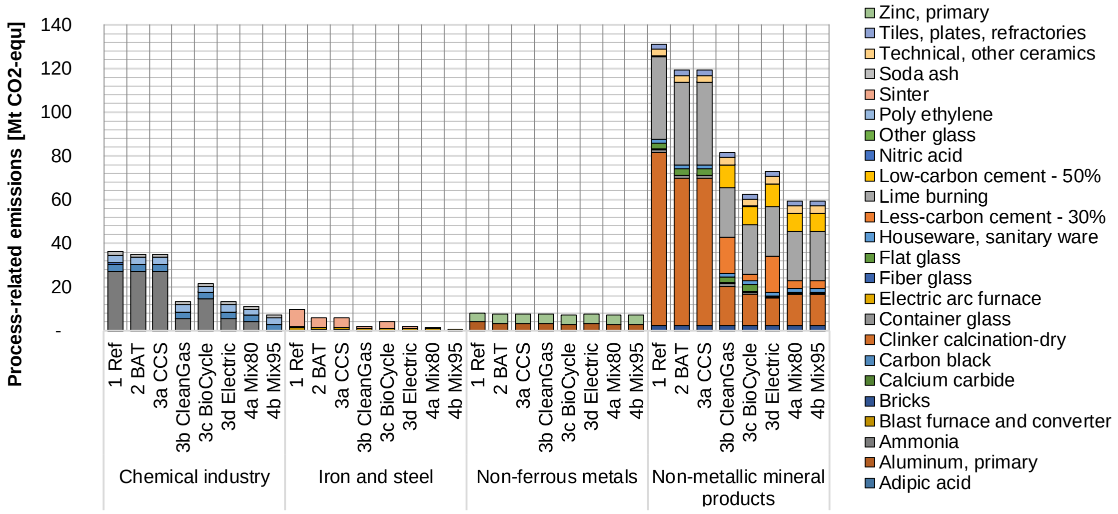
- Lime emissions go down by 40% as a result of lower production, because nearly 40% of lime is today used in basic oxygen steelmaking, which will have been phased out in the scenario. In 2050 about 22 Mt CO2 are still emitted by lime production, some of which is then subject to CCS.
- Clinker related emissions decrease by about 67% as a result of material efficiency and new low-carbon cement types. However, even production of some of the low-carbon cements still emits CO2 and not all plants are replaced due to the high inertia in the construction industry. In 2050 about 25 Mt CO2 remain from cement production. Of these 25 Mt, a high share is stored via CCS.
- Process emissions that occur during conventional ammonia production via steam reforming are completely mitigated via replacements, by shifting towards hydrogen produced from renewable energy sources via electrolysis ("ammonia H2").

- In the steel industry, process emissions from sinter and blast furnaces are also reduced to zero via the full replacement with alternative steel production routes.

With a total of 62 Mt CO2-equ emissions in 2050 across all emission sources in the scenario 4b Mix95, the smaller sources of process emissions also become very important on the way towards CO2-neutrality.

These smaller sources include among others, emissions from soda ash (1.4 Mt CO2-equ in 2050), polyethylene (2.8 Mt), carbon black (3 Mt), electric arc furnace (1 Mt), primary zinc (4 Mt), primary aluminium (3.1 Mt), ceramics (7 Mt), glass (1.4 Mt) and bricks (3.4 Mt). In total, these smaller sources account for 28.1 Mt CO2-equ in 2050 in the scenario 4b Mix95. This is equivalent to 45% of the overall remaining emissions in 2050. CCS will most likely not be an option for these very distributed sources. Consequently, emission reductions beyond 95% compared to 1990 need to also find solutions for these sources. The assessment and identification of such solutions is subject to future studies and was not part of this work.

Figure 3.16 Remaining (gross) process emissions by sector and process in 2050 before CO2 capture (EU-28)



3.3.4 Carbon capture and storage (CCS)

CCS is included in two scenarios: 3a CCS and 4b Mix95. The technology assumptions for CCS are summarised below. Capture rates between 60 and 100% were assumed (see Table 3.2). The specific energy demand for capture is assumed at about 220 kWh/ tonne of CO2 captured. In both scenarios, we assume that only electricity is used for emission capture, which is expected to be realistic after 2030 (Kuramochi et al. 2012). The diffusion of CCS technology is assumed exogenously as summarised in Table 3.3. In the scenario 3a CCS, towards 2050 nearly the entire production capacity is equipped with capture technology for major processes in the chemicals, cement, lime and steel sectors. Due to more diverse production capacities and smaller CO2-streams, the glass and paper industries show a less ambitious diffusion of CCS. In the scenario 3a CCS 50% of the capacity in both sectors is equipped with CCS. The scenario 4b Mix95 does only assume CCS for clinker and lime production as well as refineries, because other major emitters already mitigate emissions via other options.

Table 3.2 Assumed CCS capture rates by sector for all scenarios

Sector	2030	2040	2050
Chemicals	90%	95%	95%
Cement	70%	80%	80%
Glass	70%	80%	80%
Lime	80%	90%	100%
Iron and steel	60%	65%	65%
Pulp and paper	60%	65%	65%

Table 3.3 Assumed CCS diffusion by sector as share of total production capacity

	3a CCS			4b Mix95		
Sector	2030	2040	2050	2030	2040	2050
Chemicals	8%	85%	95%	0%	0%	0%
Cement	1%	20%	90%	1%	20%	95%
Glass	0%	5%	50%	0%	0%	0%
Lime	19%	57%	95%	19%	57%	95%
Iron and steel	3%	69%	95%	0%	0%	0%
Pulp and paper	0%	5%	50%	0%	0%	0%
Refineries	3%	69%	95%	3%	69%	95%

The resulting impact of the diffusion of CCS equipment in terms of CO2 captured and additional energy consumption for the capture process is shown in the following figures.

Accordingly, the total CO2 captured in 2050 in the scenario 3a CCS increases to about 294 Mt CO2/a. The demand is dominated by the cement and lime sectors but chemicals and iron and steel also play an important role. The use of biomass mainly in the paper industry results in bio-energy CCS (BECCS).

In the scenario 4b Mix95, the total CO2 captured in 2050 is substantially lower with about 46 Mt CO2/a. This is explained by three main factors: first, alternative production technologies gain large market shares of mostly 100% in all energy-intensive sectors (e.g. low-carbon cement, H2-based chemicals and steel). Second, in glass and paper, CCS was not allowed as it is more unlikely in these sectors. Third, renewable electricity and clean gas reduce CO2 emissions drastically, which leaves little space for additional CCS. Consequently, a major application of CCS is the non-metallic minerals industry, where process emissions are difficult to mitigate. Here, it is mainly lime burning that applies CCS, because alternative mitigation options are not available.

To conclude, while the large-scale introduction of CCS might be related to substantial lock-ins, it might play a reasonable role in scenarios that aim for CO2-neutrality. The application of CCS to generate "negative emissions" via BECCS or via the capture of synthetic methane, in particular, could be an option to compensate for the many remaining small and distributed emission sources that would be costly to mitigate.

Figure 3.17 CO2 captured via CCS by sector and scenario (EU-28)

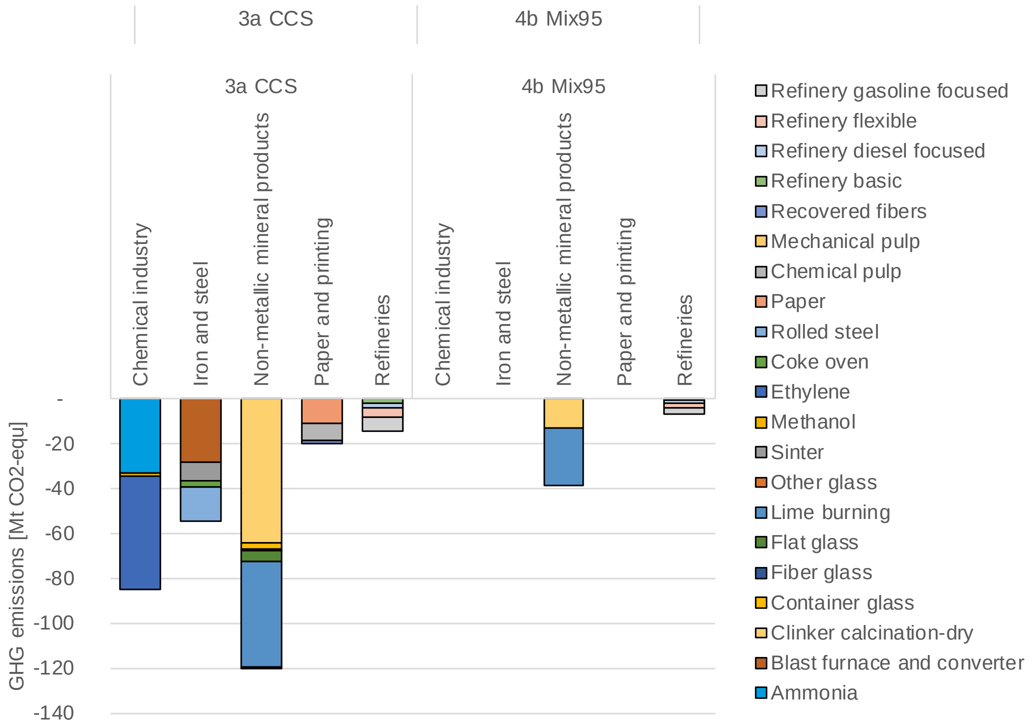
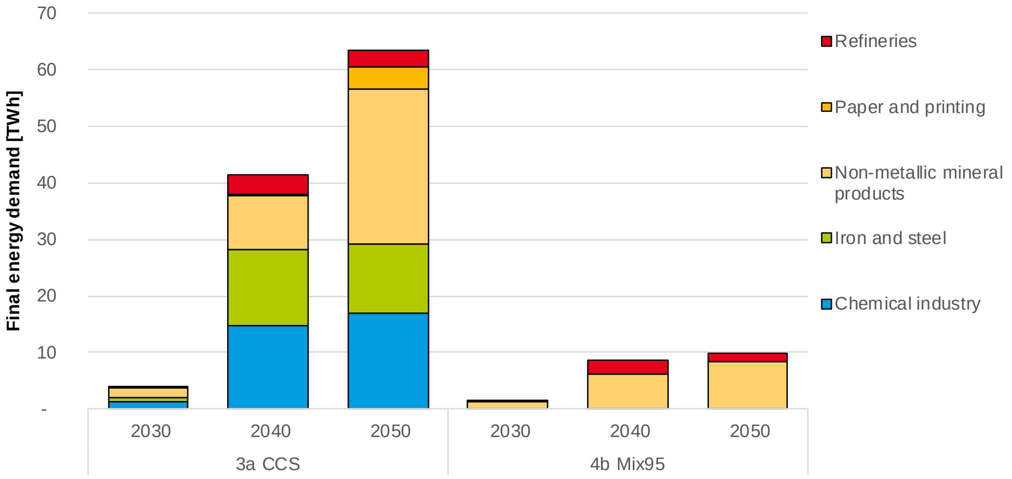


Figure 3.18 CO2 captured via CCS by process and scenario in 2050 (EU-28)

CO2 capture is a very energy-intensive process. It adds an additional electricity demand of 63 and 10 TWh to the scenarios 3a CCS and 4b Mix95, respectively. This is equal to about 6% (3a CCS) and 1% (4b Mix95) of the industrial sector electricity demand in 2015.

Figure 3.19 Additional electricity consumption of CO2 capture by sector (EU-28)



3.3.5 Costs, investment and energy expenditures

Our definition and analysis of costs follows a system costs approach that accounts for all costs related to the technical change in the energy system (CAPEX and OPEX incl. energy expenditures). The ultimate goal is the calculation of changes in the total energy system costs compared to the reference scenario. This involves the following definitions:

- The **total energy system costs** are the sum of the costs of capital (annuity payments of investment expenditures) and the energy expenditures in a certain year. Thus, all expenditures plus costs of finance are considered. The energy system costs can be cumulated over time periods.
- The **costs of capital** for a given year are calculated as the sum of all annuities payments for that specific year. Annuity payments are calculated using a discount rate of 7%, which reflects current weighted average costs of capital for industry (WACCs) in the EU.[7] The same discount rate is used for all scenarios. Further, for the calculation of annuities the technical lifetime of equipment is used. This means e.g. 25 years for industrial furnaces, 15 years for steam systems, 35 years for buildings and 30 years for CCS infrastructure.
- **Investment expenditures**: CAPEX (Upfront investments) and OPEX (excluding energy expenditures). Can be reported for individual years or cumulated over periods of time.
- **Energy expenditures**: are reported as annual values or cumulative values over several years. They are based on average industry energy prices per country and energy carrier.

The following additional assumptions are made:

- All costs are reported as the difference compared to scenario 1 Ref if not otherwise stated.
- Only costs related to the technical energy system are reported. This excludes e.g. external costs, macro-economic effects, etc.
- Costs are nominal with the reference year 2015.
- As for the entire report, the system boundary is the industry sector, which excludes the production of secondary energy carriers like electricity, district heating or hydrogen. Therefore, investment estimates do not include the associated costs, though they are captured indirectly through the assumed energy expenditures.
- Investments expenditures and saved material expenditures related to downstream material efficiency and circular economy are not included due to a very low data availability and a huge diversity in technologies and activities in this field.

The development of **energy expenditures** over time compared across the scenarios shows huge differences. Figure 3.20 shows the total energy expenditures in the EU-28 industry as a time series towards 2050. Starting with about 260 billion

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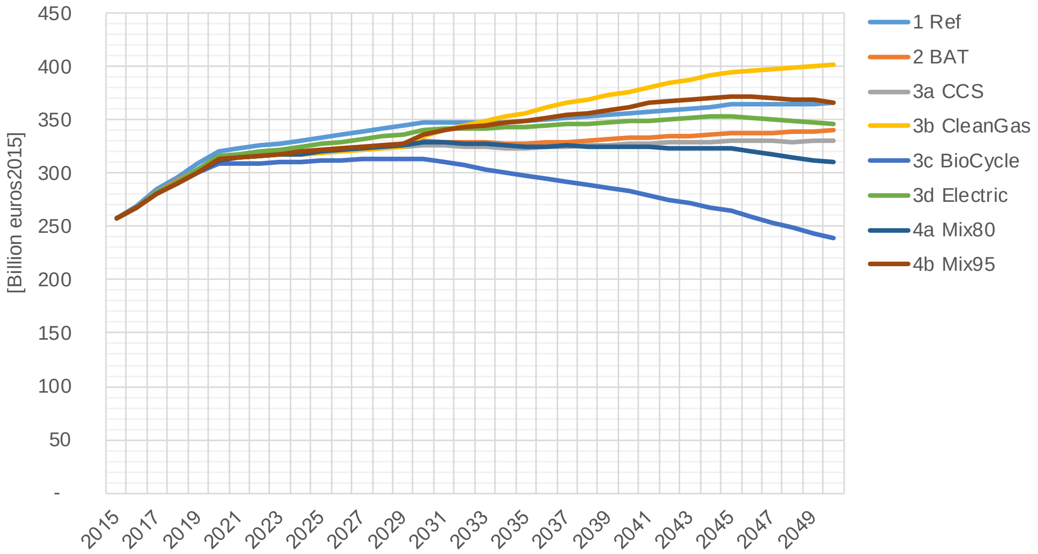
[7] Note that the 7% discount rate has been used for the cost calculation after the model runs were conducted. This discount rate is not to be confused with discount rates used to simulate investment decisions of individual actors during the simulation run. Here, other discount rates are used depending on the scenario and the actor/investment.

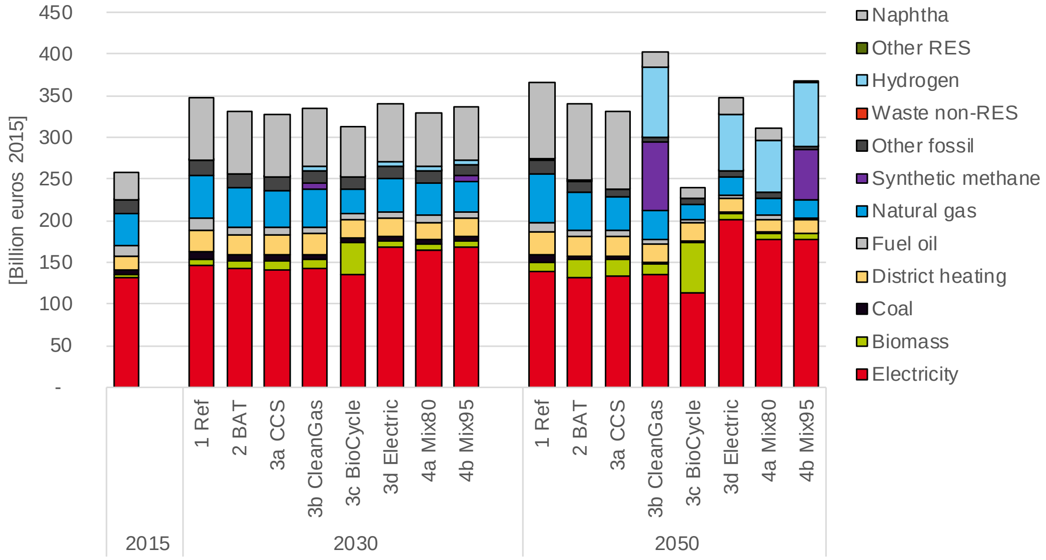
euros in 2015, an increase towards 2020 can be observed, which is explained by rising energy prices in the short term. Also after 2020, increasing prices for fossil fuels (fuel oil, natural gas, naphtha) drive the overall energy expenditures upwards in all scenarios, whereas this effect is overcompensated by factors that reduce costs in some scenarios. After 2020, the scenario *3c BioCycle* shows drastically falling energy expenditures, driven by energy savings induced via a large-scale shift to biomass as a relatively cheap energy carrier and to some extent also by material efficiency and circular economy improvements. Energy expenditures in the reference scenario increase to 366 billion in 2050, which reflects an increase by 42% compared to 2015. The *scenario 3d Electric* arrives at an about 20 billion euros lower energy bill in 2050, where additional energy efficiency gains are compensated for by a switch to electricity entailing higher average energy prices. *Scenarios 3b CleanGas and 4b Mix95* both show the highest increase with 56% and 42%, respectively. This is in both cases driven by the switch from natural gas to synthetic methane (and hydrogen). In *scenario 4b Mix95* the increase is curbed by additional gains in material efficiency. The annual energy expenditures in 2050 are at about the same level as they are in the reference scenario.

Figure 3.20 Total annual energy expenditures by scenario, EU-28



Regarding the individual energy carriers, energy expenditures are dominated by electricity in most scenarios throughout the years 2015, 2030 and 2050 as shown in Figure 3.21. While also the expenditures for naphtha as feedstock gain importance already in 2030 due both an increasing naphtha price and increasing demand for ethylene and other olefines. In 2050, hydrogen and synthetic methane also gain important shares in the scenarios 3b CleanGas and 4b Mix95. The shares of individual energy carriers provide additional explanations of the scenario differences. E.g. the decline in energy expenditures from scenario 1 Ref to scenario 2 BAT is explained by additional energy efficiency improvements (inducing electricity savings mainly), but also biomass replacing more expensive natural gas. The increasing price of naphtha (+125% from 2015 to 2050) is a factor that increases the energy expenditures in the reference scenario and scenarios 2 and 3a, which do continue to use naphtha as main feedstock.

Figure 3.21 Annual industry sector energy expenditures by scenario and energy carrier in 2015, 2030 and 2050

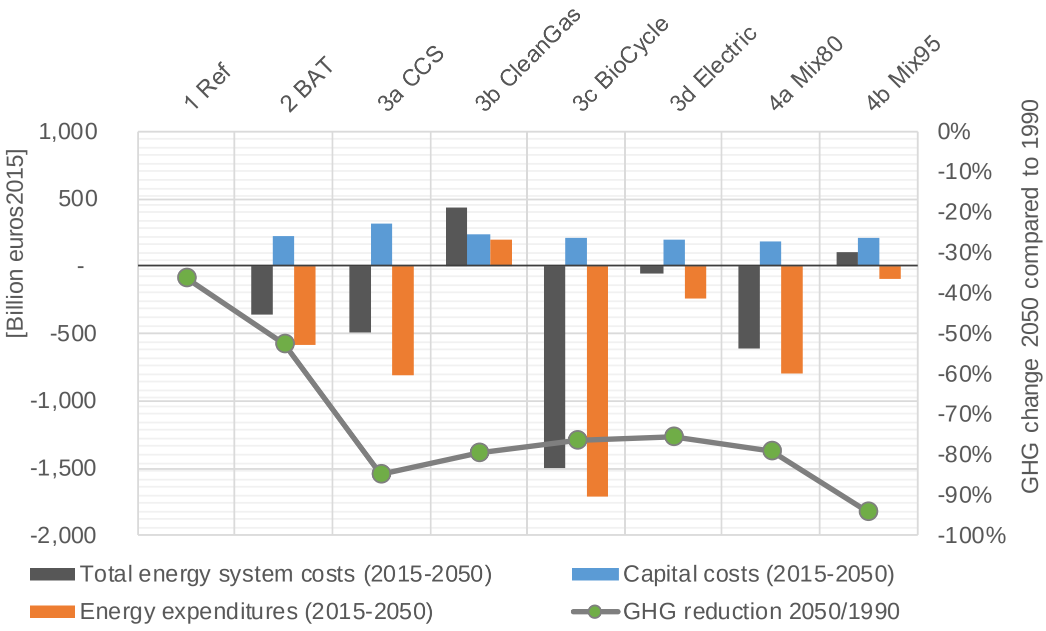


The overall cumulated **additional investment expenditures** from 2015 to 2050 compared to scenario 1 Ref are dominated by energy efficiency investments in building renovation, process optimisation and steam distribution systems in all scenarios. Scenario 3a CCS shows the highest investments, driven by the CCS capture, transport and storage infrastructure. Innovative low-carbon production processes like low-carbon cement, hydrogen-based chemicals or steel production routes make up for a smaller share of total (cumulated additional) investment expenditures. Four main reasons can be identified for this:

1. The additional costs of the innovative process compared only to the reference process are accounted for. For example, it is assumed that investment cycles are unchanged and that investment in innovative technologies takes place when re-investment would be undertaken anyway. Especially for the scenario 4b Mix95, this is a strong assumption, when technology diffusion needs to be relatively fast.
2. Hydrogen and synthetic methane are produced outside the system boundary. The costs of producing both are accounted as energy expenditures.
3. While large production plants demand huge individual investments, their total numbers are relatively small compared to the hundreds of thousands of investments in industrial buildings refurbishment, heating systems, etc.
4. Before 2030, investments in low-carbon production processes is marginal, main activity is R&D, which is not reflected in the cost assessment.

Overall, results for **total energy system costs** of the industry sector are summarised in Figure 3.22. The figure shows the cumulated costs over the entire time period from 2015 to 2050. It also shows capital costs and energy expenditures separately. Both are calculated as the difference compared to the scenario 1 Ref.

Figure 3.22 Cumulated total energy system costs from 2015 to 2050 by scenario as the difference to scenario 1 Ref (nominal values in Euro2015)



Note: Changes in investment and material expenditures due to downstream material efficiency are not included in this figure. These would change the system costs for all scenarios but mainly for scenarios 3c, 4a and 4b.

We can draw the following main conclusions for the individual scenarios:

- In scenario 1 Ref, energy expenditures are dominated by electricity purchases while increasing fossil fuel prices also increase the long-term energy expenditures for of natural gas, fuel oil, coal and naphtha. Also here, substantial investments take place, e.g. in energy efficiency improvements or in CHP heat supply units.
- *In scenario 2 BAT,* capital costs increase by about 220 billion euros. This increase, however, is overcompensated by savings in energy expenditures, which account for nearly 580 billion euros resulting in a reduction of net energy system costs of about 360 billion euros. The main drivers are energy efficiency investments and a moderate fuel switch to biomass as well as higher recycling rates for steel, paper and glass.
- In *scenario 3a CCS* (cumulated differential) increase in capital costs of about 310 billion euros, mainly driven by CCS capture, transport and storage infrastructure. The additional investment needs are overcompensated by further improved energy efficiency compared to BAT, through innovative energy-efficient technologies resulting in lower energy expenditures and lower energy system costs of about 810 billion euros.
- *Scenario 3b CleanGas* shows similar capital costs as scenario 2 BAT, whereas the energy expenditures increase by about 433 billion euros compared to scenario 1 Ref. This increase is driven by the high price of synthetic methane and, to a lesser extent, hydrogen. With the assumed system boundary, we assume that industry buys hydrogen and synthetic methane as it buys electricity. Thus, the actual investment expenditures for electrolysers etc. are included in the synthetic methane/hydrogen price. As a result the scenario shows about 200 billion euros higher total energy system

costs than the reference scenario. Note that the strongly increasing naphtha price (+125% from 2015 to 2050) makes the substitution by hydrogen as feedstock less costly in this scenario.

- *Scenario 3c BioCycle* has additional capital costs of about 210 billion euros and substantial lower energy expenditures of 1,700 billion euros. This is mainly driven by the switch to biomass as energy source as well as feedstock and a reduction of energy and feedstock demand via downstream material efficiency and circular economy measures. Note that downstream investments are not included in neither investment expenditures nor material expenditures. These would result in different total costs. However, the diversity of measures undertaken, and the low data availability currently do not allow the quantification of such investments. For feedstocks, the increase in naphtha prices (and other fossils) is a major reason for the strongly negative difference in energy expenditures, because it is replaced by comparably cheap biomass or saved via material efficiency and recycling of plastics. To be more precisely, the reduction of plastics demand and the reduced production of olefines alone reduces cumulated expenditures by about 300 billion euros. The replacement of naphtha as feedstock for ethylene production saves another 500 billion euros compared to the reference scenario. Although, the high use of biomass requires imports from international markets, which involves much higher biomass prices compared to today's use in industry, these prices are still substantially below the prices of fossil fuels, which are being replaced.
- *Scenario 3d Electric* shows (additional cumulated) capital costs of 200 billion euros and energy expenditures that are 250 billion euros lower than the reference scenario. The comparably high energy expenditures are explained by a large-scale shift to electricity, which has a higher price than the other fuels it replaces.
- *Scenario 4a Mix80* has a cumulated capital costs of 180 billion euros with energy expenditures about 790 billion euros lower than the reference scenario. While the switch to electricity increases energy expenditures, the material efficiency progress overcompensates this increase. The overall cumulated total energy system costs are about 610 billion euros lower than in the reference scenario.
- Finally, *scenario 4b Mix95* has additional cumulated total capital costs of about 200 billion euros and shows a decrease in energy expenditures of about 100 billion euros. The higher energy expenditures compared to scenario 4a Mix80 are mainly explained by the more ambitious level (-95% GHG reduction compared to 1990), which introduces the large-scale use of synthetic methane and hydrogen. The total cumulated energy system costs are about 100 billion euros (or ~1%) higher than in the reference scenario. To summarise, the combination of energy and material efficiency, recycling and increasing fossil fuel prices compensates for the extensive use of high-value energy carriers like synthetic methane, hydrogen and electricity resulting in similar overall energy expenditures as in the reference scenario.

Overall, it can be seen that changes in (cumulated) energy system costs are dominated by energy expenditures. Clean gas and electricity are relatively expensive options that dominate the respective scenarios heavily. Biomass might be a relatively cheap option but might not be available in that quantity. However, a reduction of about 80% GHG emissions (scenario 4a Mix80) seems possible with net negative energy system costs compared to the reference scenario, meaning that savings in energy expenditures overcompensate additional capital costs from investments. Energy efficiency plays a very important role in keeping the costs low. A more ambitious reduction (95% reduction) increases both the capital costs and energy expenditures. Particularly, if clean gas is part of the energy mix.

Regarding energy expenditures, the seemingly high differences of several hundreds of billion euros should be put into perspective when compared to the overall cumulated energy expenditures, which range between about 10,000 and 12,000 billion euros from 2015 to 2050 across the scenarios. Thus, savings of 100 billion euros, as in the scenario 4b Mix95, are approximately 1% of overall cumulated energy expenditures.

A major assumption made is that re-investment cycles do not change, meaning that investments in new production plants take place at the end of their lifetime when they would have been replaced anyway. This assumption considers only the differential costs of new technologies compared to the conventional technology. If market diffusion is required to happen very fast as in the case of the scenario 4b Mix95, this assumption becomes more unlikely and early replacement might be needed. This aspect is further discussed in section 3.3.6.

It has to be underlined that the costs of improvements of material efficiency and circular economy have not been included in this assessment. This affects all scenarios (even the reference scenario), but most of all scenarios 3c, 4a and 4b. The currently available (empirical) data does not allow an industry-wide quantification and the heterogeneity of measures and potentials is very high and still not well structured. Including costs of material efficiency and circular economy would most likely increase the investment expenditures and reduce the material expenditures. Recent publications indicate that the available potentials are huge (even larger than assumed here) and that a large share of the potentials is available at net negative costs meaning that it is cost-effective to do (Material Economics 2018). More precisely, the same study argues that 140 Mt CO2 could be mitigated within the EU by improved material efficiency and circular economy at negative costs (measured in euros/t CO2). Also here, the uncertainty is yet very high and the diversity of measures huge. These e.g. include flat and car sharing, re-using plastics products, extension of lifetime and remanufacturing of cars as well as better and more recycling of aluminium, steel and plastics.

Finally, it needs to be underlined that the energy expenditures are highly sensitive to energy price assumptions, which per definition are very uncertain and not predictable. The assumed increase in fossil fuels prices reduces the additional costs of the decarbonisation scenarios compared to the reference scenario. Thus, results have to be interpreted in the light of these assumptions and uncertainties.

3.3.6 Pathways, lock-ins and diffusion dynamics

In all the decarbonisation scenarios, the major change in the industrial production structure takes place between 2030 and 2050 leaving only about 20 years for technology diffusion. While scenarios 3a to 4a assume incomplete diffusion reaching market shares of about 80% by 2050, the scenario 4b Mix95 assumes a nearly full market penetration by 2050 and can be considered very ambitious in this regard. The diffusion path of radically new production processes has been an exogenous input to the scenarios.

Therefore, the scenarios can say little about the actual speed of process replacement and diffusion. They can, however, allow important conclusions on the overall direction of process change to be drawn. More particularly, they allow one to draw conclusions on whether the scenario is on track to deliver additional GHG reductions beyond 2050 or whether it will result in a lock-in situation where additional reduction might require the early replacement of young capital stock making the scenario costlier in the very long-term. For the individual scenarios this compatibility with long-term CO2-neutral industrial production is summarised as follows:

- **1 Ref**: the development is not on track. Towards 2050, the entire production capacity will be replaced or substantially retrofitted but based on technologies and processes that are not compatible with a long-term transition.
- **2 BAT**: while some elements, such as ambitious energy efficiency improvements, are in line with a long-term transition, even many of the energy efficiency optimisations are linked to existing fossil-based production routes. While these certainly have short-term benefits, they represent too carbon intensive assets in the long term.
- **3a CCS**: this scenario achieves substantial GHG reductions of more than 80% while maintaining the fossil-based production processes in all sectors. While the energy system costs are lower than in other scenarios (3b CleanGas or 3d Electric), it is a solution that relies on a technology for which public acceptance concerns exist and in the very long term storage capacity is limited.
- **3b CleanGas**: if synthetic methane and hydrogen are energy carriers that will be produced sustainably at reasonable costs in the long run, this scenario does not involve major lock-ins or stranded assets. If, however, in the long term the direct use of electricity or increased circular economy is more reasonable, this scenario involves major lock-ins.
- **3c BioCycle**: biomass-based heat supply can be a stranded asset if, for example, electric heating becomes cost-effective early. However, the capital expenditures involved are lower than, for example, clean gas. Multi-fuel burners allow for some flexibility for reasonable investments.
- **3d Electric**: similar to scenario 3b, if electricity generation is supplied by renewables and cost-effective storage solutions are found, this scenario represents a path with a high long-term compatibility and a low number of stranded assets.
- **4a Mix80**: similar to 3c and 3d, but less pronounced.
- **4b Mix95**: the use of CCS and clean gas can represent a stranded asset if other technologies turn out to be cost-competitive in the long term.

All scenarios face a danger of stranded assets before 2030 as it is assumed that major process shifts only occur afterwards. Investments in new oxygen steel production, Portland cement plants or steam crackers before 2030 either require replacement again before 2050 or increase the share of remaining emissions in 2050.

The likelihood of such re-investment in fossil-based production technology is further discussed based on the age of the existing capital stock.

For the steel industry, for example, the following figures show the age of the existing capital stock related to the production capacity of oxygen steel and the capacity of electric arc furnaces in Europe. Accordingly, Fleiter et al. (2016) conclude for blast furnaces: "70% of the total operating blast furnace capacity is older than 35 years. Assuming a normal technical lifetime of about 45 to 50 years, this part of the installed capacity would be at the end of its life cycle in 2025." The situation is similar for electric arc furnaces, which were built later, but also typically have shorter lifetimes: "around 60% of EAFs in EU-28+3 will have reached the end of the assumed life span of 25-30 years during the next five to ten years" (Fleiter et al. 2016).

Figure 3.23 Plant capacity and age distribution of blast furnaces in EU-28+No+CH+Is (Source: Stahlinstitut VDEh (2015) and (Fleiter et al. 2016))

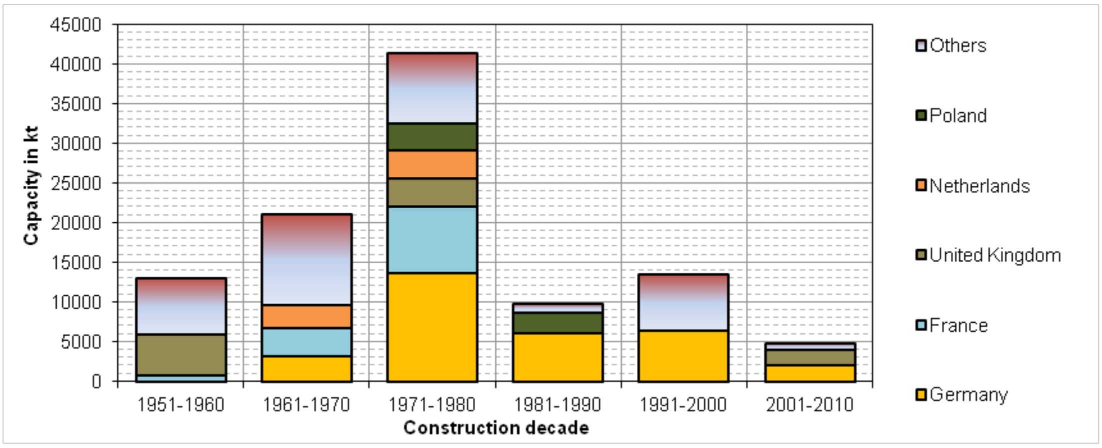
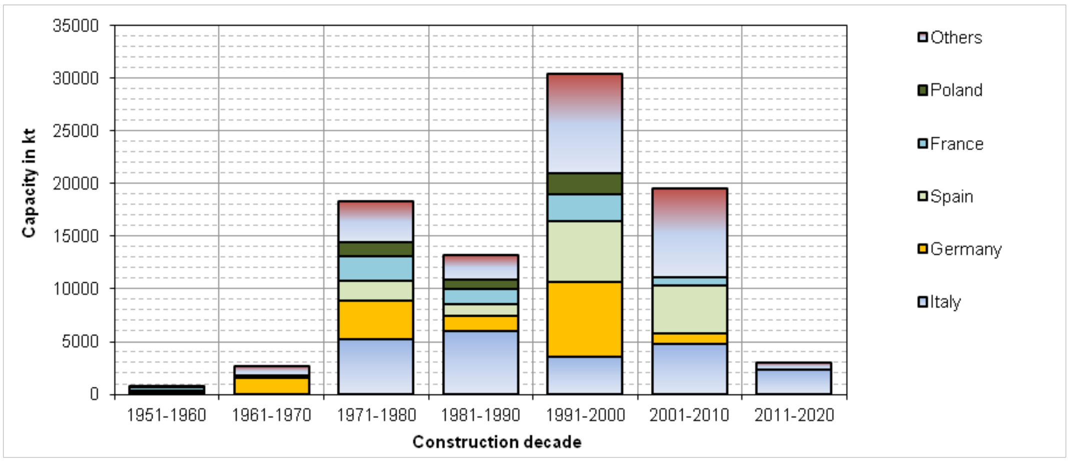


Figure 3.24 Plant capacity and age distribution of electric arc furnaces in EU-28+No+CH+Is (Source: Stahlinstitut VDEh (2015) and (Fleiter et al. 2016))



The diffusion of steam generation technologies is modelled in FORECAST based on a detailed stock model which tracks individual vintages and makes investment decisions based on the relative cost-effectiveness of alternative process heat supply options. Steam generation technologies are used throughout all sectors. The relative long lifetime of 20 years (steam boiler) or even more than 30 years (CHP steam engine) makes investment decisions in the coming decade relevant for 2050.

The model FORECAST assumes that the retirement of old generation capacity takes place according to a probability, which is low for young plants and increases when plants become older. Thus, some of the plants built in 2020 will still be in the stock in 2050. Figure 3.25 shows the resulting development of the stock of coal-fired steam engines in Germany from 2015 to 2050 for selected scenarios. The figure allows the tracking of technology age in 5-year vintages. Investments in steam engines are determined by their cost of heat supply compared to alternative supply options. These, in turn, are among others affected by energy prices, CO2 prices and the assumed financial support for renewable heat supply.

Figure 3.25 shows that in scenario 1 Ref, coal-fired steam engines are profitable throughout the entire period until 2050. That is, the increase in the CO2 price in the ETS to 85 euros/t CO2 in 2050 is not able to stop this trend. In the scenario 2 BAT a much higher CO2 price of 200 euros/t CO2 in 2050 substantially decreases the market share of coal boilers in the years after 2030. However, in 2050 a substantial share of boilers still work and run. In addition, the scenario 4a Mix 80 assumes that the CO2 price also applies for non-ETS companies and that from 2020 onwards a high degree of financial support for electric boilers is introduced. Accordingly, the market transformation is faster, but in 2050 coal fired capacity, some of which was built before 2020, still makes up an important share of the market. In scenario 4b Mix95 an even earlier increase in the CO2 price is assumed, reaching 200 euros/t CO2 as early as 2040, combined with an "early replacement" of existing coal-fired generation capacities taking place in 2040. Here, the faster CO2 price increase further reduces the construction of new coal-based steam generation after 2020[8] and leads to the retirement of existing capacity in 2040. Due to the combination of a high CO2 price and the financial support for electric boilers, new capacity after 2040 is not coal-based and in 2050 coal as energy carrier has been virtually phased out in steam generation.

While this stylized example is used to show the dynamics and inertia of stock turnover and its influence regarding meeting the 2050 target, it underlines a number of assumptions. However, the example illustrates how investments in the coming decade can affect GHG reduction targets in 2050 and that either early action (market or policy driven) is needed, or investments will need to be replaced before their ordinary lifetime. The latter, however, increases capital costs. In this particular case, the increase in capital costs is about 5 billion euros for the entire EU-28 as shown in Figure 3.26.

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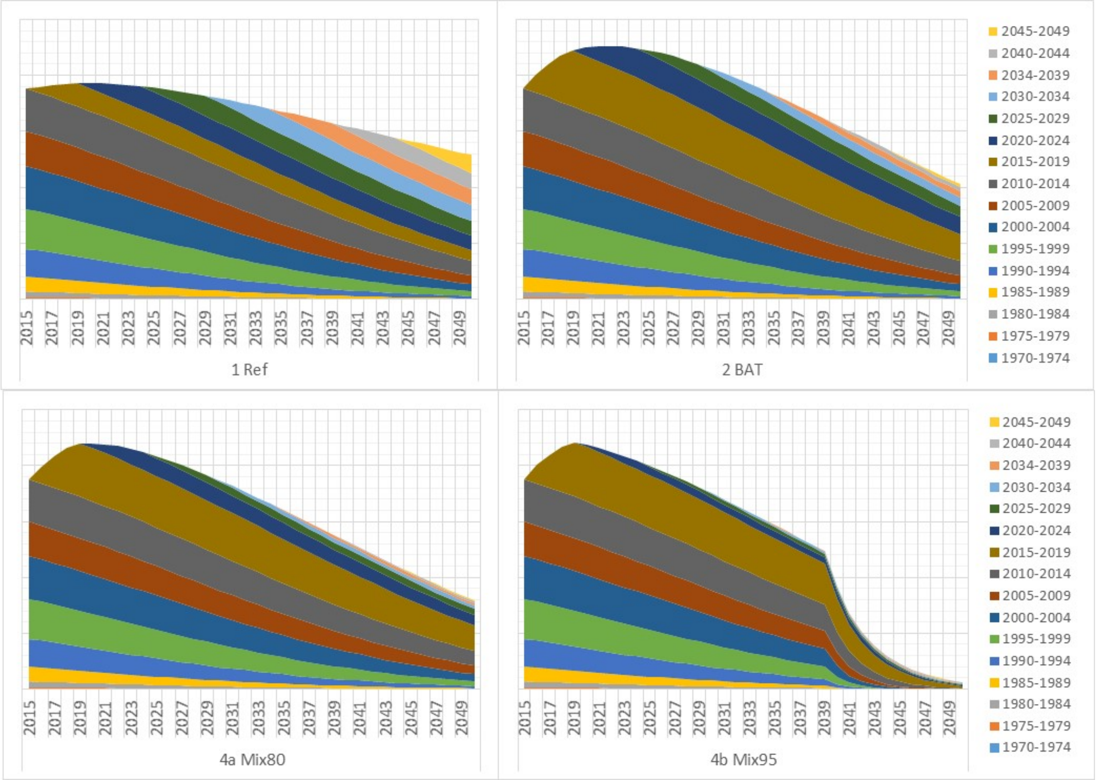
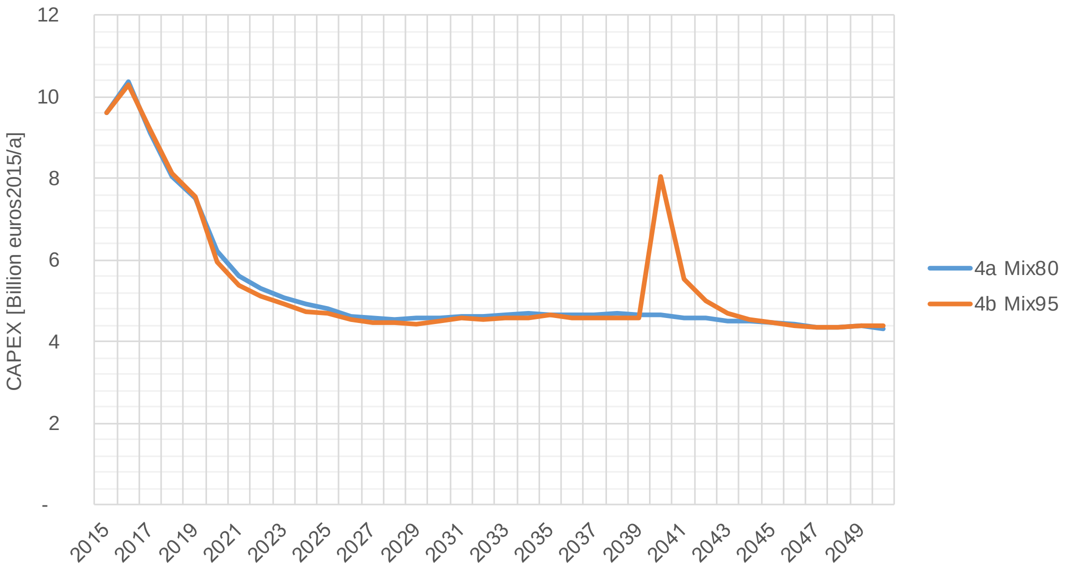
[8]

Figure 3.25 Stock of coal-fired steam engines (CHP) used for process heat generation in Germany by scenario over time



Note that the investment in new coal-fired CHP taking place until 2020 is a model result driven by (a) the fact that the model identifies it as the cheapest technology until 2020 where CO2 prices are not yet high enough, and (b) the fact that no foresight is assumed for the CO2 price, thus there are no future expectations for a much higher CO2 price to alter these investment patterns. In reality other criteria may be included in these decisions, for example quality of available coal, simplicity in the handling of gas-based heating, etc, which are captured in the modelling by behavioural parameters.

Figure 3.26 Annual CAPEX of investments in steam generation capacity in the EU-28 for two scenarios in comparison



Note that the sudden jump in CAPEX in 2040 is due to the introduction of early replacement of old boilers. While in the model old coal boilers are instantly replaced in the years 2040-2042, this process might also take a few years more with the same impact on the emissions in 2050.

3.4 Results by sub-sector

3.4.1 Iron and steel industry

CO2 emissions and energy demand in the iron and steel industry in Europe are dominated by the use of coal. It is required as a reducing agent in the blast furnace.

While the scenario 1 Ref shows a slow decrease of emissions towards 2050, the scenario 2 BAT achieves emission reduction of 51% compared to 2015 mainly driven by the switch from oxygen steel to electric steel, which accounts for 67% of total crude steel production in 2050. The share of electric steel is similar in the scenarios 3a, 3b and 3d. The scenarios 3b CleanGas reduces emissions by 88% compared to 2015 by replacing 88% of the oxygen steel production route by direct reduction based on hydrogen (DR H2 + EAF). Similarly, in the scenario 4d Electric, oxygen steel is replaced by electrolysis steel, which is assumed to be available after 2030. The scenario 3c BioCycle achieves a reduction of 69% with material efficiency and the innovative use of electric steel also for high-quality products increasing the share in total crude steel to 77% in 2050. The scenario 4b Mix95 then fully replaces oxygen steel with alternative routes and achieves a reduction of 96%. It also uses synthetic methane to replace the remaining natural gas use.

Overall, decarbonisation in the iron and steel industry heavily depends on the market introduction and fast diffusion of innovative CO2-free steel production routes either using hydrogen or electricity. An ambitious deployment of scrap-based steel production making use of an expected future increase in scrap availability also has huge mitigation potential.

Figure 3.27 GHG emissions in the iron and steel industry by energy carrier and scenario (EU-28)

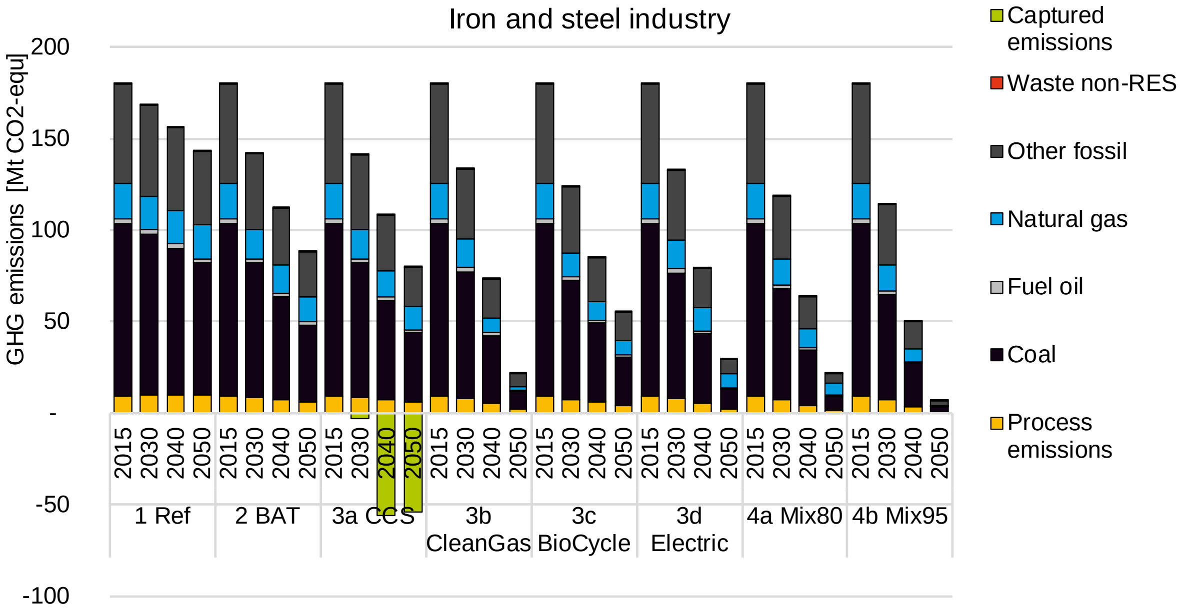


Figure 3.28 Final energy demand in the iron and steel industry by energy carrier and scenario (EU-28)

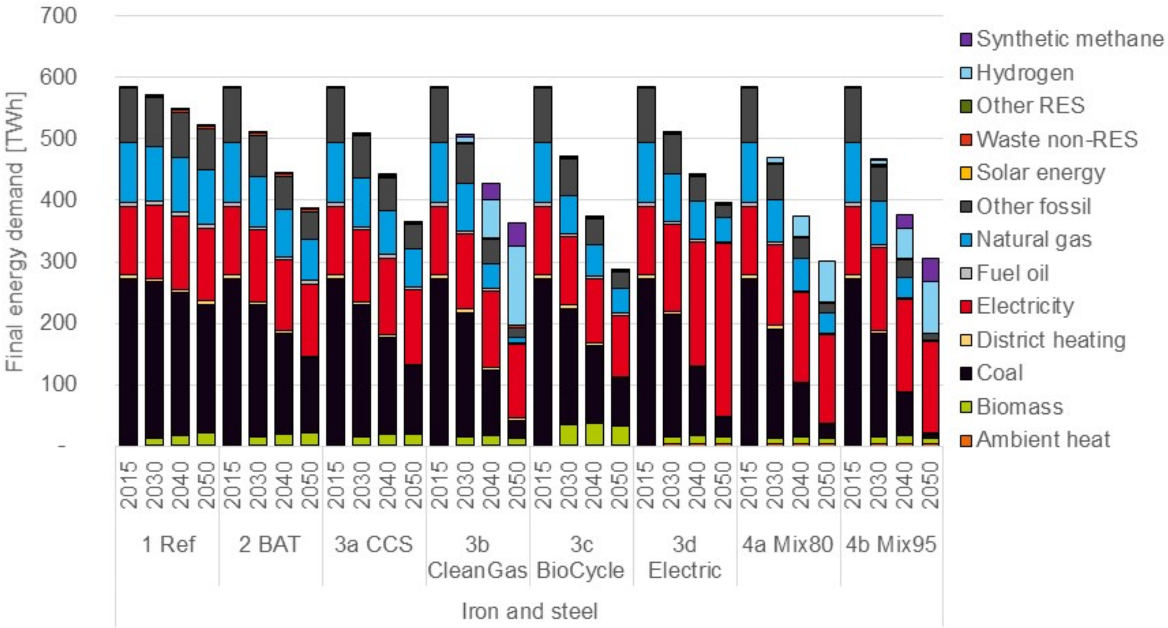
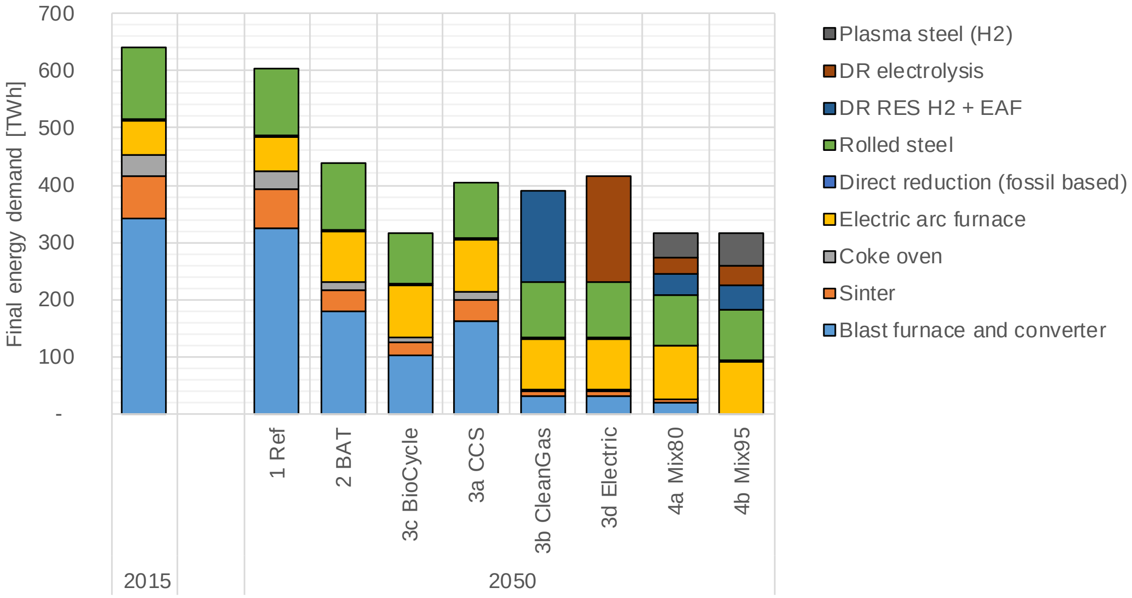


Figure 3.29 Bottom-up final energy demand in the iron and steel industry by process and scenario (EU-28)



3.4.2 Chemical industry

GHG emissions in the EU's chemical industry are dominated by a widespread use of natural gas with some other remaining fossil fuels and process-related emissions in ammonia production. Besides the use of fuels for energy, the chemical industry also uses a substantial share of energy carriers as feedstocks, among others for olefins (ethylene, propylene, others), ammonia and methanol production. Both energy consumption and feedstock are dominated by the production of ethylene and other olefins.

Scenario results show a stable development of GHG emissions in the reference scenario, while the application of the best available technologies achieves a slow reduction of 15% in 2050 compared to 2015, which is driven by energy efficiency improvements and a more pronounced increase in biomass use (scenario 2 BAT). Applying CCS in all major processes reduces emissions by 90% in scenario 3a CCS. This relatively large share is achieved by also including CCS where biomass is used (partly), inducing "negative emissions". Scenario 3b CleanGas achieves a 77% GHG reduction compared to 2015, mainly via the large-scale use of synthetic methane in the gas grid (share increases to 80% in 2050) and a switch to hydrogen-based processes in ethylene and methanol production (see feedstocks in Figure 3.30). As a result of the introduction of clean gas, the use of biomass decreases on a lower level than; for example, in scenario 3a. In scenario 3c BioCycle emissions are reduced by 63% compared to 2015. This is achieved by a fast and comprehensive deployment of biomass, which attains a market share of 31% in total final energy demand in 2050. Also, in feedstock use, biomass (bioethanol) replaces naphtha and natural gas. Besides the switch to biomass, the ambitious improvements in material efficiency and circular economy along the entire value chain drive down the demand for energy-intensive products as well as resulting energy demand and emissions. For example, it is assumed that plastics recycling, substitution and re-use reduces the demand for ethylene by 12% compared to 2015. Also, reduced demand for fertilisers results in a decrease in ammonia production of more than 40% in 2050 compared to 2015. Consequently, scenario 3c BioCycle is also the scenario with the lowest final energy and feedstock demand. Moreover, scenario 3d Electric achieves substantial emission cuts of about 70%, mainly by using hydrogen-based processes and switching process heat generation to the direct use of electricity. As a consequence, direct electricity demand increases by 78% compared to 2015 to arrive at 323 TWh. A hydrogen use of 485 TWh for feedstocks adds to the direct electricity use if domestically produced via electrolysis. Assuming an efficiency of 70% for electrolysis would result in a total electricity use by the chemical industry of about 1,016 TWh in 2050, which is nearly the same as the electricity use of the entire industry sector in 2015 with about 1,050 TWh. Scenario 4a Mix80 follows very similar paths as scenario 3d Electric and achieves a reduction of 73%. Scenario 4b Mix95 achieves a 91% reduction by using 95% synthetic methane in the gas grid, replacing the remaining fossil fuel boilers before their end-of-life, increasing the share of hydrogen-based processes to 100% and assuming a faster increase in CO2 prices. The remaining emissions in scenario 4b Mix95 stem from smaller sources of process emissions: soda ash (1.4 Mt CO2-equ), polyethylene (2.8 Mt), carbon black (3 Mt).

To conclude, the chemical industry can decarbonise via different pathways and technologies. The major challenges are feedstocks, process emissions and the high share of natural gas. However, hydrogen might play a central role in decarbonising the chemical industry.

Figure 3.30 GHG emissions in the chemical industry by energy carrier and scenario (EU-28)

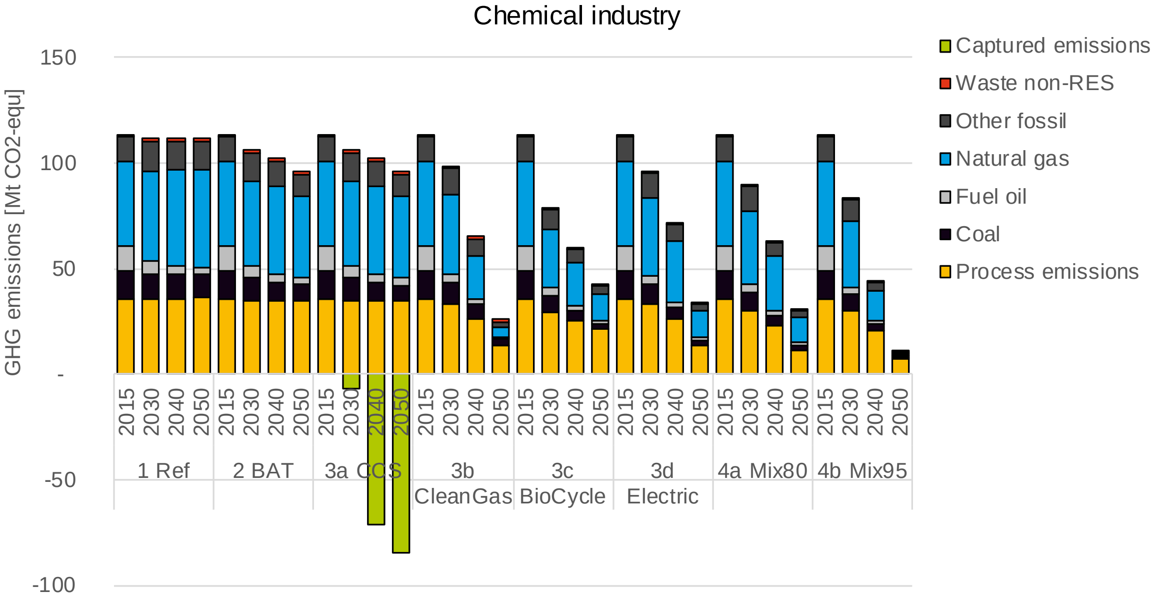


Figure 3.31 Final energy demand in the chemical industry by energy carrier and scenario (EU-28) excluding feedstock demand

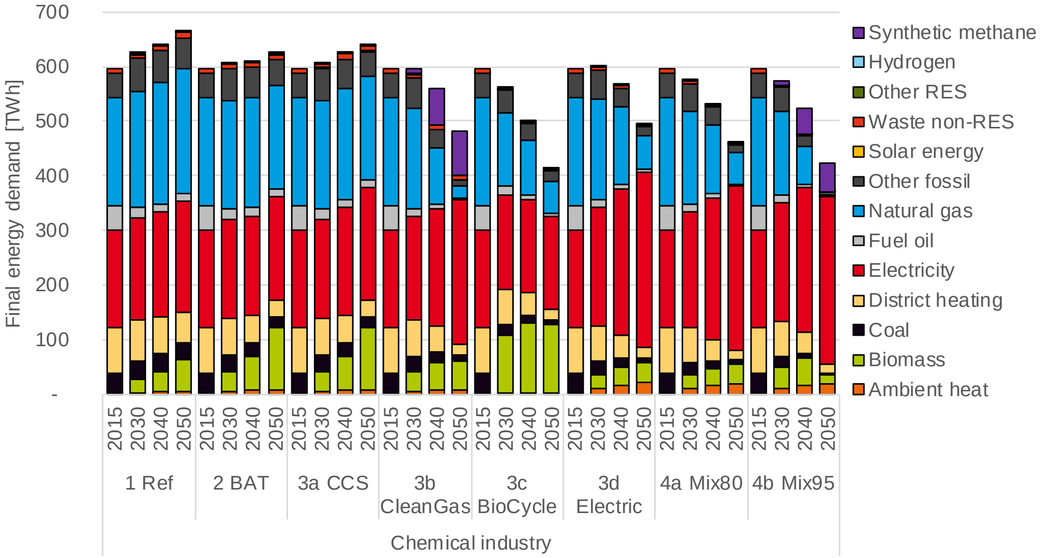


Figure 3.32 shows the evolution of feedstock demand for ethylene, ammonia and methanol production. Scenarios 1-3a show a very steady development based on today's traditional production routes via steam cracking of naphtha (ethylene and other olefins) and Haber-Bosch synthesis for ammonia production using hydrogen, which is mainly generated via steam reforming from natural gas. In scenarios 3b CleanGas, 3d Electric, 4a Mix80 and 4a Mix95 a major part of the fossil-based production routes is replaced by routes that use hydrogen from renewable energy sources produced via electrolysis. In scenario 3c BioCycle it is assumed that fossil feedstocks will be replaced by bio-based feedstocks. For example, bioethanol is used for the production of olefins such as ethylene.

Note that Figure 3.31 only includes the energy consumption of production steps located within the chemical industry (e.g. the steam cracking). The electricity consumption of hydrogen production is not included.

A summary of system boundaries and assumptions taken for feedstock calculations is provided in the annex.

Figure 3.32 Energy content of feedstock demand for ethylene (and other olefines), ammonia and methanol production by type of feedstock and scenario (EU-28)

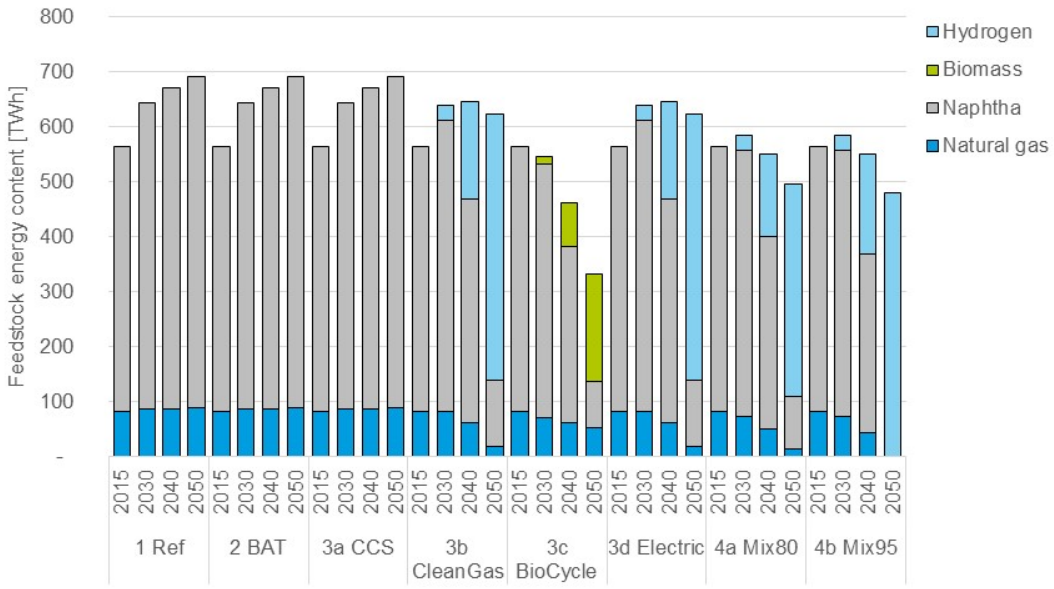
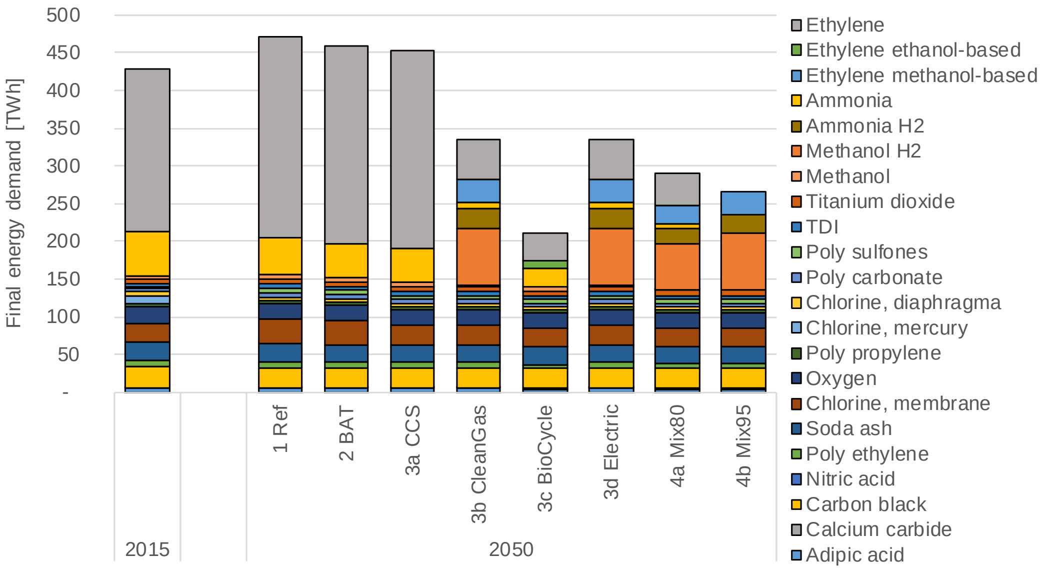


Figure 3.33 Bottom-up final energy demand in the chemical industry by process (EU-28).



The figure only covers processes individually considered in FORECAST via bottom-up calculation.

3.4.3 Non-metallic mineral industry

The major share of GHG emissions in the non-metallic minerals industry is related to cement and lime production. Other important sources are glass, brick and ceramic production. Ambitious long-term decarbonisation strategies need to tackle process-related emissions stemming from the cement and lime production.

The reference scenario shows a relatively stable development of GHG emissions where increases in the share of biomass are compensated for by rising cement production. In scenario 2 BAT a more ambitious switch from CO2-intensive fuels such as coal, petrol coke, fuel oil towards biomass-based energy carriers and maximum improvements in energy efficiency reduce emissions by 16% in 2050 compared to 2015. A large-scale roll-out of CCS achieves a reduction of 81% (scenario 3a CCS). The use of synthetic methane and the diffusion of low-carbon cement types replacing Portland cement allows a reduction of about 50% by 2050. However, substantial process emissions remain in this scenario, as most low-carbon cement types still emit process-related CO2 and the entire production capacity is not replaced. Scenario 3c BioCycle achieves a reduction of 62% by applying biomass as the dominant energy carrier (increasing from 19 TWh in 2015 to 165 TWh in 2050) and introduces additional material efficiency and recycling improvements along the concrete value chain in the construction industry. The reduced demand for cement translates into lower production and lower process-related emissions. Scenario 3d Electric shows an ambitious switch to electricity combined with low-carbon cements reducing emissions by about 45%. This includes electric clinker and glass furnaces. Process-related emissions, however, remain as in scenario 3b CleanGas. Scenario 4a Mix80 uses electric furnaces for glass melting, an ambitious diffusion of low-carbon cements and material efficiency and recycling improvements in the construction industry and achieves a reduction of 56%. Scenario Mix95 adds to this the use of synthetic methane in the gas grid as well as CCS for the remaining conventional clinker and lime furnaces resulting in a reduction of 86% by 2050.

Results across all scenarios show that the non-metallic minerals sector and particularly the cement and lime production pose major challenges in the decarbonisation of the industry sector. If CCS is not used, the effectiveness of decarbonisation depends to a large extent on the diffusion speed of low-carbon cements and fundamental improvements in material efficiency and recycling in the construction industry.

Figure 3.34 GHG emissions in the non-metallic minerals industry by energy carrier and scenario (EU-28)

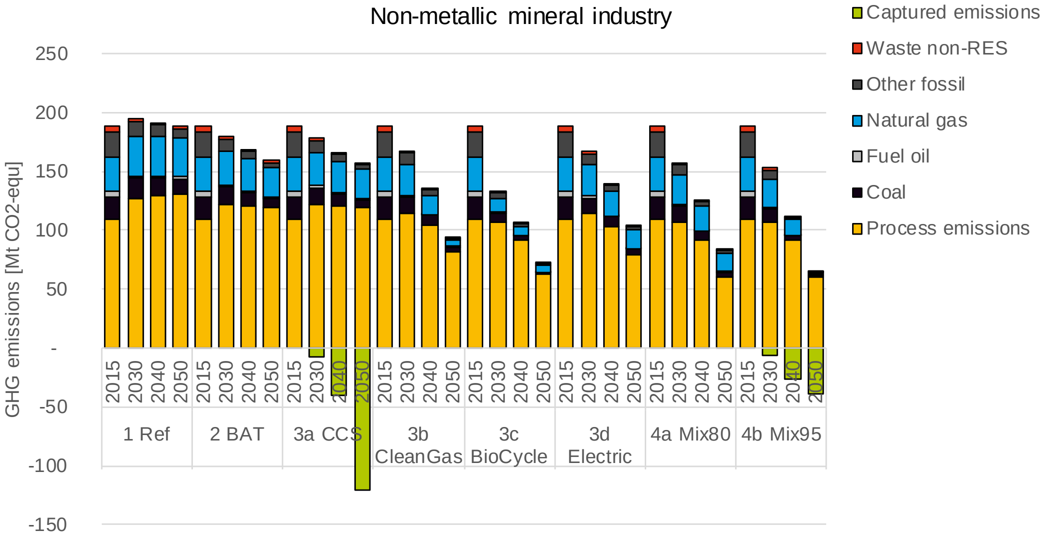


Figure 3.35 Final energy demand in the non-metallic minerals industry by energy carrier and scenario (EU-28)

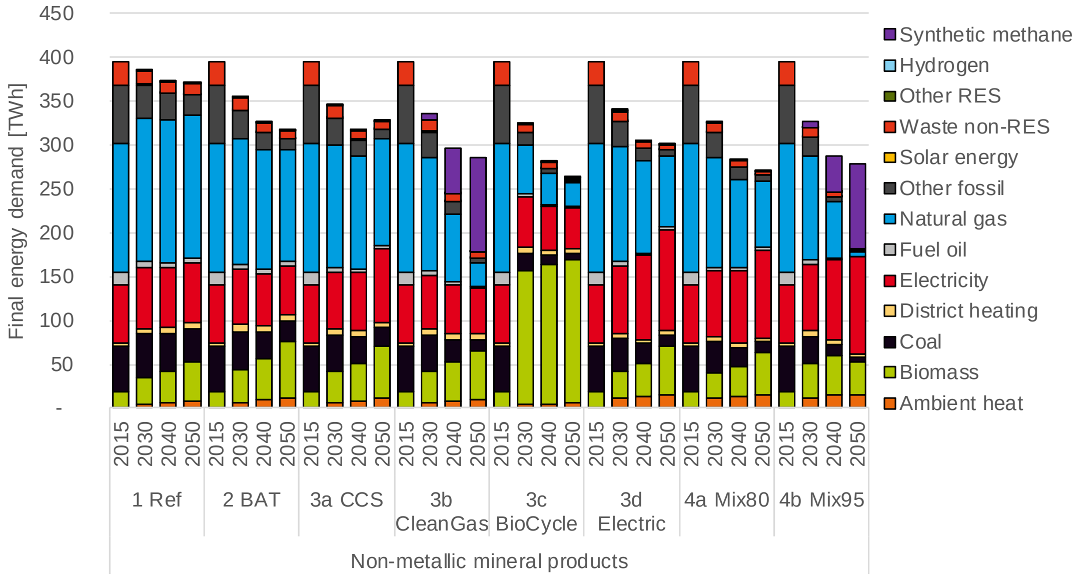
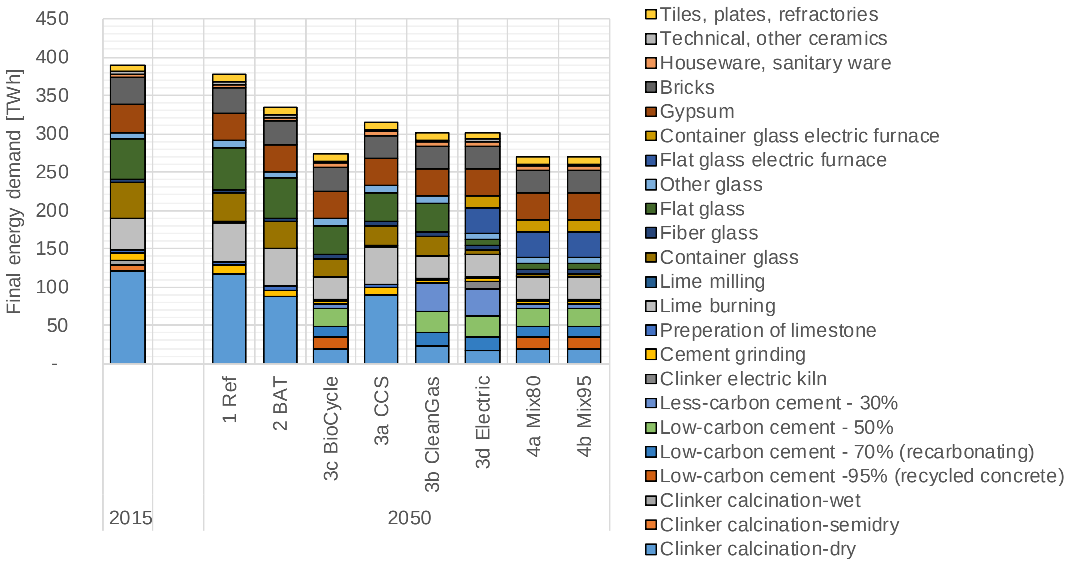


Figure 3.36 Bottom-up final energy demand in the non-metallic minerals industry by process and scenario in 2015 and 2050 (EU-28)



3.4.4 Pulp and paper industry

GHG emissions in the pulp and paper industry mainly stem from the use of natural gas and to a smaller extent from coal. Even in 2015 more than one third of the final energy demand is supplied by biomass reflecting the industry's good access to biomass resources as well as bio-based production residues.

Scenario results show that the emissions in the reference scenario slowly increase and the scenario 2 BAT achieves a reduction of 11% by 2050 compared to 1990 driven by energy-efficiency improvements. By deploying CCS, a reduction of nearly 100% is achieved, although only about half of the paper mills are equipped with CO2 capture installations (BECCS). The main reason for the high share is the capture of biomass-sourced CO2 emissions and the generation of so called "negative emissions". Scenario 3b CleanGas reduces GHG emissions by about 50%, as does scenario 3c BioCycle, which supports the use of biomass and increases paper recycling, particularly in countries which currently have low recycling rates. The use of electricity for steam generation in scenario 3d results in a reduction of 42%. Scenarios 4a Mix80 and 4b Mix95 reduce emissions by 50% and 88%, respectively. The scenario 4b is effective via a combination of supporting electric steam boilers (and heat pumps where possible), replacing natural gas by synthetic methane and phasing out remaining coal-fired boilers and steam engines by "early replacement" before their end-of-life after 2040.

Further decarbonisation towards a CO2-neutral EU pulp and paper industry seems also possible by 2050 or in the years to follow. The scenarios indicate a high danger of lock-ins when investments in fossil-based steam generation capacity are undertaken in the coming decade and CO2 prices are not yet high enough to set effective incentives for low-carbon process heat generation. Whereas on the other hand, the industry has a great potential for decarbonisation via biomass (and electricity) use. In a world where some large paper mills with good access to storage sites are equipped with CCS, the industry has the potential to generate "negative emissions" via BECCS and compensate, for example, for process-related emissions in other industries.

Figure 3.37 GHG emissions in the pulp and paper industry by energy carrier and scenario (EU-28)

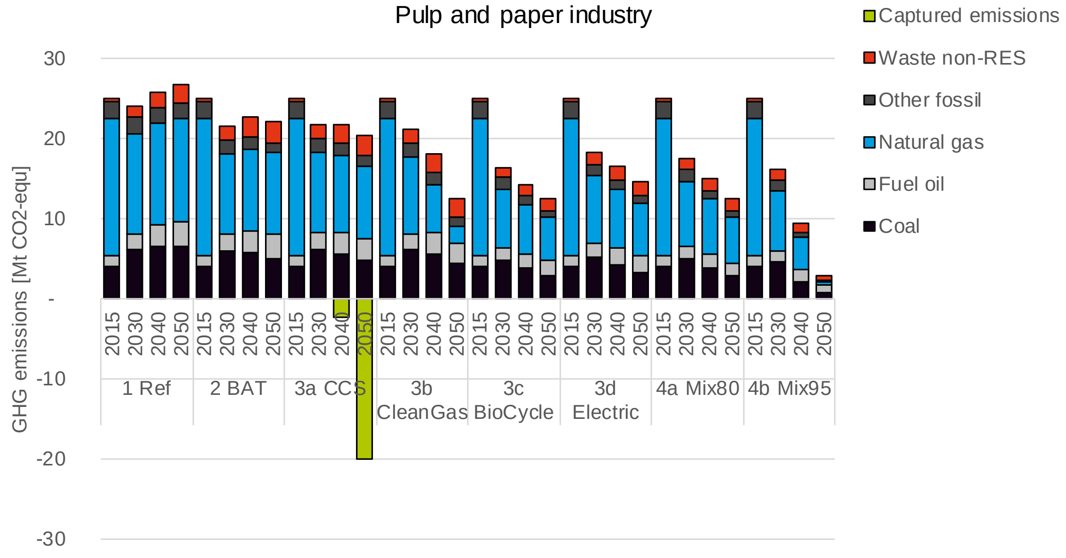
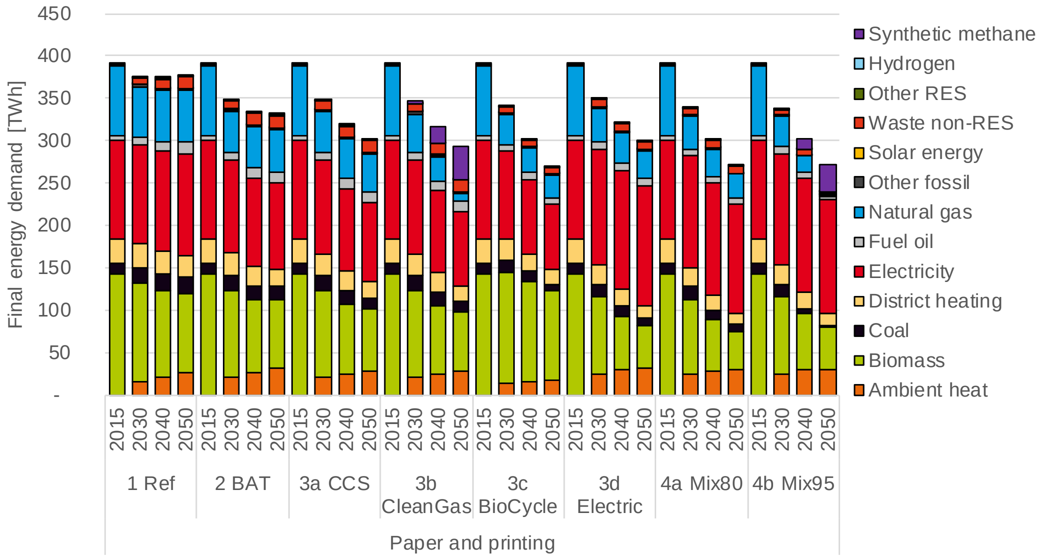


Figure 3.38 Final energy demand in the pulp and paper industry by energy carrier and scenario (EU-28)



3.4.5 Non-ferrous metals industry

Energy consumption in the non-ferrous metals industry is largely dominated by electricity and natural gas. Consequently, the main sources of GHG emissions are the use of natural gas and various smaller sources of process-related emissions.

The scenarios, including even the reference scenario, show a reduction of GHG emissions of about 21% in 2050 compared to 2015. The BAT scenario achieves a 32% reduction, driven by energy efficiency and a fuel switch towards biomass. CCS is not applied in the industry. Replacing natural gas with synthetic methane (scenario 3b), biomass (3c) or electricity (3d) results in additional, but overall moderate reductions of 47%, 43%, and 38%, respectively. The main reason is the relatively high proportion of process-related emissions. These are not addressed in any of the scenarios, with scenario 4b Mix95 reducing emissions by "only" 57%.

Further reductions beyond this will require tackling process-related emissions from the production of primary zinc (4 Mt) and primary aluminium (3.1 Mt).

Figure 3.39 GHG emissions in the non-ferrous metals industry by energy carrier and scenario (EU-28)

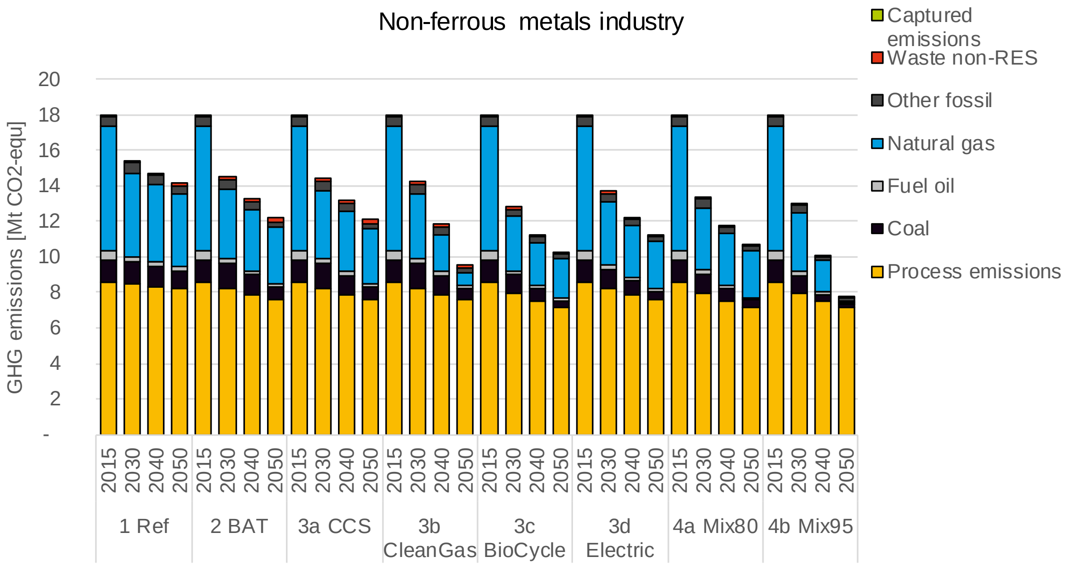
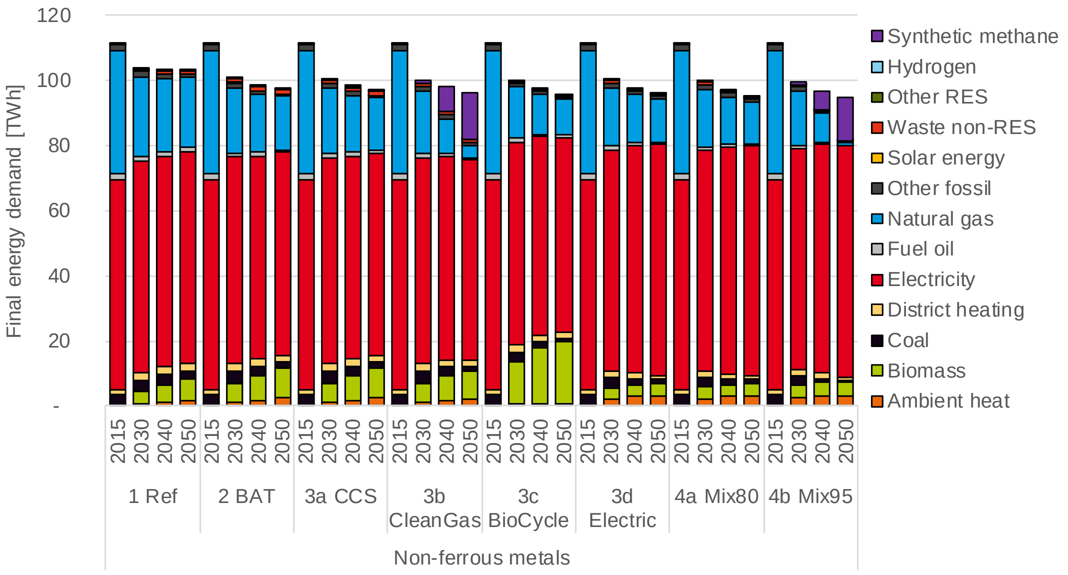


Figure 3.40 Final energy demand in the non-ferrous metals industry by energy carrier and carrier and scenario (EU-28)



3.4.6 Refinery industry

Emissions in the refinery industry are dominated by the use of refinery gas, which is a by-product of refinery activities. It supplies more than half of the refinery industry's final energy demand in the EU. Natural gas and fuel oil also play an important role.

The scenario results are strongly driven by the development of the demand for refinery products, i.e. heating oil and petrol/diesel. Both already decrease in scenarios 1 Ref and 2 BAT driving down emissions 35% and 44%, respectively. The decarbonisation scenarios 3a to 4a achieve reductions of about 71 to 83%, driven by a combination of fuel switch and demand reduction. The financial support of electricity for process heat supply is less effective than in other industries, because in refineries it competes with refinery gas, which is available at very low costs. Scenario 4b Mix95 assumes an even stronger reduction for refinery products as such ambitious scenarios will require similar actions across all sectors. The remaining emissions are reduced via a combination of synthetic methane and CCS use. Overall, the refinery sector emissions will primarily be impacted by the energy transition. On the one hand, the industry faces reducing demand if the transition is effective in the buildings and transport sectors, while on the other hand the industry might also become a producer of CO2-free bio-based or synthetic energy carriers.

Figure 3.41 GHG emissions in the non-ferrous metals industry by energy carrier and scenario (EU-28)

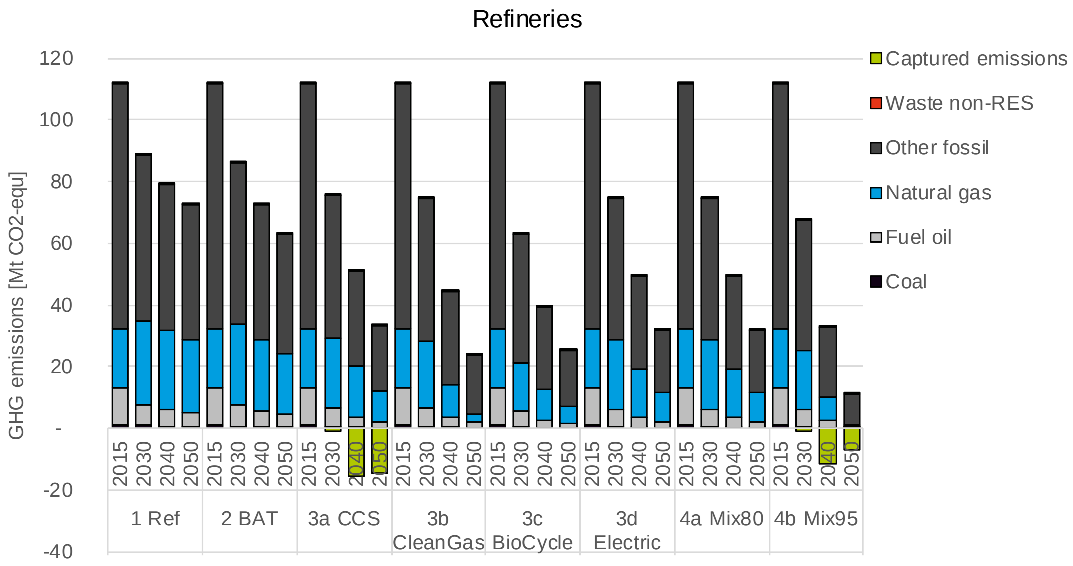
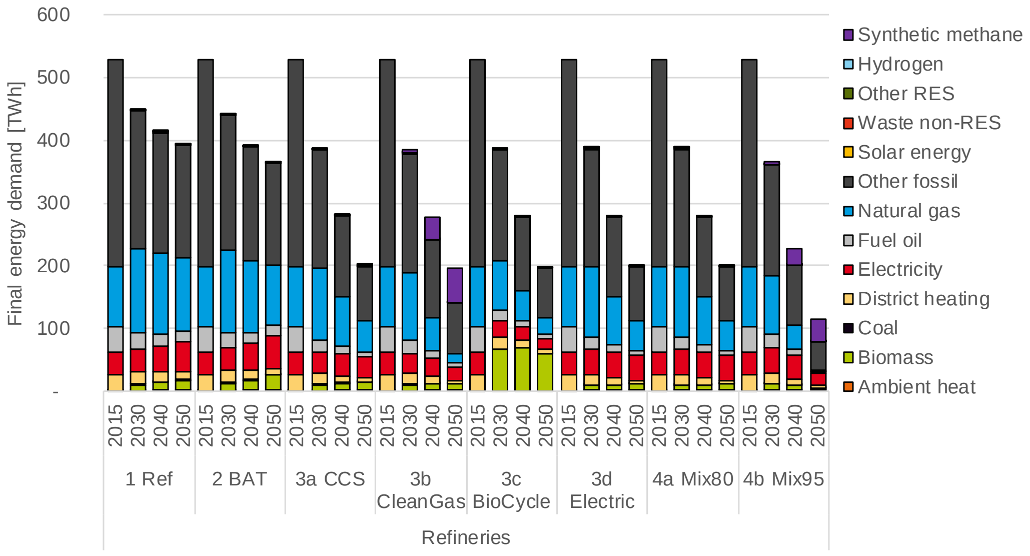


Figure 3.42 Final energy demand in the refinery industry by energy carrier and scenario (EU-28)



4 Conclusions

With regard to GHG reduction potentials and pathways the following conclusions can be drawn:

- With the **current policies** and trends, a slow reduction of GHG emissions in industry continues, but this is far from an ambitious decarbonisation target (scenario 1 Ref).
- Applying the **best available technologies** in energy efficiency, recycling and fuel switch achieves further emission reductions arriving at about 59% reduction in 2050 compared to 1990 (scenario 2 BAT). This, however, is not in line with the goals of the Paris agreement. Also, it is not on track towards deeper decarbonisation beyond 2050. Still, the ambitious progress in energy efficiency is a foundation for the other decarbonisation scenarios that reduces overall system costs.
- For a **deeper decarbonisation**, innovative low-carbon production technologies (e.g. low-carbon cement, hydrogen-based chemicals, electricity-based steelmaking), a comprehensive circular economy, material efficiency along the value chain, CO2-free secondary energy carriers (electricity, synthetic methane and hydrogen) and more biomass or CCS are necessary.
- Integrating such decarbonisation options can achieve an **80% reduction**, but this might **not be optimal** from a perspective that takes into account costs, lock-in effects and other limitations such as the acceptance and sustainability of solutions (scenarios 3a-3d).
- A pathway focussing on **clean gas** (3b CleanGas) introduces high energy expenditures. **Biomass** (3c BioCycle) on the other hand might be cheaper but is simply not available in the quantities required. **CCS** (3a CCS) shows reasonable costs but high uncertainty regarding market introduction and has a high danger of lock-ins if the rest of the system does not change. Direct use of **electricity** requires substantial changes in the production system (e.g. electric clinker kilns) and leads to a high burden on the electricity sector (4d electric).
- **Combining** several of the above **mitigation options** (hydrogen in chemicals and steel, innovative low-carbon cements, electrification, material efficiency and circular economy) achieves a **reduction** of about **82%** (scenario 4a Mix80), excluding CCS and synthetic methane and limiting biomass consumption to today’s demand. Such a pathway achieves the desired reductions and allows deeper decarbonisation beyond 2050 without substantial lock-ins and at lower costs than the four decarbonisation scenarios with a strong technology focus (i.e., scenario 4a Mix80).
- Adding additional mitigation options (CCS for remaining process emissions, synthetic methane in the gas grid, early replacement of fossil-based steam generation and 100% process innovations) a **reduction of 95%** can be achieved by 2050 (scenario 4b Mix95). Compared to the 80% reduction, only relatively low additional investments are required, however, the annual energy expenditures increase substantially by about 60 billion euros/year in the year 2050 mainly driven by a stronger switch to synthetic methane, hydrogen and electricity. While we conclude that by using CCS and clean gas (and other options) a reduction of 95% is possible, the opposite conclusion "CCS and clean gas are both needed to achieve a reduction of at least 95%" cannot be drawn. Indeed, more analyses would be necessary to explore this statement.

Across all scenarios, some general conclusions can be drawn:

- In all scenarios, additional **costs** compared to the reference scenario are dominated by **energy expenditures**. Here, the ranges are large across the scenarios. While scenarios using synthetic methane and hydrogen, to a large extent, (3b CleanGas and 4b Mix95) show higher annual energy expenditures than the reference scenario, other scenarios show substantially lower energy expenditures mainly due to material efficiency gains and comparably low biomass prices (3c BioCycle).

- **Energy efficiency** is important in each transition pathway and a strong factor in reducing overall energy system costs as well as other impacts.
- A fully **renewable electricity generation** is an enabler or even a prerequisite for ambitious decarbonisation (if biomass as a large-scale option is excluded).
- GHG reduction of 80% and beyond compared to 1990 requires **innovative technologies**.

To conclude, transforming the industrial sector to close to CO2-neutrality by the middle of the century is possible, but also requires a fundamental change in the **policy and regulatory framework**.

This includes the support of R&D activities (directly and indirectly by e.g. generating niche markets); the revision of economic incentives (CO2 price, taxing of secondary energy carriers like electricity); new incentives for sustainable value chains down to the final consumer; a transition of the construction industry away from being a major consumer of GHG-intensive industrial products; the development of infrastructure (transport of CO2, electricity grid). At the same time, it needs to be ensured that industrial production in Europe remains competitive.

As such, policy makers will also need to look more closely at the demand side. This is not only necessary for unlocking the remaining (high) potentials for material efficiency and circularity, but also for designing markets that generate demand for innovative low-carbon basic materials products, which will allow companies to make large-scale investments in production plants, particularly in first-of-a-kind and subsequent plants.

It must be noted that the analysis, of course, includes a set of **assumptions** that are by definition uncertain**.** These include, among others, assumptions regarding the future development of the economy, energy prices, the future availability, costs and performance of new technologies. Particularly data on (future) investments and costs are very uncertain and challenging to collect for a broad set of technologies.

As such, this analysis is not meant to be a forecast of future developments but to provide insights and findings from the comparison of alternative hypothetical scenarios.

Further research should focus on:

- assessing the **role of re-investment cycles**, the age of the capital stock and the impact on transition speeds as well as costs;
- **exploring uncertainties** e.g. with regard to energy price assumptions but also technology development
- **interactions with other sectors**, especially in pathways with a high degree of sector coupling (clean gas, electricity);
- **exploring the supply side of resources needed** (this includes clean gas, electricity, biomass but also CO_2 for the production of synthetic methane);
- **exploring solutions** for mitigation scenarios beyond a 90% reduction more widely. This includes assessing mitigation potentials of smaller process emission sources (bricks, ceramics, carbon black, primary aluminium, primary zinc, etc.), which gain a high importance in deep decarbonisation scenarios but were not the focus of this study. Furthermore, it means developing multiple scenarios that aim towards at least a 95% reduction for industry.

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Annex 1 Model description

A1.1 What is the FORECAST model?

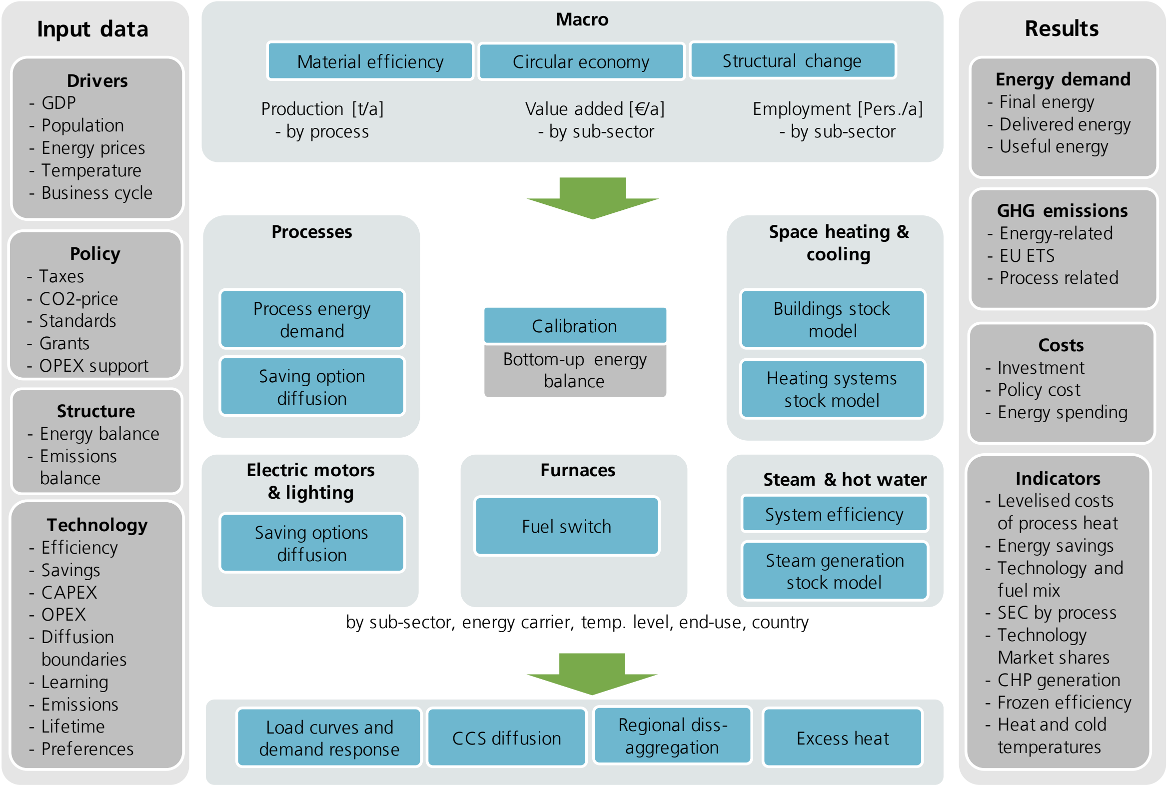
The **FORECAST** modelling platform aims to develop long-term scenarios for the future energy demand of individual countries and world regions until 2050. It is based on a bottom-up modelling approach considering the dynamics of technologies and socio-economic drivers. The model allows one to address various research questions related to energy demand including scenarios for the future demand of individual energy carriers such as electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions as well as abatement cost curves and ex-ante policy impact assessments.

Energy-intensive processes are explicitly considered, while other technologies and energy-using equipment are modelled as cross-cutting technologies.

FORECAST is a simulation model used to support investment decisions, taking into consideration barriers to the adoption of energy efficient technologies as well as various policy instruments such as standards, taxes and subsidies. Different approaches are used to simulate technology diffusion, including diffusion curves, vintage stock models and discrete choice simulation.

Figure A1.1 shows the simplified structure of FORECAST-Industry. The main macro-economic drivers are industrial production for over 70 individually modelled basic materials products, gross value added for less energy-intensive sub-sectors and the employment numbers. Five sub-modules cover: basic materials processes, space heating, electric motor systems, furnaces and steam systems.

Figure A1.1 Overview of the bottom-up model FORECAST-Industry



Source: FORECAST

For this study, the three sub-modules related to the CO2-intensive industries are of high importance:

1. **Energy-intensive processes**: this module covers 76 individual processes/products via their (physical) production output and specific energy consumption (SEC). The diffusion of about 200 individual saving options is modelled based on their payback period (Fleiter et al. 2013; Fleiter et al. 2012). Saving options can represent energy efficiency improvements, but also internal use of excess heat, material efficiency or savings of process-related emissions.
2. **Space heating and cooling**: space heating accounts for about 9% of final energy demand in the German industry. We use a vintage stock model for buildings and space heating technologies. The model distinguishes between offices and production facilities for individual sub-sectors. It considers the construction, refurbishment and demolition of buildings as well as the construction and dismantling of space heating technologies. Investment in space heating technologies such as natural gas boilers or heat pumps is determined based on a discrete choice approach (Biere et al. 2014).
3. **Electric motor systems and lighting**: these cross-cutting technologies (CCTs) include pumps, ventilation systems, compressed air systems, machine tools, cold appliances, other motor appliances and lighting. The module captures individual units as well as the entire motor-driven system, including losses in transmission between conversion units. The diffusion of saving options is modelled in a similar way to the approach used for process-specific saving options.
4. **Furnaces**: energy demand in furnaces uses the bottom-up estimations from the module "energy-intensive processes". Furnaces are found across most industrial sub-sectors and are very specific to the production process. Typically, they require a very high temperature heat. The furnaces module simulates price-based fuel switching using a random utility model (for more details, see Rehfeldt et al. (2018)).
5. **Steam and hot water systems**: the remaining process heat (<500°C) is used in steam (and hot water) systems. The module covers generation and distribution of steam and hot water. For distribution, efficiency improvements for each scenario are based on the available literature. Steam generation is modelled using a vintage stock model simulating the replacement of the entire steam generation technology stock. More than 20 individual technologies are taken into account, including natural gas boilers, CHP units, biomass boilers, heat pumps, electric boilers and fuel cells. Fuel switch is determined as a result of competition among the individual technologies using the total cost of ownership (for more details, see Biere (2015)).

In the following section, the **sub-module for energy-intensive processes** is described in detail. For additional model descriptions, we refer to the FORECAST website.[9]

The hierarchical structure of the sub-module is presented in Figure A1.2. For each country, the industry as a whole is the highest level of aggregation. Using the sectoral definition from Eurostat energy balances, the industry is divided into sub-sectors such as the iron and steel industry or the pulp and paper industry. Within each sector, more than 70 processes are defined that represent major products or industrial production processes (e.g. steel finishing or wood grinding for the production of mechanical pulp). For each process, saving options are defined, which reduce the specific energy consumption and process-related GHG emissions by diffusing through the technology stock. Diffusion depends on boundaries and payback time.

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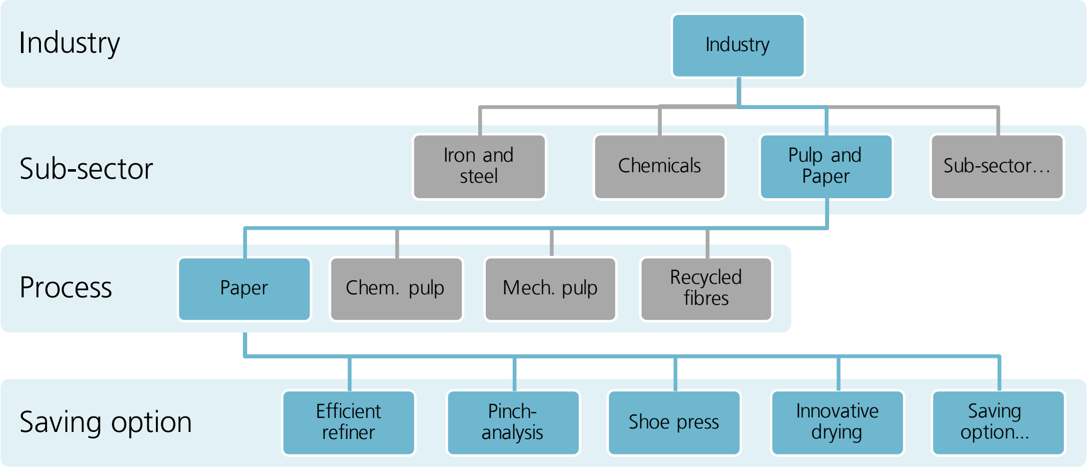
[9] http://www.forecast-model.eu/

Figure A1.2 Hierarchical structure of the FORECAST sub-module for energy-intensive processes



Source: FORECAST

For process-specific technologies, the main driver is the projection of physical production (e.g. tonnes of crude steel from blast furnaces). The 40 most energy- and greenhouse gas-intensive processes are considered separately in the model. For each of these processes, the specific energy consumption/GHG-emissions, temperature ranges and the physical production output per country are important modelling parameters.

Depending on the data availability, processes can consist of small individual production steps (e.g. burning of clinker in the cement industry) or entire production lines for individual products or product groups (e.g. production of paper).

In total, FORECAST currently considers more than 70 individual process as listed in Table A1.1 allowing for a huge level of detail.

Table A1.1 Overview of products covered in FORECAST-Industry for bottom-up calculation by sub-sector

Non-metallic minerals	Chemicals	Non-ferrous metals	Iron and steel
Container glass	Adipic acid	Aluminium, primary	Sinter
Flat glass	Ammonia	Aluminium, secondary	Oxygen steel
Fibreglass	Calcium carbide	Aluminium extruding	Electric steel
Other glass	Carbon black	Aluminium foundries	Rolled steel
Houseware, sanitary ware	Chlorine, diaphragm	Aluminium rolling	Coke oven coke
Technical, other ceramics	Chlorine, membrane	Copper, primary	Smelting reduction
Tiles, plates, refractories	Chlorine, mercury	Copper, secondary	Direct reduction
Clinker calcination-dry	Ethylene	Copper further treatment	DR RES H2 steel
Clinker calcination-semidry	Methanol	Zinc, primary	DR RES electrolysis steel
Clinker calcination-wet	Nitric acid	Zinc, secondary	
Preparation of limestone	Oxygen		
Gypsum	Polycarbonates		
Cement grinding	Polyethylene		

Lime milling	Polypropylene		
Bricks	Polysulfones		
Lime burning	Soda ash		
Glass electric melting	TDI		
Less carbon cement (30%)	Titanium dioxide		
Low carbon cement (50%)	Ammonia H2		
Low carbon cement (70%)	Methanol H2		
	Ethylene methanol-based		
	Ethylene ethanol-based		
Petrochemicals	**Food, drink and tobacco**	**Pulp and paper**	**Others**
Refinery type 1	Sugar	Paper	Plastics: extrusion
Refinery type 2	Dairy	Chemical pulp	Plastics: injection moulding
Refinery type 3	Brewing	Mechanical pulp	Plastics: blow moulding
Refinery type 4	Meat processing	Recovered fibres	
	Bread & bakery		
	Starch		

The **production data** for the individual processes is collected by country and is regarded as the backbone of the FORECAST model. While no individual data source is available that provides data for all products, production data is collected from a variety of sources as shown in Table A1.2.

Table A1.2 Main data sources for historic production data of processes by country

Sub-sector / process	Data source	Completeness/quality of data
Iron and steel	World Steel Association	Very complete
Cement	Cembureau, Odyssee	Very complete
Glass	Glassglobal	Complete, but calculated based on capacity and utilisation by country
Pulp and paper	German Pulp and Paper Association (VDP), FAO Stat	Very complete
Aluminium and copper	US Geological survey	Complete for primary and secondary aluminium, less so for further treatment
Chemicals: Ammonia	UNFCCC	Complete, but some uncertainty
Chemicals: Ethylene	UNFCCC	Complete, but some uncertainty
Chemicals: Oxygen	Eurostat	Complete, but some uncertainty and data for some small countries missing
Chemicals: Methanol	UNFCCC	Many gaps
Chemicals: Polyethylene	UN Commodity Production Database	Some uncertainty

Sub-sector / process	Data source	Completeness/quality of data
Food, drink and tobacco	Mainly UN Commodity Production Database, UN data, German brewery association	Several gaps

The modelling of individual saving options (mitigation options) in FORECAST is briefly described below. For a more detailed description, refer to Fleiter et al. (2012).

Saving options unfold their impact on energy consumption and GHG-emissions by diffusing through the modelled technology stock and, thus, reducing the specific energy consumption or specific process-related emissions of individual production processes. Saving options can be incremental changes as well as radically new production processes.

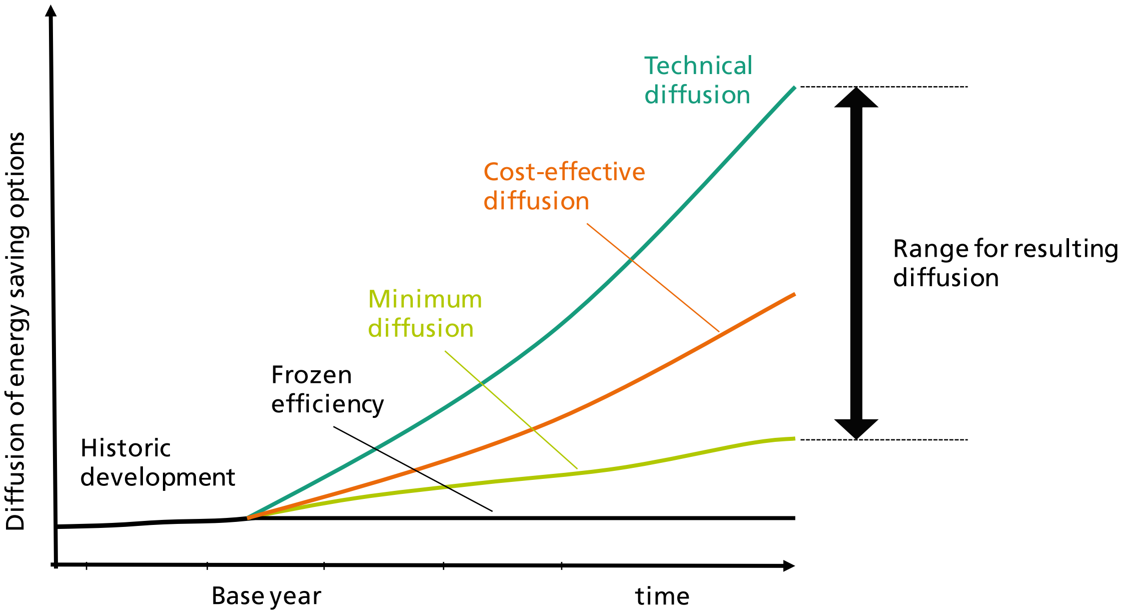
The diffusion of saving options is based on the payback time, which depends on energy savings, energy prices and the carbon price.

The diffusion is limited by a minimum and a maximum/technical diffusion, as shown in Figure A1.3.

- The ‘minimum diffusion’ represents a path, in which the replacement of capital stock results in slowly increasing efficiency. This is not cost-driven.
- The ‘technical diffusion’ represents the fastest market diffusion that is achievable without early replacement of capital stock.

Both diffusion paths provide a range for the resulting diffusion, which is based on considerations of profitability and investment decisions. While alternative investment criteria can be applied, the most commonly used is the payback time of the saving options.

Figure A1.3 Schematic representation of saving option diffusion in FORECAST



The payback time is calculated as follows for each saving option (so), year (t) and country (c).

$$PBT_{so,c,t} = \frac{C^{I}_{t,so}}{C^{E}_{t,so,c} + C^{EUA}_{t,so,c} - C^{R}_{t,so}}$$

With:

C_I: initial investment cost (CAPEX),

C_E: energy cost savings,

C_{EUA}: EU allowance cost savings,

C_R: running cost of mitigation option (OPEX).

In order to consider heterogeneity among companies (different levels of energy efficiency, different energy prices, which all lead to varying cost-effectiveness of savings options), a distribution of payback time expectations is applied. Thus, with increasing payback time, the share of companies investing decreases. Typically, companies require payback times of 2-3 years for energy-efficiency improvements. Consequently, a very short payback time results in a diffusion rate close to the technical diffusion and a very long payback time results in a low diffusion close to the minimum diffusion.

The FORECAST model is among the most detailed bottom-up simulation models available that capture the entire European industry. To our knowledge, it is the only bottom-up model available with the complete Eurostat final energy demand and EU ETS sector coverage. The following table gives an overview of how the various types of mitigation options are included in FORECAST.

Table A1.3 Type of mitigation options and inclusion in FORECAST

Mitigation option	Implementation in FORECAST
Incremental and BAT energy efficiency improvement	The model explicitly considers the diffusion of more than 200 energy efficiency measures included in the sub-modules on *processes* and on *electric motor systems*. These include for example excess heat use, optimised control systems, high-efficiency electric motors, variable speed drives, or very sector specific technologies like coke dry quenching in steel or the shoe press in paper-making. Diffusion is modelled based on the payback time and assumptions about minimum and maximum diffusion boundaries.
Advanced energy- and resource-efficient processes	More radical process innovations are included in the model similarly to the above energy-efficiency measures. Their diffusion, however, starts later by defining an earliest market introduction. In addition, options that only mitigate process emissions can be included. Examples are new types of cement clinker with better energy performance or thin slab or strip casting in steel finishing.
Fuel and feedstock switching	Fuel and feedstock switching are simulated in the sub-modules on furnaces and steam systems by explicitly taking energy and CO2 prices and the profitability of alternative technologies into account (example: switch to biomass or electric boilers to provide steam in paper and chemicals industries). If fuel switching is strongly related to the introduction of new production processes, it is also included in the sub-module for energy-intensive processes (e.g. diffusion of RES-H2 direct reduction to replace basic oxygen furnace route in steelmaking).
CCS and CCU	Industrial carbon capture and storage/use (iCCUS) is modelled in FORECAST on a process level. The model allows one to identify the major GHG point sources most appropriate for iCCUS (e.g. integrated steelworks, cement plants, ammonia or ethylene plants). The diffusion of CCS is based

Mitigation option	Implementation in FORECAST
	on techno-economic assumptions including the earliest market entry, CAPEX and OPEX, capture rate, energy consumption, etc.
Recycling and circular economy	Recycling and circular economy can be modelled with FORECAST for the major energy-intensive processes and products (e.g. steel, aluminium, copper, paper, glass, plastics or potentially cement). The model works with projecting past recycling rates in a baseline scenario, while an ambitious circular economy scenario includes higher recycling rates that are capped by the availability of recovered materials (e.g. steel-scrap availability).
Downstream innovations (incl. product innovation and switch, material efficiency, trends towards higher gross value added, etc.)	FORECAST includes product innovation and substitution as exogenous assumptions in the production output. E.g. replacing cement and bricks with wood results in lower cement production and consequently a lower energy demand and lower emissions. Similarly, material efficiency and a change of business models are considered: e.g. in the construction industry new concrete mix designs might save cement as might optimised construction designs that require a minimum of cement and steel. However, downstream mitigation options can show a huge degree of heterogeneity and are difficult to include systematically and comprehensively in energy system models. E.g. capturing all emission-related effects along the value chain (e.g. energy needed for the collection of recovered materials) is particularly challenging and not possible in today's energy system models. For the basic materials products, anyhow, a major source of CO2 emissions is the production process, which is included in FORECAST in detail.

Annex 2 System boundaries taken for calculation of feedstock demand

Table A2.1 Summary of assumptions for feedstock estimation

Assumptions for feedstock estimation - summary

Traditional routes	Process	GJ/t	Input
Ammonia feedstock natural gas demand	Ammonia	15.2	Natural gas
Methanol feedstock natural gas demand	Methanol	21.5	Natural gas
Ethylene feedstock naphta demand	Ethylene	79.7	Naphtha
Innovative routes			
Ethanol-Ethylene route biomass demand (glucose)	Ethylene ethanol-based	46.5	Biomass
Methanol-Ethylene route H2 demand	Ethylene methanol-based	45.4	Methanol
Ammonia feedstock hydrogen demand	Ammonia H2	25.2	Hydrogen
Methanol feedstock hydrogen demand	Methanol H2	26.8	Hydrogen

In order to properly interpret the results on feedstock energy demand for the alternative ethylene routes, the definition of system boundaries is very critical. In the following section a brief explanation is provided (see also figures below). Three process routes for the production of high-value chemicals (HVC: ethylene, propylene, others) are considered: conventional steam cracking based on naphtha, dehydration of hydrogen-based methanol and dehydration of biomass-based ethanol. The latter two are potentially GHG-neutral, the former one represents the status quo.

Dotted lines represent the respective system boundaries. Regarding the feedstock-streams, it must be noted that naphtha carries an energy content (approx. 44 GJ), so does the sugar beet (approx. 50 GJ), while water does not. Of the 87.1 GJ energy demand in electrolysis, 70% (61 GJ) are embedded in the hydrogen produced.

Figure A2.1 Overview of process flow for alternative ethylene production routes and the system boundaries applied in this analysis (dotted lines)

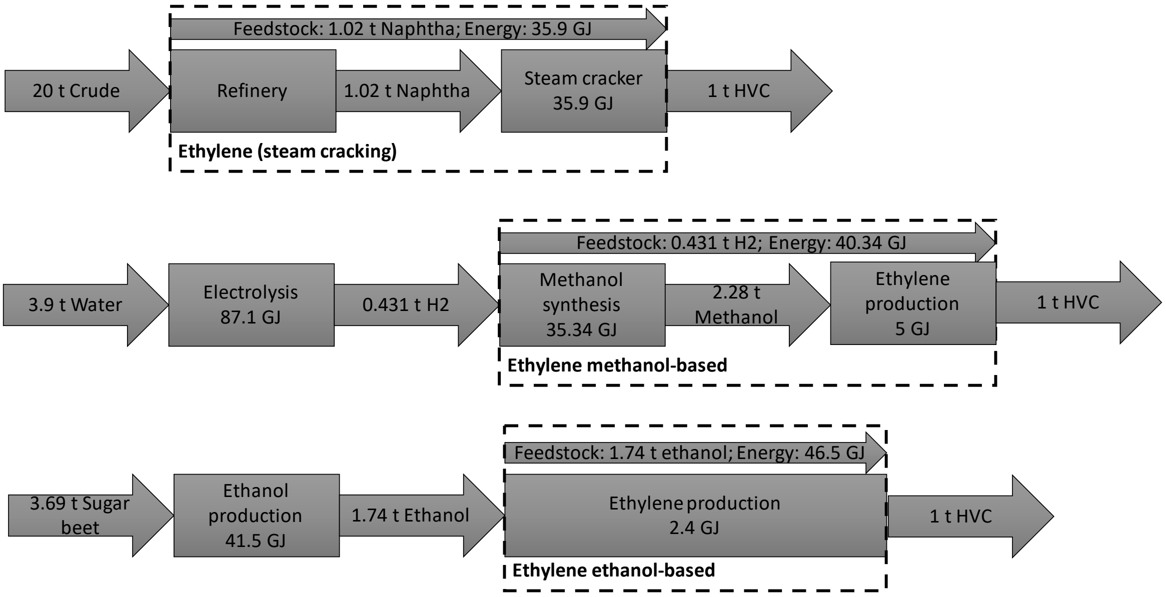


Figure A2.2 Overview of process flow for alternative ammonia routes and the system boundaries applied in this analysis (dotted lines)

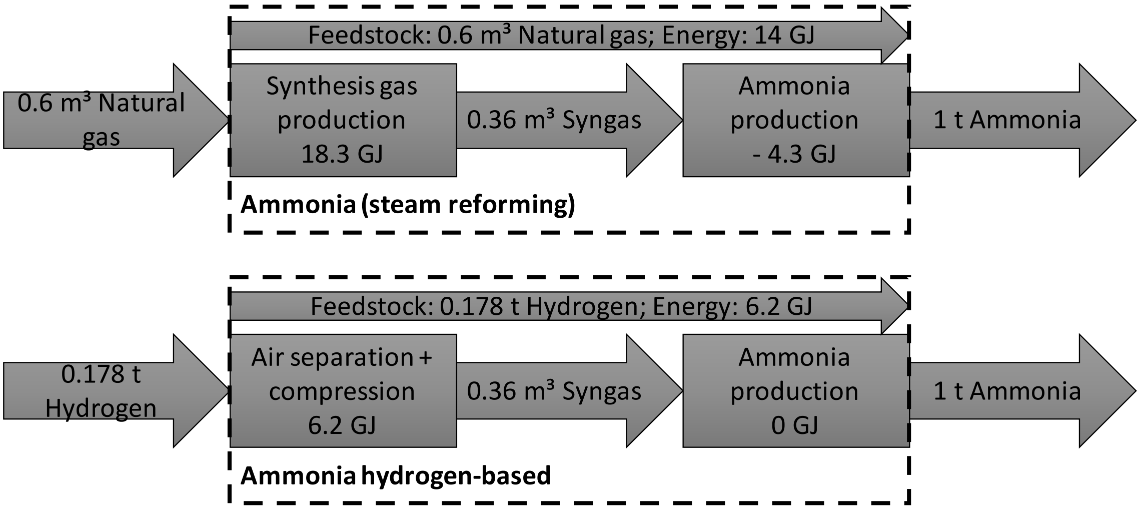
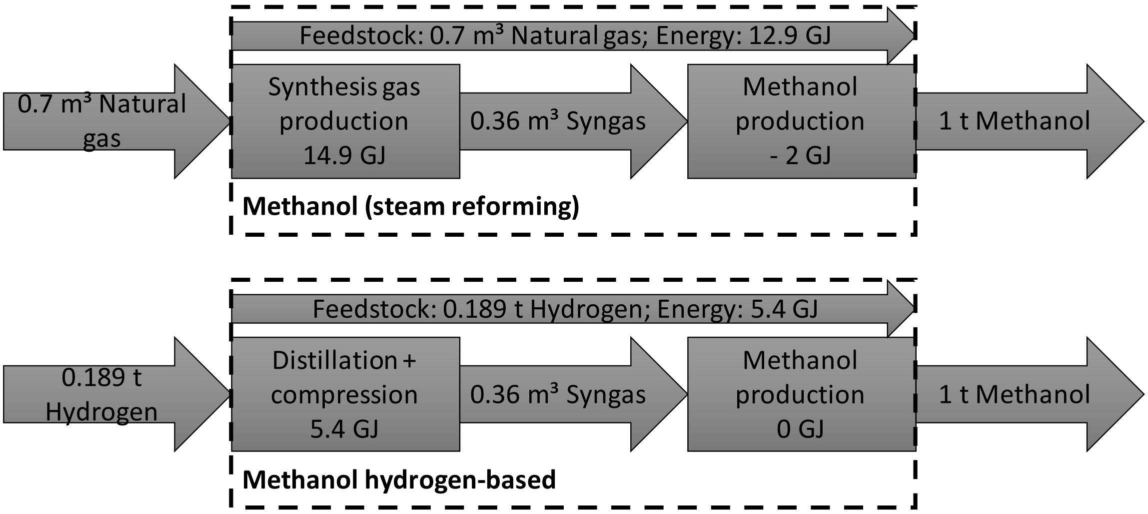


Figure A2.3 Overview of process flow for alternative methanol routes and the system boundaries applied in this analysis (dotted lines)



Annex 3 Results tables

A3.1 Final energy demand

Table A3.1 Final energy demand by energy carrier and scenario from 2015 to 2050 (excluding feedstock demand) [TWh]

	2015	2020	2030	2040	2050	Change 2050/2015
1 Ref	**3,739**	**3,709**	**3,660**	**3,673**	**3,742**	**0%**
Ambient heat	-	27	62	96	133	
Biomass	251	275	312	343	386	54%
Coal	401	431	435	420	399	-1%
District heating	212	232	232	218	199	-6%
Electricity	1,041	1,078	1,079	1,112	1,173	13%
Fuel oil	233	171	126	106	95	-59%
Natural gas	1,008	954	937	931	925	-8%
Other fossil	556	499	425	379	349	-37%
Solar energy	0	3	5	6	6	3,885%
Waste non-RES	37	37	45	59	72	93%
Other RES	0	1	2	2	2	6,140%
Hydrogen	-	0	1	1	1	
Synthetic methane	-	-	-	-	-	
2 BAT	**3,739**	**3,660**	**3,461**	**3,340**	**3,329**	**-11%**
Ambient heat	-	54	113	157	203	
Biomass	251	296	364	427	550	119%
Coal	401	439	386	298	216	-46%
District heating	212	233	223	187	150	-29%
Electricity	1,041	1,076	1,039	1,052	1,107	6%
Fuel oil	233	142	85	68	64	-73%
Natural gas	1,008	877	792	753	692	-31%
Other fossil	556	492	392	320	272	-51%
Solar energy	0	6	8	6	4	2,233%
Waste non-RES	37	43	58	69	70	87%
Other RES	0	1	1	1	1	2,504%
Hydrogen	-	0	1	1	1	
Synthetic methane	-	-	-	-	-	
3a CCS	**3,739**	**3,647**	**3,398**	**3,219**	**3,141**	**-16%**

	2015	2020	2030	2040	2050	Change 2050/2015
Ambient heat	-	54	112	154	198	
Biomass	251	294	358	413	524	109%
Coal	401	439	385	290	201	-50%
District heating	212	233	221	184	148	-30%
Electricity	1,041	1,075	1,037	1,070	1,124	8%
Fuel oil	233	141	82	62	54	-77%
Natural gas	1,008	873	770	706	627	-38%
Other fossil	556	487	365	265	192	-65%
Solar energy	0	6	8	6	4	2,233%
Waste non-RES	37	43	58	68	67	80%
Other RES	0	1	1	1	1	2,078%
Hydrogen	-	0	1	1	1	
Synthetic methane	-	-	-	-	-	
3b CleanGas	**3,739**	**3,643**	**3,374**	**3,108**	**2,907**	**-22%**
Ambient heat	-	54	113	152	185	
Biomass	251	295	363	398	423	69%
Coal	401	438	366	227	97	-76%
District heating	212	233	219	177	132	-38%
Electricity	1,041	1,075	1,048	1,072	1,127	8%
Fuel oil	233	141	76	53	37	-84%
Natural gas	1,008	871	725	411	122	-88%
Other fossil	556	486	355	224	123	-78%
Solar energy	0	6	8	6	5	3,117%
Waste non-RES	37	42	56	63	57	54%
Other RES	0	1	1	1	1	1,344%
Hydrogen	-	0	7	51	107	
Synthetic methane	-	-	38	274	490	
3c BioCycle	**3,739**	**3,614**	**3,296**	**2,975**	**2,729**	**-27%**
Ambient heat	-	47	62	73	98	
Biomass	251	330	832	953	970	287%
Coal	401	424	301	194	118	-71%
District heating	212	228	198	157	124	-41%
Electricity	1,041	1,069	992	954	949	-9%
Fuel oil	233	139	67	43	32	-86%

	2015	2020	2030	2040	2050	Change 2050/2015
Natural gas	1,008	849	498	363	272	-73%
Other fossil	556	481	306	202	133	-76%
Solar energy	0	5	4	2	2	834%
Waste non-RES	37	40	35	33	31	-18%
Other RES	0	1	1	0	0	1,001%
Hydrogen	-	0	1	1	0	
Synthetic methane	-	-	-	-	-	
3d Electric	**3,739**	**3,644**	**3,392**	**3,157**	**3,005**	**-20%**
Ambient heat	-	64	179	236	274	
Biomass	251	284	271	252	268	7%
Coal	401	434	337	199	82	-80%
District heating	212	228	188	136	96	-55%
Electricity	1,041	1,097	1,258	1,483	1,718	65%
Fuel oil	233	141	72	48	35	-85%
Natural gas	1,008	863	691	533	361	-64%
Other fossil	556	486	349	226	135	-76%
Solar energy	0	5	5	3	2	1,038%
Waste non-RES	37	41	41	39	34	-8%
Other RES	0	1	1	1	1	1,235%
Hydrogen	-	0	1	1	1	
Synthetic methane	-	-	-	-	-	
4a Mix80	**3,739**	**3,615**	**3,299**	**3,005**	**2,807**	**-25%**
Ambient heat	-	64	178	233	270	
Biomass	251	282	264	240	250	0%
Coal	401	426	312	171	69	-83%
District heating	212	227	186	134	94	-56%
Electricity	1,041	1,093	1,236	1,394	1,530	47%
Fuel oil	233	140	69	45	33	-86%
Natural gas	1,008	855	665	502	340	-66%
Other fossil	556	482	338	215	129	-77%
Solar energy	0	5	5	3	2	1,038%
Waste non-RES	37	41	40	37	32	-14%
Other RES	0	1	1	1	0	1,152%
Hydrogen	-	0	6	30	58	

	2015	2020	2030	2040	2050	Change 2050/2015
Synthetic methane	-	-	-	-	-	
4b Mix95	**3,739**	**3,615**	**3,288**	**2,968**	**2,698**	**-28%**
Ambient heat	-	65	183	244	263	
Biomass	251	287	307	300	229	-9%
Coal	401	421	286	109	23	-94%
District heating	212	228	189	137	92	-57%
Electricity	1,041	1,095	1,253	1,430	1,539	48%
Fuel oil	233	140	68	33	15	-94%
Natural gas	1,008	854	608	291	19	-98%
Other fossil	556	479	314	157	65	-88%
Solar energy	0	5	5	3	3	1,519%
Waste non-RES	37	40	36	26	11	-71%
Other RES	0	1	1	0	0	485%
Hydrogen	-	0	7	43	73	
Synthetic methane	-	-	32	194	367	

Table A3.2 Feedstock demand by scenario and energy carrier [TWh]

	Natural gas	Naphtha	Biomass	Hydrogen
1 Ref				
2015	83	481		
2030	85	558		
2040	88	582		
2050	90	602		
2 BAT				
2015	83	481		
2030	85	558		
2040	88	582		
2050	90	602		
3a CCS				
2015	83	481		
2030	85	558		
2040	88	582		
2050	90	602		
3b CleanGas				

	Natural gas	Naphtha	Biomass	Hydrogen
2015	83	481	-	-
2030	81	530	-	28
2040	61	407	-	176
2050	18	120	-	485
3c BioCycle				
2015	82	481	-	-
2030	70	462	14	-
2040	61	320	80	-
2050	52	84	197	-
3d Electric				
2015	83	481	-	-
2030	81	530	-	28
2040	61	407	-	176
2050	18	120	-	485
4a Mix80				
2015	83	481	-	-
2030	73	484	-	26
2040	51	349	-	150
2050	14	96	-	384
4b Mix95				
2015	83	481	-	-
2030	73	484	-	26
2040	44	324	-	181
2050	-	-	-	480