EUCALC

Explore sustainable European futures

Energy intensive industry demand

D3.2

February 2020

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

Project Acronym and Name	EU Calculator: trade-offs and pathways towards sustainable and low-carbon European Societies - EUCalc
Grant Agreement Number	730459
Document Type	Report
Work Package	Manufacturing and Production
Document Title	D3.2
Main authors	Hannes Warmuth, Bianca Pfefferer, Stefania Tron, Monika Auer
Partner in charge	ÖGUT
Contributing partners	
Release date	February 2020
Distribution	*All involved authors and co-authors agreed on the publication*

Short Description

This report describes the input data and levers definition of the Production and Manufacturing module as well as the level settings for the industrial energy demand conversion routes as input for modelling. It shows results for the energy intensive manufacturing and production sectors.

Quality check	
Name of reviewer	**Date**
Morgan Raffray (Imperial College)	**19.07.2019**
Michel Cornet (Climact)	**22.07.2019**

Statement of originality:

This deliverable contains original unpublished work except where clearly indicated otherwise.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

Table of Contents

List of Tables

List of Figures

List of abbreviations

BF-BOF – Blast Furnace - Basic Oxygen Furnace

CAPEX – Capital Expenditure

CC – Carbon Capture in Manufacturing and Production

CCS – Carbon Capture and Storage

CCU – Carbon Capture and Usage

EAF – Electric arc furnace

DRI – Direct Reduction Iron

GHG – Greenhouse gas emissions

GTAP – Global Trade Analysis Project

LULUCF – Land Use, Land-Use Change and Forestry

OPEX – Operational Expenditure

TRL – Technology Readiness Level

1 Introduction

In recent years, European business and industry have begun to make steady progress towards decarbonisation, with direct GHG emissions in 2016 falling by 38% from 1990 levels, particularly due to reductions in fossil fuel consumption in energy intensive industries. Yet, according to the UNFCCC Inventory, in 2016 industry still represented 21% of EU's total GHG emissions, of which slightly more than half comes from direct fuel combustion and the rest from industrial processes and product use. In addition to the above, electricity consumption in European industries accounts for 36% of total consumption, indicating the high indirect emissions of the sector. The scope of the EU Calculator (EUCalc) is to assess the decarbonisation potential that could be employed in the European manufacturing and production sector, primarily in the energy-intensive sectors such as iron and steel, chemicals, non-metallic minerals and pulp and paper. Although the use of the best available technologies is not sufficient to meet the EU carbon mitigation goals by 2050, energy efficiency improvements, the use of low-carbon energy and deepening the concept of circularity are required to perform the transition to a low-carbon future. The aim of this policy brief is to focus on the aspect of technological innovation in most relevant European industries and to stress the conditions and requirements needed.

Industrial CO_2 emissions are a major concern as Europe tries to achieve the deep emission reductions required for its climate commitments. Yet, current mitigation efforts in the industrial sector need to be accelerated to first achieve compliance with the Paris Agreement and then bring European industries to carbon neutrality. As indicated in the Roadmap to 2050 (EC 2011), almost 25% of the remaining emissions of the decarbonisation scenario in 2050 come from the industry sector. This clearly poses important challenges for industrial sectors in general, and for energy intensive industries in particular.

To narrow the "emissions gap" – the gap between the reduction commitments of CO_2 emissions and the actual CO_2 emission reduction – low-carbon and innovative technologies are required; a field where European industries historically have a strong record in pioneering future. As highlighted in this report, most of the needed technologies for achieving climate neutrality in the industrial sectors are currently at TRL's from 3 to 6, so not to be invented but to be scaled at significant sizes and to be introduced into markets. This means that apart from remaining R&D challenges the main challenges will be to bring these technologies (such as hydrogen-based steel making, electrified crackers and cement ovens etc.) into markets fast enough.

The manufacturing module in EUCalc requires a large set of input data, comprising main drivers such as activity data from demand modules (transport, lifestyles and buildings), technology specific parameters on energy and emissions, as well as policy parameters. The aim of this report is to describe the input data and the levers definition of the manufacturing module, as well as levels setting for the industrial energy demand conversion routes as input for modelling. The output of the model is calibrated to most recent EUROSTAT statistics (JRC-IDEES, Mantzos et al., 2018) including the energy balances, employment, energy prices, and industrial production on country and process level. For the industry sector of the European Union the most energy-intensive industries were considered. These comprise the manufacturing of steel, cement, ammonia, other chemicals (including carbon fibres), paper and pulp, aluminium, copper, glass and lime.

This report shall provide a structured, documented and transparent view on an energy efficient decarbonisation pathway for the manufacturing and production sector of the European Union until 2050. Relevant developments and levers for the reduction of energy demand and emissions are identified and described in different stages of development expressed in four ambition levels, ranging from low level – business as usual – to a ground-breaking change.

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

For the description of each lever and ambition level, a comprehensive literature research was carried out. The assumptions, background literature of historic trends as well as relevant works and studies are documented in this report as well as in Deliverable 3.1[1]. The interfaces to other modules of this project concerning input and output data are described.

The climate targets of the European Union are focussing on emission reduction, increasing the share of renewable energies and improving energy efficiency to mitigate the effects of climate change. Industry is an energy intensive sector in the European Union. In 2016, the manufacturing and production sector represented around 25% of the EU-28 final energy consumption and around 19% of EU-28 GHG emissions (European Commission, 2019). Therefore, efficient technologies and pathways to reduce energy demand and emissions are already partly applied or in research. Recycling, technology development, material efficiency or the use of more renewable energies in the energy carrier mix are some examples for optimisation potential in the industry sector.

[1] Note: Deliverable 3.1 (type “other”) documents the technical implementation of the “manufacturing and production” module within EUCalc. Other than providing insights on deep decarbonisation pathways for the manufacturing and production sector, deliverable 3.1 reflects on the general model architecture, interactions with other sub-modules, and assumptions.

2 About the European Calculator

The debate on decarbonizing Europe evolved over time from being the concern of national governments to encompassing a cross-border heterogeneity of economic sectors, businesses, regional decision makers and individuals. Simulation tools supporting policymaking were mostly shaped by finical scientific debates and failed to engage with the new diversity of actors willing to drive transformation.

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

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

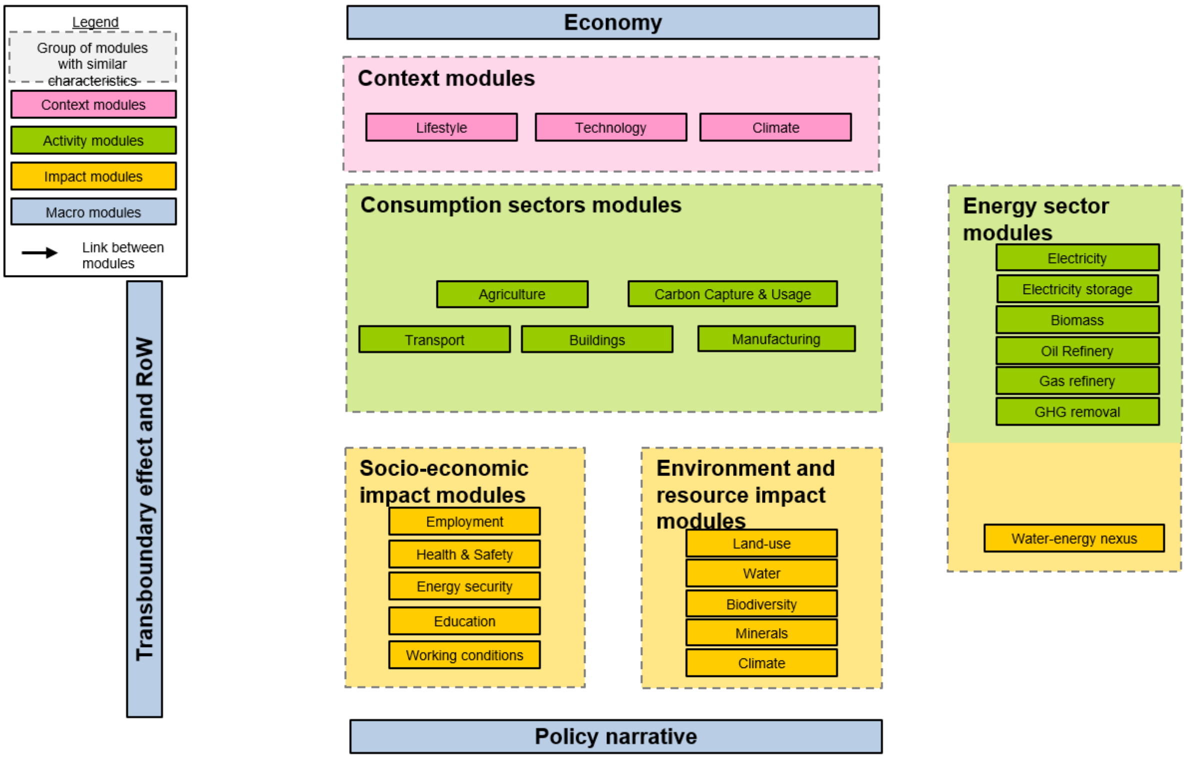

Figure 1: Modular structure of the EUCalc model

The European Calculator model consists of interconnected modules (Figure 1).

3 Manufacturing and Production

The aim of the module (referred to as Manufacturing module) is to provide projections based on common literature and expert validated ambition level settings until 2050 for European countries (EU28 + Switzerland) for the following:

- Direct CO_2 equivalent emissions per industrial sector [Mt CO_2e]
- Energy demand (broken down by energy carrier) [TWh]
- Material production per industrial sector [Mt]
- The overall direct cost of production (Capex and Opex) [M€]

The Manufacturing module in EUCalc primarily focuses on energy intensive industrial sectors (see

Figure *2*). The heavy industrial sectors — iron and steel, cement, chemicals, and pulp and paper — are also among the main industries responsible in terms of emissions generated (see

Figure *3*). Energy intensive processes such as the production of aluminium, glass and lime are not considered as heavy industrial sectors (in terms of total energy consumption). However, they are included in this deliverable as their specific energy consumption is quite significant.

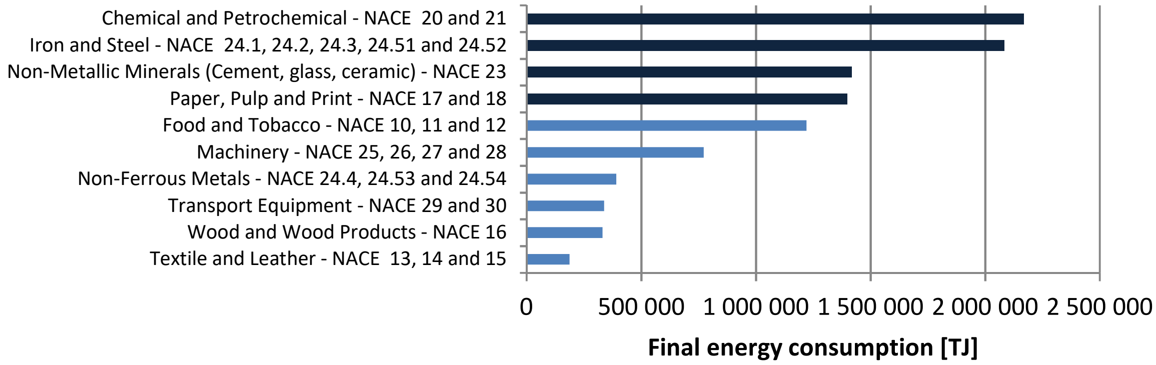

Figure 2: Total energy consumption in 2015 in EU28, the industries modelled in the manufacturing and production module are in dark blue (ÖGUT based on Eurostat data – complete energy balance nrg_110a)

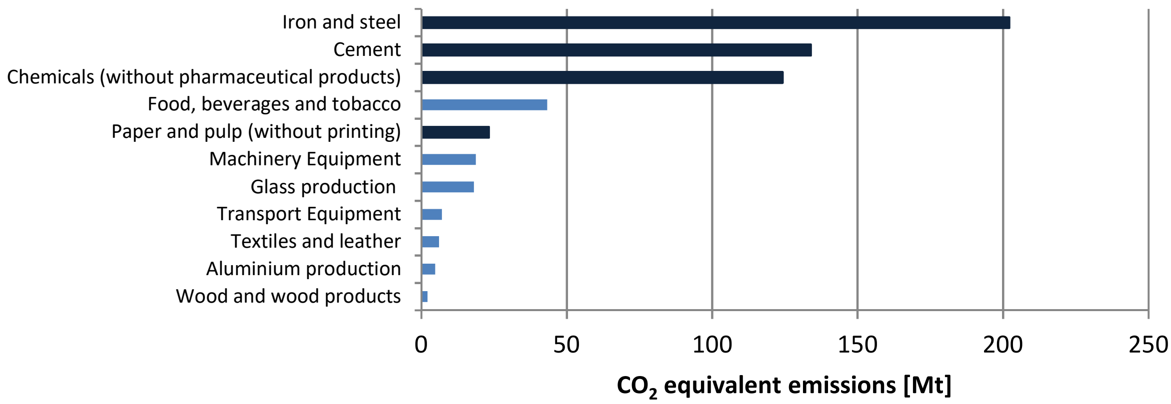

Figure 3: CO_2 equivalent emissions in 2015 in EU28, the industries modelled in the manufacturing and production module are in dark blue (JRC-IDEES- Mantzos et al., 2018)

Table 1 shows the scope of the module, which comprises an extensive list of products, manufacturing sectors, production technologies and energy carriers.

Table 1: Scope of the manufacturing and production module

NEW PRODUCT DEMAND	
From Lifestyle Module (WP1)	- Ships [num]
- Plastic packaging [t]	- Trains [num]
- Paper packaging [t]	- Planes [num]
- Aluminium packaging [t]	- Trolley-cables [km]
- Glass packaging [t]	- Roads [km]
- Paper printing and graphic [t]	- Rails [km]
- Paper sanitary and household [t]	- Streetlights [km]
From Transport Module (WP2.2)	**From Building Module (WP2.1)**
- Int. combustion engine cars [num]	- Residential buildings [m^2]
- Int. combustion engine trucks [num]	- Non-residential buildings [m^2]
- Int. combustion engine buses [num]	- Insulation residential buildings [m^2]
- Int. combustion engine motorcycles [num]	- Insulat. non-residential buildings [m^2]
- Fuel cell cars [num]	- Fridges [num]
- Fuel cell trucks [num]	- Washing machines [num]
- Fuel cell buses [num]	- Dishwashers [num]
- Fuel cell motorcycles [num]	- Freezers [num]
- Electric cars [num]	- Dryers [num]

<table>
<tr><td>
- Electric trucks [num]
- Electric buses [num]
- Electric motorcycles [num]
- Plug-in hybrid cars [num]
- Plug-in hybrid trucks [num]
- Plug-in hybrid buses [num]
- Plug-in hybrid motorcycles [num]
</td><td>
- TVs [num]
- Smartphones [num]
- Computers [num]
- District heating pipes [km]

From Agriculture Module (WP4.3)
- N-fertilizers [t]
</td></tr>
<tr><th>INDUSTRIES AND TECHNOLOGIES</th><th>ENERGY CARRIERS</th></tr>
<tr><td>
• Steel [Mt]
Blast furnace - basic oxy. furnace (BF-BOF) [%]
Scrap- Electric arc furnace (scrap-EAF) [%]
Hydrogen - Direct reduced iron (DRI) [%]
HIsarna [%]
• Cement [Mt]
Dry kilns [%]
Wet kilns [%]
Geopolymers [%]
• Chemical ammonia [Mt]
• Other chemicals (incl. carbon fibres) [Mt]
• Paper and pulp [Mt]
Wood pulp [%]
Recycling [%]
• Aluminium [Mt]
Primary production [%]
Secondary production [%]
• Glass [Mt]
• Lime [Mt]
• Copper [Mt]
• Non-energy intensive sectors
Transport equipment, Food, beverages and tobacco, Textiles and leather, Machinery equipment, Wood and wood products, Other industries [-]
</td><td>
- Coal [TWh]
- Oil [TWh]
- Natural gas [TWh]
- Solid biomass [TWh]
- Liquid biomass [TWh]
- Gaseous biomass [TWh]
- Electricity [TWh]
- Hydrogen [TWh]
- Waste [TWh]
</td></tr>
</table>

The calculations are divided into four subsequent steps (product, material, energy and feedstock and emission level), shown in the calculation tree (Figure 4). Additionally, raw materials to produce e.g. iron are provided by the non-core module "Minerals" (WP4).

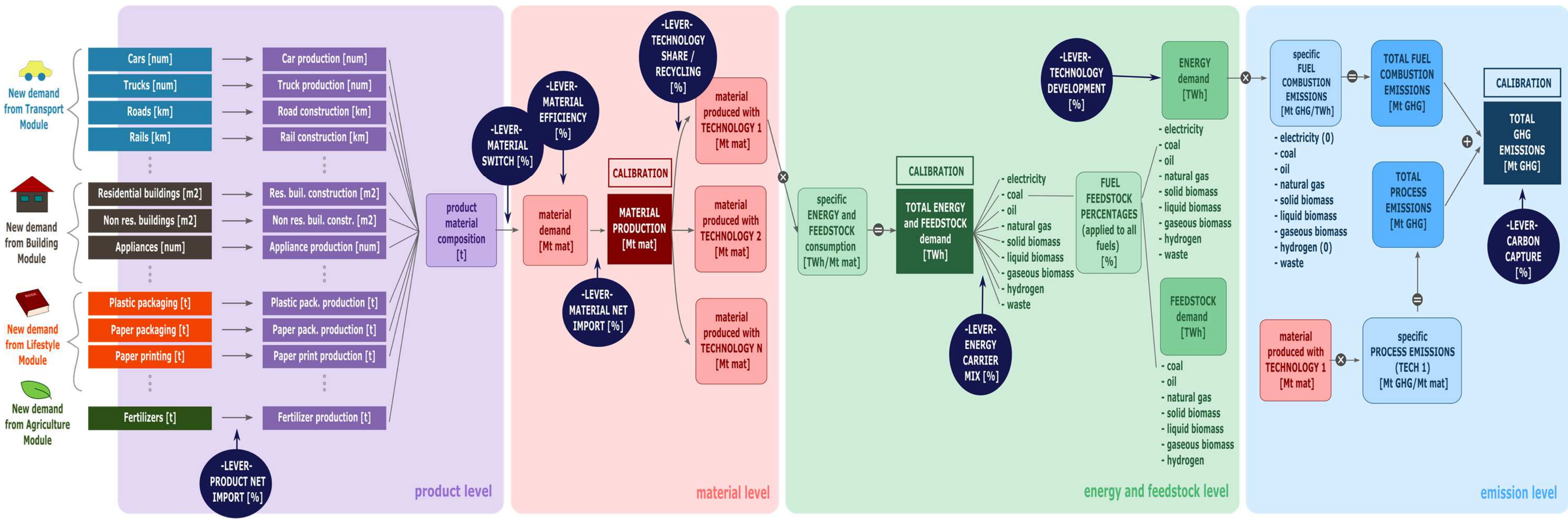

Figure 4: Manufacturing and production calculation tree for one industrial sector. Analogous calculation trees are used for each energy-intensive sector considered (steel, cement, chemicals (split in ammonia and other chemicals), paper, aluminium, glass, lime and copper). For non-energy intensive sectors, material demand is based on historic trends and the calculation tree performed for energy and emissions only.

4 Sector interactions

This section presents the input/output data used for the Production and Manufacturing module, as well as the sources and the interactions with other modules (shown in Figure 5).

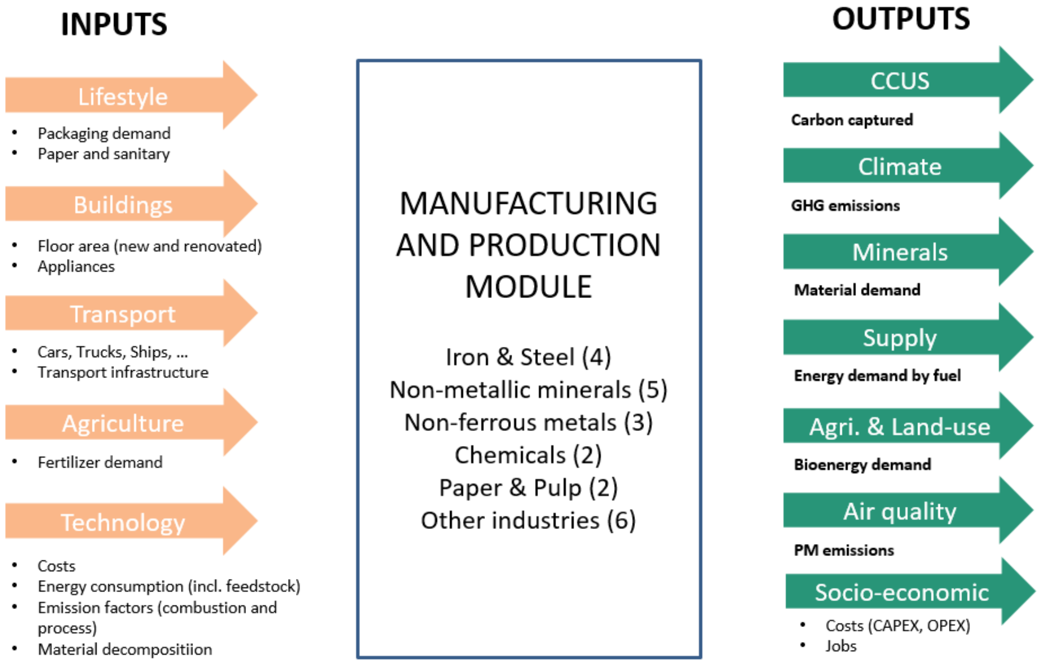

Figure 5: Sector interactions of the manufacturing and production module within EUCalc

For each demand (transport, buildings, fertilizers in agriculture, and consumer goods in lifestyles) as well as industrial sector, a detailed material decomposition to take into account an activity-to-product and sequentially product-to-material link was achieved. Starting with the definition of the value chain and decomposing products into materials, demand trajectories were modelled resulting in total material production, final energy demand and related GHG emissions. Environmental (for example climate, air quality) and socio-economic (for example jobs and employment) impact modules subsequently process industrial activity data.

4.1 Inputs from other modules

4.1.1 Technology

The Technology module (WP1) defines specific energy consumption and specific process emissions per technology. It also includes the material switch ratios as well as material intensities per product, as laid down in the material decomposition table. Several technological configurations (in terms of technology diffusion) are available. However, no different geographical, social, economic, institutional environments are taken into account, which characterize the different EU member countries. The deployment and diffusion of emerging technologies (breakthrough technologies) in industrial sector are considered.

4.1.2 Lifestyle

Behavioural aspects, consumer aspects, values systems, and the active role of users in the innovation system are crucial factors and considered by a number of consumer goods. The Lifestyle module (WP1) provides projections on the amount of plastic, paper, aluminium and glass packaging, printing, and graphic paper, sanitary and household paper consumed in each European country per year until 2050 (see Table 1). Accounting for the net import rates the Manufacturing module calculates how many tons of these products are produced in each country and how much material (paper and plastic) will be needed.

4.1.3 Buildings

The Building module (WP2.1) provides the surface (net area) of new buildings that will be constructed until 2050 in each European country as well as the surface of already existing buildings that will be renovated (see Table 1). The Manufacturing module assesses the required amount of materials (steel, cement, chemicals, etc.) and estimates the future annual production of these industrial sectors by taking into consideration the net import rate of materials.

Another input from the Building module is the number of new appliances and length of district heating pipes that are installed every year (see Table 1). Accounting of the net imports of these products, the Manufacturing module assesses how much materials will be required for their manufacturing.

4.1.4 Transport

The input of the Transport module (WP2.2) is the yearly demand of new vehicles (cars, trucks, ships, trains, and planes as detailed list in Table 1). The Transport module provides also the length of new transport infrastructures (roads, railways and trolley cables) that will be constructed every year until 2050. The Manufacturing module estimates the materials that will be required for the construction of roads and railways and for the manufacturing of cars, trucks, etc.

4.1.5 Agriculture

The Agriculture module (WP4.3) provides the yearly fertilizer demand to the Manufacturing module, which assesses the amount of ammonia necessary to produce it.

4.1.6 Trade

To link the domestic demand for products (cfr sections above) and how much materials are manufactured in each country, the industry module takes into account the share of domestic production. For manufacturing, this is at the level of products (e.g. share of cars produced domestically) and materials (e.g. share of steel produced domestically). For food, this is at the level of the animals (share of cows grown locally) and of the crops (share of cereals grown locally).

4.2 Data from literature (historical database)

The main source used for the calibration of material production, energy consumption and emissions of the Manufacturing module is JRC-IDEES (Mantzos et al., 2018). The database was published in 2018 and is maintained by the European Commission's Joint Research Centre.

For the calibration of materials, Eurostat Prodcom database was used as additional source, providing data of total production values of materials (Eurostat, 2019).

5 Levers and ambition levels

5.1 Lever list and description

Abatement of emissions in the Manufacturing module can be achieved by using numerous decarbonisation strategies. A combination of mitigation options can bring industry emissions close to net-zero: demand-side measures, energy efficiency improvements, the substitution of fuels and feedstock, carbon capture and storage and usage and other innovations. Hereafter, the most relevant actions that need to be set in place in order to significantly reduce emissions in the manufacturing and production sector by 2050 are:

1. Substitution of materials used in products (e.g. replacing steel and cement in buildings by timber)
2. Increase the material efficiency (e.g. smart design, use of more efficient materials, reduction of yield losses in manufacturing[2])
3. Change of material production technology (e.g. switching from the primary route to the recycling route or to innovative technologies)
4. Switch to green energy carriers in the material production (e.g. from fossil fuels to biofuels and to hydrogen, considering the availability limits of these energy carriers)
5. Increase of energy efficiency for each technology
6. Use of CCU and CCS to capture waste carbon dioxide (considering the storage potential of each European country)

Each of these actions constitutes a lever in the manufacturing and production sectors. The magnitude of the emission reduction is expressed in the ambition level, which ranges from a minimal to an extraordinarily ambitious effort to tackle climate change.

In addition to these levers, two other levers are added to account for domestic production share of products and materials. These enable to assess the domestic share of production, energy demand and emissions of the industrial sectors (it is a proxy of the trade-balance). These levers, differently from the others, do not have a univocal impact on emissions. Lower domestic production shares (higher net imports) could reduce direct emissions by reducing the production of materials and products in a country. However, they could increase total emissions, if the imported materials and products are produced in countries with less efficient technologies.

Table 2 summarizes all the proposed levers. The calculation tree in Figure 4 shows, where the levers are applied in the calculations.

Table 2: List of levers for the Manufacturing module

	Lever	**Brief description**
1.	Material switch [%]	Percentage of material replaced by another in products

[2] The notion of product lifetime, which directly influences the demand for new products, is covered in each of the sectors, which demand products.

2.	Material efficiency [%]	Percentage of decrease in material demand due to smart design, use of more efficient materials, smart manufacturing (e.g. 3D printing)
3.	Technology share/Recycling [%]	Percentage of material produced with a given technology in each industry (see the list of industries and technologies in **Fehler! Verweisquelle konnte nicht gefunden werden.**). Technologies also specify if the material is recycled.
4.	Energy carrier mix [%]	Percentage of energy used along each energy carrier (electricity, coal, oil, gas, biofuels, waste, and hydrogen) in each technology. This includes feedstock.
5.	Technology development [%]	Percentage of decrease in energy consumption due to energy efficiency measures for each technology
6.	Carbon capture [%]	Percentage of CO_2 equivalent emissions captured with CC in each industry
7.	Materials domestic production share [%]	Difference between import and export of materials divided by the new demand for materials
8.	Product domestic outputs share [%]	Difference between import and export of products divided by the new demand for products

5.2 Definition of ambition levels

5.2.1 Levels 1, 2, 3, 4

For each lever four levels of ambitions to reduce emissions by 2050 are proposed. The levels are defined as:

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

More details on the ambition levels can be found in the document "EUCalc_Cross-Sectoral_Model _description _and _documentation".

5.2.2 Levels A, B, C, D

The ambition levels of the trade levers on the domestic share of production do not follow the previous 1-2-3-4 definitions. For these levers an increase in ambition level do not correspond to a larger reduction of emissions.

For this reason, we define special A-B-C-D ambition levels:

- **LEVEL A: Domestic share of production higher than the baseline scenario**
- **LEVEL B: Domestic share of production of the baseline scenario**
- **LEVEL C: Domestic share of production lower than the baseline scenario**
- **LEVEL D: Domestic share of production much lower than the baseline scenario**

5.3 Lever specifications

This chapter describes the different levers as well as their ambition levels.

5.3.1 Material switch

The material switch lever describes the main material switches occurring in products (e.g. in cars, buildings, etc.). It is expressed as the percentage of material in a product that is expected to be substituted by 2050 by a less carbon-intensive material, over the product lifecycle. To keep the model as simple as possible, only the most relevant material substitutions are represented, i.e. those that are expected to have a large impact on the product life cycle.

The material switches analysed by the Manufacturing module are focused on the building and transport sectors. The main expected substitutions are from concrete and steel to timber in buildings and from chemicals to cellulose and natural fibres in thermal insulation materials of renovated buildings. An extensive literature review has been performed in order to identify the possible timber substitution rates of cement and steel in Europe in the next decades. Several studies point out the importance of the switch to timber by comparing the embodied emissions of wood with other construction materials (e.g. Sathre and O'Connor, 2010; Werner et al., 2005; Upton et al., 2008; Gustavsson and Sathre, 2011; John et al., 2009). However, in none of them realistic projections of wood substitution percentages are provided. The ambition levels for wood substitution in buildings were initially considered equal to those, assumed in the EU CTI 2050 Roadmap Tool (2018), and then further validated at the expert consultation.

In the transport sector, the main switch foreseen is the replacement of steel with lighter materials such as aluminium or carbon-fibre reinforced plastics in vehicles. According to Modaresi et al. (2014) in 2030 in the most ambitious scenario, the composition of an average gasoline vehicle will be 26% of iron and steel and 42% of aluminium, compared to 67% iron and steel and 8% aluminium in 2010. This means that about 35-40% of steel could be replaced by aluminium by 2030. Carbon fibre reinforced polymers could also replace part of the steel used in vehicles. However, the uptake of carbon fibres substitution faces challenges related to cost and recyclability.

Based on the previous analysis it is estimated, that the substitution of steel with aluminium in cars could reach 50% by 2050 for the ambition level 4, while the substitution with carbon fibres is expected to be lower (20%), due to the expensive cost and non-recyclability of the material. The substitution potential in trucks is considered to be lower compared to cars, since the loads carried by trucks reduce the fuel savings benefits of light-weighting, as shown also in the projections of Ducker Worldwide (2017). The other levels are estimated as proportional to level 4 (respectively 0, 1/3, and 2/3).

In transport, no relevant differences are expected to occur in material switches projections across Europe, as these will be mainly driven by the future cost of the substitution materials for the automotive industry.

Possibly more differences could be foreseen in the building sector, where larger substitution rates of wood could be expected in northern countries. However, due to lack of specific projections, in the current version of the model, the ambition levels are assumed to be the same within Europe.

Following the input of the expert stakeholders, two new material switches have been added, which were originally not included:

- Chemicals replaced by natural fibres in renovated surfaces
- Chemicals replaced by cellulose (paper) in renovated surfaces

5.3.1.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050.

Table 3: Ambition levels for the lever material switch

Name / Unit	2020	2050			
		1	2	3	4
Substitution of steel by chemicals (carbon fibres) in cars [%]	0	0	7	13	20
Substitution of steel by chemicals (carbon fibres) in trucks [%]	0	0	5	10	15
Substitution of steel by aluminium in cars [%]	0	0	17	33	50
Substitution of steel by aluminium in trucks [%]	0	0	15	30	45
Substitution of steel by timber in buildings [%]	0	0	7	13	20
Substitution of concrete by timber in buildings [%]	0	0	20	40	60
Substitution of chemicals by paper (cellulose) in renovated surface [%]*	0	0	3	7	10
Substitution of chemicals by natural fibres in renovated surface [%]*	0	0	7	13	20

* The ambition levels of these material switches need to be further validated.

5.3.2 Material efficiency

This lever represents the percentage of decrease of material used in products due to a number of factors, including designs that require less material, use of better materials, improvement of manufacturing yields, and reuse after disposal among others. Hereafter, the material efficiency strategies for each material considered are described.

The ambition levels for material efficiency of **cement** and **steel** have been validated by using as a reference for level 4 the results obtained by the OECD/IEA study for the Material Efficiency Scenario excluding the impact of lifetime extension, which is not considered in the lever material efficiency (OECD/IEA, 2019, upcoming). The ambition levels of the material efficiency will be counterchecked to account for possible changes in the results of the analysis once the study is published.

For **ammonia**, the ambition level 4 is considered equal to the most ambitious level proposed by EU CTI 2050 Roadmap Tool (2018) for 'chemical ammonia' in the material intensity lever. Level 4 of the group **other chemicals** is assessed as an average of the most ambitious levels of 'Chemical Others' and 'Chemical HVC' of EU CTI 2050 Roadmap Tool (2018).

The material efficiency of **paper** can be optimised by substituting or reducing production materials (e.g. the manufacturing of lighter paper). The material recovery (wood fibre) or the increased recycling of paper are also considered in the levels of ambition.

The material efficiency levels for **aluminium** have been validated by using the results of the OECD/IEA study for the Material Efficiency variant (MEF) for level 4.

Material efficiency in the **lime** industry can be achieved by using granulated blast-furnace slags and coal ash can replace clinker (made from limestone) in the cement production (Material economics, 2018).

In the **copper** sector, material efficiency can be achieved by producing thinner and higher performing copper alloys, which are increasingly requested by downstream users in order to save both resources and energy during the useful lifetime of their products (European Copper Institute, 2014). Also, the reduction of the thickness of copper tubes or the usage of 3D printing can reduce the material demand without affecting functionality (International Copper Association, 2017).

The other ambition levels are estimated as proportional to level 4 (¼, ½, and ¾, respectively).

No significant differences in material efficiency projections across Europe emerged from the literature review. Therefore, the ambition levels are kept equal for each European country.

5.3.2.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050.

Table 4: Ambition levels for the lever material efficiency

Name Unit	2020	2050			
		1	2	3	4
Steel [%]	0	8	16	25	33
Cement [%]	0	2	4	7	10
Ammonia [%]	0	2	4	7	10
Other chemicals [%]	0	7	15	22	30
Paper [%]	0	3	5	8	10
Aluminium [%]	0	4	7	10	14
Glass [%]	0	3	5	8	12
Lime [%]	0	3	5	8	14
Copper [%]	0	3	5	8	14

5.3.3 Technology share

This lever describes, within each industry, the percentage of material produced using each of the available technologies. In this lever, the share of recycled materials as well as the deployment of new emerging technologies is considered.

Table 5: Specific energy consumption and process emissions per technology

Name	Specific energy consumption [TWh/Mt] 2015	Specific process emissions [Mt/Mt] 2015
Steel – BF-BOF	4.9	1.46
Steel – scrap-EAF	1.36	0.08
Steel – HIsarna	3.92	1.17
Steel – hydrogen-DRI	3.48	0.7
Cement – dry-kilns	0.83	0.52
Cement – wet-kilns	1.76	0.52
Cement – geopolymers	0.65	-
Chemicals –Basic	13.26	0.45
Chemicals – Ammonia	9.73	2.1
Paper – wood pulp	6.04	-
Paper – recycled	3.11	-
Aluminium – primary	13.9	1.6
Aluminium – secondary	1.87	0.3
Glass	2.42	0.2
Lime	1.18	0.85
Copper	4.72	0.6

Currently in Europe **steel** is produced with two steelmaking processes: primary route (BF-BOF) and recycling route (scrap-EAF). The share of scrap-EAF has increased from 20% in the 1970s to around 40% recently (JRC, 2013) and will continue to increase in the future due to a larger availability of scrap (Eurofer, 2013). However, a prospective shift to recycling is confined by scrap availability and its quality. The quite conservative scenario provided by BCG and VDEh (2013) estimates that the recycling route will reach a share of 44% in Europe by 2050.

Another steelmaking process currently not used in is the direct reduction-based technology (DRI). This technology consists of the direct reduction of iron ores into solid primary iron. Usually, the reducing agent used in this process is natural gas. Due to the higher cost of natural gas, the gas-DRI route cannot compete with the BF-BOF route in Europe. However, an alternative is to use hydrogen instead of gas as a reducing agent (hydrogen-DRI).

The HIsarna process is another innovative technology for steel production. This technology is a substitute for the BF-BOF route and would allow a decrease in energy use and emissions by at least 20% (Tata Steel, 2018). The increase of percentage of CO_2 in exhaust gases makes this technology an ideal candidate for carbon capture. Combined with CCS, with this process, the potential reduction of CO_2e emissions released to the atmosphere is 70–80% (JRC, 2013).

Another breakthrough technology proposed in the ULCOS project is electrolysis of iron ore (ULCOLWIN). This technology, however, is still at the laboratory research phase and could become a candidate process route only if carbon-free electricity becomes competitive.

Based on the previous analysis, it is estimated that in the most ambitious case (level 4), scrap-EAF technology will reach a share of 70% on average in Europe and the new emerging technologies, HIsarna and hydrogen-DRI, could each reach a maximum share of 10% with the remaining 10% of steel still produced with BF-BOF. Still at the laboratory phase, it is not expected by the authors that electrolysis will play a major role in the steel industry by 2050 even in the most ambitious scenario. The projection of BCG and VDEh (2013) of 44% share of the recycling route is considered to be ambitious but achievable (level 2). For the less ambitious scenario (level 1) we hypothesize that the technology share will remain the same as in 2015. Intermediate values were assigned to level 2 and 3.

Cement production is a two-step process. First, clinker is produced from raw materials (limestone) by heating in a rotary kiln at temperatures up to 1,500°C. This step can be a dry, wet, semi-dry or semi-wet process. After the clinker is produced, the second step involves gypsum (calcium sulphates) and possibly additional materials, such as coal fly ash, natural pozzolanas being added to the clinker. Most of the CO_2 emissions and energy use of the cement industry are related to the first step, the production of the clinker, which is obtained throughout the calcination of limestone.

A way to reduce the process emissions during the calcination process is the use of new cement chemistries. A wide variety of new chemistries are being developed and among them, geopolymers based cement could eliminate nearly all process emissions (Energy Transition Commission, 2018). The penetration in the market will be limited by the level of investment required, the lack of availability of the required mineral feedstock. Unless there are major development breakthroughs, new chemistries seem unlikely to provide a path towards total decarbonisation across all locations (Energy Transition Commission, 2018). According to Favier et al. (2018) no more than 10% of cement can be replaced by these alternatives by 2050.

It is estimated, that in the most ambitious scenario all the wet facilities will be phased out and 20% of the cement produced will be replaced by geopolymers based cement (the projection of 10% replacement by Favier et al. (2018) is adopted for very ambitious but achievable level 3).

In Europe, pulp and **paper** industry is the fourth largest industrial energy consumer (see Figure 2). There are two main routes to produce pulp: from virgin wood or from recovered paper. European recycling rates have increased from around 40% in 1991 to 72.3% in 2017 (Roth et al., 2016; CEPI, 2018). In Europe, only about 46.4% of the paper produced comes from recycled fibre, 22.7% from integrated pulp, 17.4% from market pulp and 13.4% from non-fibrous materials (CEPI, 2018). Pulp production from recycled fibres is less carbon and energy intensive than pulp production from virgin wood. Substituting virgin woods for recycled fibres would reduce emissions by about 37% (Roth et al., 2016).

The technology share of paper in ambition level 1 is considered to be the same as of 2015 (based on CEPI (2018), excluding the share of paper from non-fibrous materials). For the most ambitious scenario, estimated paper production from recycled fibres could reach a maximum of 90%. From the literature review, it did not emerge a clear picture of breakthrough technologies that could possibly be deployed by 2050, therefore none of them is considered at the moment.

The **chemical** industry covers a large number of products and the technology used in the manufacturing process varies from one product to the other. The number of product-specific technologies is very high and consider them all would bring a lot of uncertainties in the assumptions, considering also the lack of specific data. We decided to consider separately only the **ammonia** production and group the other chemicals together. The choice to model ammonia is two-fold: firstly, ammonia production is one of the most carbon-intensive industrial processes and secondly, it is necessary to have it separately to satisfy the fertilizer demand from the Agriculture module.

The manufacturing of **aluminium** is divided in two processes: the production of primary aluminium (aluminium primary) and secondary or recycled aluminium (aluminium secondary). The share of secondary aluminium produced in Europe has increased since 1995 and currently accounts more than half of the aluminium production. According to Groot et al (2012) recycling will remain an important stable resource stream. A faster growth is unlikely due to already high recycling rates and the reliance on a scrap stream form end-of-life products. According to Voet et al. (2014) the maximum attainable global secondary production fraction is around 50% due to increasing aluminium demand and the available amount of aluminium scrap. The share of the recycling route is estimated by 55% in Europe in 2050.

Common raw materials for the **glass** production are silica, sodium carbonate, limestone and dolomite, which are heated in a furnace to about 1500-1600°C to form molten glass. After the melting follows the homogenisation to remove bubbles, the forming of the actual glass product and annealing for the removal of stress. Other product specific downstream processes are cutting, surface treatments or fiberizing. To reduce complexity glass is modelled by one technology only.

To manufacture **lime,** calcium and magnesium carbonates (limestone) are calcinated in different types of lime kilns at temperatures of 900 to 1200°C. The result is quicklime, which can be used directly or hydrated to get slaked lime. To reduce complexity lime is modelled by one technology only.

In the **copper** production process, copper concentrates (up to 30 % copper) are roasted and smelted in order to obtain copper matte, which is then further manufactured to copper anodes and then copper cathodes. For the production of secondary copper, pyrometallurgical processes are used to rework scrap and other secondary materials. To reduce complexity copper is modelled by one technology.

Nowadays, around 40% of Europe's production of copper products (around 4 million tonnes in total) is sourced from recycling. Copper produced from scrap saves approximately 80% of the energy necessary to produce primary copper from mining (European Copper Institute, 2014). Copper recycling rates are expected to slowly increase because of three main reasons: First, copper demand is expected to grow with economic growth, product innovation and the electrification of processes. Second, most copper can stay in use for several decades (e.g. in electricity infrastructure) before it becomes available for recycling (European Copper Institute, 2014).

The technology share in the steel industry varies considerably from one European country to the other. The current share is taken from Worldsteel Association (2016). In countries where the share of scrap-EAF was 100% in 2015, no further changes are contemplated. In the other countries, the share of scrap-EAF for level 4 is expected to double by 2050 with a maximum threshold of 70%. For the same countries the share of the new steelmaking technologies hydrogen-DRI and HIsarna is expected to increase with a maximum of 10% each in the most ambitious scenario. BF-BOF covers the remaining production share.

The current technology share in the cement sector has been taken from the Cement Sustainability Initiative of the World Business Council for Sustainable Development (WBCSD). In the dry kiln technology group, we aggregated both dry technologies and mixed kiln type. In the wet kiln group, we included both wet and semi wet / semi dry technologies. In countries where data were missing, we considered the European average. For the most ambitious scenario, the wet kiln route is supposed to be phased out in all countries by 2050 and the geopolymer technology to reach a 20% share.

No specific data concerning the technology share of paper industry within the single European countries have been found. Therefore, the technology share in each country is considered to be equal to the European average.

5.3.3.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050.

Table 6: Ambition levels for the lever technology share

Name / Unit	TRL	2020	2050			
			1	2	3	4
Steel – BF-BOF [%]	9	61	61	50	35	10
Steel – scrap-EAF [%]	9	39	39	44	55	70
Steel – HIsarna [%]	7	0	0	3	5	10
Steel – hydrogen-DRI [%]	4-7	0	0	3	5	10

Cement – dry-kilns [%]	9	91	91	89	87	80
Cement – wet-kilns [%]	9	9	9	6	3	0
Cement – geopolymers [%]	9	0	0	5	10	20
Chemicals –Basic [%]	9	100	100	100	100	100
Chemicals – Ammonia [%]	9	100	100	100	100	100
Paper – wood pulp [%]	9	46	46	34	22	10
Paper – recycled [%]	9	54	54	66	78	90
Aluminium – primary [%]	9	50	50	48	46	45
Aluminium – secondary [%]	9	50	50	52	54	55
Glass [%]	9	100	100	100	100	100
Lime [%]	9	100	100	100	100	100
Copper [%]	9	100	100	100	100	100

5.3.4 Energy carrier mix

This lever assesses within each industry and within each determined technology specified earlier, what is the energy carrier mix and how it is going to change by 2050. The energy carrier mix (which includes both feedstock and energy) consists of a combination of electricity, coal, oil, gas, solid biomass, liquid biomass, gaseous biomass, waste and hydrogen. Within our scope, we compare various non-fossil fuel decarbonisation options for the industry sector, such as electrification or hydrogen-based processes[3].

The energy carrier mix in each industry typically varies from one technology to the other. For example, in the steel industry the BF-BOF route uses mainly coal for the steel production, while the scrap-EAF route uses mainly electricity.

For the calibration of the current compositions of the energy carrier mix of the different technologies in 2015 the JRC-IDEES database is used, which shows a detailed split of energy consumption by subsectors, technologies, and energy carriers.

In the **steel** industry, charcoal (solid biomass) is one option to replace coal both as fuel and feedstock in BF-BOF plants (Energy Transition Commission, 2018). However, using charcoal instead of coal requires smaller furnaces and is less efficient. Hydrogen-based steelmaking and primary steel production using electricity promise major emissions reductions but firmly depend, for commercial viability, on low-cost (and renewable energy-based) hydrogen production. The technologies require more electricity than conventional steel production (through BF-BOF), and these actors would therefore benefit from increased predictability of developments in the electricity market, as well as access to sufficient amounts of low-cost, predictable renewable energy (Axelson et al., 2018)).

Replacing natural gas with zero-carbon hydrogen in the direct reduced iron (DRI) process for steel production would also mitigate emissions. However, this technology is still in the pilot phase (HYBRIT project by the Swedish steelmaker SSAB). This switch does not require a large retrofit when implemented at existing

[3] Note: E-fuels are taken into consideration in the CCUS module.

DRI facilities, but in Europe, where DRI technology is not used, the existing BF-BOF plants would mostly have to be rebuilt as DRI facilities (McKinsey, 2018).

A decarbonisation option for the **cement** sector is to substitute fossil fuels by alternative fuels (IEA, 2009). Alternative fuels include biomass, biogas, and wastes that may otherwise be burnt in incinerators, landfilled or improperly destroyed. According to Favier et al. (2018), the use of alternative fuel in the cement industry could reach a share of 40-60% in developed countries including Europe (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). Higher substitution rates may be limited by several factors like the potential impact on clinker chemistry (e.g. increase in phosphate by use of sewage sludge, increase in chlorides when waste plastics are used) and the availability of waste depending on local legislation. Another option is the use of electric or hydrogen furnaces at existing cement plants, but it would require extensive retrofitting of these facilities. The use of hydrogen fuel for high-temperature heat also poses technical and safety challenges (McKinsey, 2018).

Additionally, new binders reduce both process-related (less or no decarbonisation) and energy-related emissions (lower process temperatures, lower demand for thermal energy) compared to conventional Portland cement production (Fleiter et al., 2019).

In the **chemical** industry, the switch from fossil fuels for heat production to biomass would reduce CO_2 emissions with limited alterations to the furnace design and production setup. The substitution of fossil feedstock with bio-based feedstock in the steam cracking process could as well reduce end-of-life emissions. For example, for the production of ethylene, biodiesel could be converted to bio-naphtha and used in the existing steam cracking furnaces. An alternative process would be the use of bioethanol to produce ethylene via ethanol dehydration. The fundamentally transformative processes in the chemicals industry are largely based on reactions that involve carbon and hydrogen, where hydrogen acts as energy carrier to enable the conversion of CO_2. Different low-CO_2 pathways can be designed using low-CO_2 hydrogen (sourced from low-CO_2 electricity) as a reactant. The emission mitigation potential of the technologies in this route range significantly, with abatement potential as high as 100% (Axelson et al., 2018).

To determine the energy carrier mix for **ammonia**, we used as sources Boustead (2015), Gilbert et al. (2014), and EFMA (2000). In the ammonia production, there are two main energy carrier switches, which can be expected. The first one is the use of biogas instead of natural gas both as feedstock and fuel. The second one is the switch to hydrogen made from electrolysis. This would avoid the CO_2 emissions that are currently often used to make urea, a type of fertilizer based on ammonia and CO_2.

Since 1990, the **paper** and pulp industry has changed the composition of its fuel mix, increasing the use of biomass and decreasing reliance on oil and coal (Roth et al., 2016). According to Griffin et al. (2018), the main changes to be expected in the energy carrier mix of this industry by 2050 are an increasing use of waste-fuels, bio-fuels, and electricity and a decrease of natural gas use. Technologies for electricity-based papermaking are generally advanced (if not already commercially available). The market for electricity currently impedes widespread electrification processes (Axelson et al., 2018).

According to Moya et al. (2015) the energy carrier mix for the production of **primary aluminium** will change towards an increased usage of electricity and an increase of natural gas. Incremental technology development supports to reduce specific electricity consumption. One of the recent pilot projects in Europe is located in Karmoy, Norway. Still in pilot stage (TRL 7), this technology reduces electricity consumption with carbon anodes (Axelson et al., 2018).

Given the availability of scrap **aluminium**, the **secondary route** will play an increasingly important role in the production of aluminium. The future energy carrier mix is dominated by electricity.

In the **glass** industry, a switch to all electric melting using decarbonised electricity would eliminate CO_2 emissions from glass melting which are generated from the combustion of fossil fuels. It has to be noted that process emissions (originating from the decomposition of raw materials leading to CO_2 emissions and representing about 15% of the total glass industry's emissions) will not be eliminated by this technology. Currently, there is no all-electric furnace for melting E-glass. The cost of electricity and the quality of melting (especially with high level of cullet) and final glass products are the main barriers to uptake and further innovation in this area. Another option in the glass sector includes switching to oxy-fuel combustion utilising decarbonised electricity to produce the oxygen, use of biogas and addition of carbon-free hydrogen to the gas grid.

In the **lime** production process, most of the energy consumption is heat required in the kiln during the calcination step. A fuel switch from fossil solid fuels to natural gas or biomass is reported in EuLA (2014). In addition, an increased use of waste as well as solid and gaseous biomass as fuels for a further decarbonisation of the fuel mix is considered until 2050. Another option is the use of solar heat.

For the manufacturing of **copper,** the energy carrier mix consists of electricity, and hydrocarbon fuels. The energy demand and energy carrier mix heavily depends on the ore grade, which has been decreasing lately. Since electricity is expected to become CO_2 neutral in the future, the gradual electrification of the thermal processes of copper production is a strategy to be considered (Kulczycka et al., 2017). The use of biomass provides options for carbon reduction in the copper production process.

From the literature review, differences in the energy mix projections in different countries were not highlighted. For this reason, it is assumed that no significant differences are expected to occur among European countries, also concerning the degree of biomass use.

5.3.4.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050. This table only shows the energy carrier mix for steel BF-BOF and cement wet-kilns as examples. The complete table can be found in Deliverable 3.1.

Table 7: Ambition levels for the lever energy carrier mix (extract)

Material	Technology	Energy carrier	2020	2050			
				1	2	3	4
Steel	BF-BOF	To electricity [%]	0	0	1	0	0
		To hydrogen [%]	0	0	0	0	0
		Solid to gas [%]	0	0	2	3	5
		Liquid to gas [%]	0	0	2	3	5
		To biomass [%]	0	0	10	10	10
Cement	wet-kilns	To electricity [%]	0	0	0	0	0
		To hydrogen [%]	0	0	0	0	0
		Solid to gas [%]	0	0	0	0	0
		Liquid to gas [%]	0	0	0	0	0
		To biomass [%]	0	0	41	70	100

5.3.5 Technology development

The technology development lever quantifies the increase in energy efficiency (incremental and radical) in the technologies used to produce steel, cement, chemicals, paper, aluminium, glass, lime, transport equipment, food, beverages and tobacco, textiles and leather, machinery equipment wood and wood products as well as products form other industries and copper. The mitigation options are included on an individual technology level. The percentage reflects the decrease in energy consumption by 2050 due to energy efficiency measures. Fuel switching is modelled endogenously in the energy carrier mix, see chapter 5.3.4.

Regarding iron and **steel** production, not all European BF-BOF operators are close to the optimum in terms of energy efficiency and thus more potential to save energy is available by bringing them up to the level of best performers (JRC, 2013). One example is the deployment of the innovative Top Gas Recycling technology (ULCOS project) that could increase the performance of the blast furnace by separating the off-gases and reinjecting the useful components into the furnace as reducing agents. The following table shows technology options for the iron and steel production.

Table 8: Technology options for the iron and steel production

Technology option	TRL	Max. Emissions reductions	Energy savings	Market readiness	Ref. Technology
Hydrogen based direct reduction (H2-DR)	7	up to 95%	20%	2030/2035	BF/BOF
Electrolysis of iron ore	6	up to 95%	40%	2040	BF/BOF
Smelting reduction (without CCS)	5-6	up to 35%	20%	2025	BF/BOF
Top gas recycling blast furnace (without CCS)	7	up to 25%	15%	2025+	Blast furnace

The **cement** industry in Europe is phasing out inefficient long dry kilns as well as the wet production process. Major retrofits in existing facilities to increase energy efficiency require high investment costs. However, it is unlikely that large capital investment from private or public institutions in the cement infrastructure will occur in Europe due to the slow economic growth and the existing over production capacity of the cement industry (Favier et al., 2018). A technology, where there is room for progress in the European cement plants is waste heat recovery (Favier et al., 2018).

The European **paper** and pulp sector has heavily invested in combined heat and power (CHP) in the past years. In 2010, the electricity production from CHP was 50% of their electrical consumption (JRC, 2013). The improvement of specific energy consumption from 1991 to 2016 has been 17.7% (CEPI, 2018). Several innovative technologies have not been able to demonstrate market viability yet and for this reason, current research and demonstration are nearly stalled (JRC, 2013).

The energy efficiency of the European **chemical** industry has increased considerably in the last decades. Despite increasing production volumes by 78% between 1990 and 2014, energy consumption decreased by 22% in the same period (DECHEMA, 2017). According to the DECHEMA study, there is a relatively low potential for efficiency improvement due to the strong measures already applied in the past. Their estimation is an improvement of 0.56% p.a. for further efficiency measures.

Incremental technology for **aluminium primary** is making important progress in Europe through one of the recent pilot projects located in Karmoy, Norway. Still in pilot stage (TRL 7), this is the most efficient known technology to reduce electricity consumption with carbon anodes. Other energy efficiency options include wetted anodes, multipolar cells or a novel design of anodes that make electrolysis more efficient by allowing better circulation within the electrolyte bath. For the manufacturing of **secondary aluminium,** optimising of scrap sorting and melting in terms of quantity and quality is essential to decrease the energy demand. Therefore, more efficient, robust and sensitive technologies and alloy-based sorting technologies are required. Furthermore, the oxy-fuel technology uses lower temperatures in the recycling and melting processes, consumes significantly less energy and increases the productivity of aluminium melting plants (European Aluminium, 2016).

In the **glass** sector, waste heat can be used to preheat the raw materials entering the furnace. Currently this is limited to preheating of either cullet only or batches containing more than 40% cullet, otherwise clogging problems and dust carry-over would occur. Therefore, it is necessary to increase the availability and affordability of good quality cullet. The use of pelletised batch would remove this limitation and solve the issue of batch carry-over, which is often associated with the use of pre-heaters but is not yet mature. However, pre-heating raw materials cannot be coupled with electric melting, as the flue gas temperature in this case is too low.

In the **lime** sector, we evaluate the following energy efficiency options: switching from horizontal to vertical kilns, installing heat exchangers in horizontal kilns, switching from vertical kilns to vertical kilns PFRK, improved use of waste heat, energy recovery in hydration, efficient insulation lining to minimize the shell heat losses, optimal combustion process, improved processed and input control.

According to recent literature, the **copper** sector can reduce its energy demand by usage of the following technologies: upgrades of equipment like the replacement of electric motors and the installation of variable speed controls, new or adapted furnaces, thermal insulation of furnaces, buildings and steam networks. In the primary copper manufacturing the process technologies of pyrometallurgy, fire refining and electro-refining can be optimized according to De Vita A. et al. (2018).

A unique database to assess the ambition levels regarding the increase in energy efficiency in the different technologies and industries was used: the recent assessment of the decarbonisation technologies for the PRIMES model (De Vita et al., 2018). The study provides two scenarios: '2030' and 'Ultimate' with a range of values for both scenarios for all the industrial sector and technologies analysed in the EUCalc model. Level 1 has been identified as the lower value of the '2030' scenario and level 4 the maximum value of the 'Ultimate' scenario. The value adopted is an average (e.g. for steel – BF-BOF, the process is divided into sintering, blast furnace, process furnace, casting and rolling). For the novel technologies considered in this module: steel-HIsarna, steel-hydrogen-DRI, cement-geopolymers, no improvement in energy efficiency is expected from the moment they will be deployed till 2050.

The potential percentage increase in energy efficiency is expected to be the same in the different European countries. The next step will be to differentiate this value by country in order to account for current differences in industrial energy efficiencies across Europe.

5.3.5.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050.

Table 9: Ambition levels for the lever technology development

Name / Unit	2020	2050			
		1	2	3	4
Steel - BF-BOF [%]	0	5	11	18	24
Steel - scrap-EAF [%]	0	4	10	15	21
Steel - HIsarna [%]	0	0	0	0	0
Steel - hydrogen-DRI [%]	0	0	0	0	0
Cement - dry-kiln [%]	0	3	6	10	13
Cement - wet-kiln [%]	0	3	6	10	13
Cement - geopolymers [%]	0	0	0	0	0
Ammonia [%]	0	3	9	14	20
Other chemicals [%]	0	5	13	22	30
Paper - woodpulp [%]	0	4	10	16	22
Paper - recycled [%]	0	4	10	16	22
Aluminium - primary [%]	0	5	11	18	24
Aluminium - secondary [%]	0	5	11	18	24
Glass [%]	0	3	7	11	15
Lime [%]	0	3	7	12	16
Copper [%]	0	8	12	16	20

5.3.6 Carbon capture

This lever shows the deployment of carbon capture (CC) by 2050 in manufacturing and production. It includes three technologies, namely: pre-combustion, post-combustion and oxy-fuels. Each technology further contains sub-technologies such as absorption (e.g. MEA) adsorption (e.g. PSA) or membrane separation. The percentage represents the CO_2 emissions captured with CC in each industry. The Manufacturing module assesses the potential for the use of CC in each industry considered. The technologies used to capture the CO_2 emissions and the energy demand for these processes are determined by the CCUS module (WP3.2). For a more detailed description of the different types of CC technologies employed, please refer to the documentation of the CCUS module.

The **cement** industry shows a good potential for the use of CCS as CO_2 emissions are concentrated in few locations (JRC, 2013). This technology is the only one that can currently fully abate process-related CO_2 emissions from cement production (McKinsey, 2018). Nonetheless, the deployment of carbon capture and storage could double the price of cement. The cost of CCS decreases with higher CO_2 concentration, thus a way to limit the cost of CCS for the cement industry would be the use of innovative kilns able to separate exhaust gases from fuel combustion (low in CO_2) from exhaust gases of calcination (process emissions almost pure in CO_2) (Energy Transition Commission, 2018).

In the **steel** industry, CCS could be applied in existing BF-BOF facilities without altering the production process. According to Eurofer (2013), this could lead to a reduction of about 25% of the CO_2 emissions. The increase of the percentage of CO_2 in exhaust gases, as in HIsarna steelmaking technology, would allow reducing the CC costs (McKinsey, 2018). Therefore, a larger application of CC is expected for this technology.

In the **chemical** industry, CCS could be applied to the production of ammonia, methanol, as well as high-value chemicals such as ethylene, propylene and aromatics (IEA, 2016). The nearly pure stream of CO_2 in **ammonia** production would allow capturing emissions with CCS at low cost (McKinsey, 2018). However, in most of the ammonia production facilities, a large part of the CO_2 emitted is currently used to produce urea fertilizer. In the chemical industry there is also good potential for CCU deployment. The production of urea as a downstream product of ammonia it is the largest carbon capture and use process currently in existence (DECHEMA, 2017). In addition to urea, a number of other chemicals such as acetic acid and PVC can be synthesized by using the captured CO_2. Carbon dioxide can be an alternative raw material base for the chemical industry.

In the **paper** and pulp industry, most of the carbon emissions originate from the biomass combustion, which in certain conditions can be considered carbon neutral. The use of CCS and CCU could allow the paper industry to act as a carbon sink (JRC, 2018).

In the **aluminium** and **glass** industries, currently no potential options for the usage of CCS/CCU technologies are available.

The production of **lime** is very carbon intensive. During the production process, CO_2 originating from the raw materials is released. Process emissions account for approximately 70% of the total released emissions. Therefore, a big potential for reduction of the carbon intensity by using CCS and/or CCU is given. Examples are calcium carbonate looping, CO_2 capture by direct usage of algae or carbon capture using limestone, oxyfuel or by using mineralisation. Also lime carbonation in lime mortars or in soil stabilization is possible. Another CC technology is direct separation, which aims to enable the efficient capture of the unavoidable process emissions from lime and cement production.

For the **copper** manufacturing, currently no viable option for the usage of CCS/CCU technologies is available.

The ambition levels adopted for CC are mainly based on the projections provided by IEA (2017) shown in Figure 6. This figure shows the share of production equipped with CCS in three scenarios. If we consider, that in plants equipped with CCS all the CO_2 emissions are captured, this share is equivalent to the percentage of CO_2 captured compared to the total emissions. Ambition level 2 is considered to correspond to the reference technology scenario (RTS), ambition level 3 to the 2 degrees scenario (2DS), and level 4 below 2 degrees scenario (B2DS).

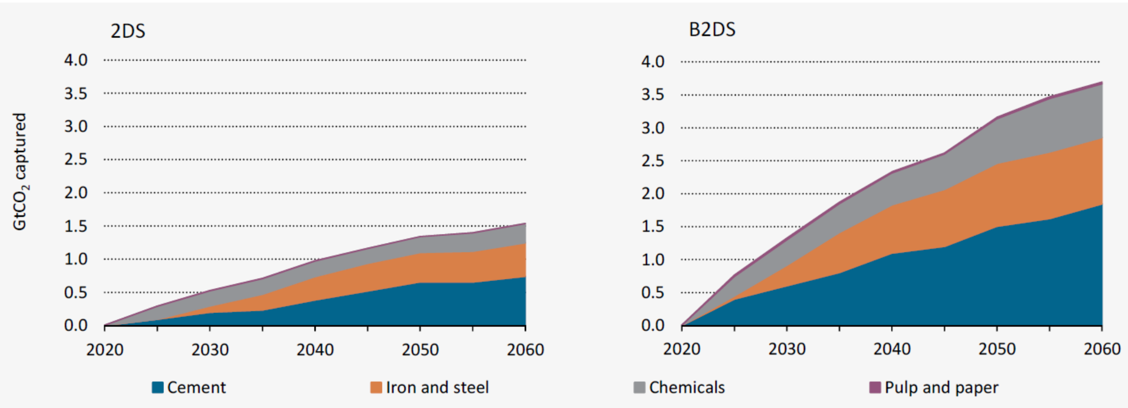

Figure 6: CO_2 captured and stored from industry by subsector in the 2 degrees scenario (2DS) and in the below 2 degrees scenario (B2DS) (IEA, 2017)

5.3.6.1 Ambition levels

The ambition levels (1, 2, 3, and 4) in the table below are referred to the year 2050. Only the technologies with a potential for CC are shown in the table.

Table 10: Ambition levels for the lever carbon capture

Name / Unit	2020	2050			
		1	2	3	4
Steel - BF-BOF [%]	0	0	5	20	40
Steel - scrap-EAF [%]	0	0	0	0	20
Steel – HIsarna [%]	0	0	15	30	50
Cement - dry-kiln [%]	0	0	20	40	65
Cement - wet-kiln [%]	0	0	20	40	65
Cement – geopolymers [%]	0	0	0	20	40
Ammonia [%]	0	0	10	20	45
Other chemicals [%]	0	0	10	20	45
Paper – wood pulp [%]	0	0	0	0	20
Paper – recycled [%]	0	0	0	0	20
Lime [%]	0	0	10	30	70

5.3.7 Domestic share of product and material production

The domestic share levers allow the user to see the impact of trade balance of product and materials on industrial production, energy consumption, and emissions of the Manufacturing module. It is expressed as the ratio (in percentage) of net import over demand.

The historical and projection values of the domestic share ratios are provided for the 2050 baseline scenario by the Trade module (WP7). Table 11**Fehler! Verweisquelle konnte nicht gefunden werden.** shows the correspondences between the list of products and materials analysed in the Manufacturing module and the sectors of the GTAP model, which is the model used to estimate net import projections by the Trade module (Cantuche et al., 2016).

Table 11: Correspondences between products and materials of the Manufacturing module and GTAP sectors

Products and materials	GTAP sector	GTAP sector code	GTAP sector description
Residential buildings	/	/	/
Non-residential buildings	/	/	/
Insulation residential buildings	/	/	/
Insulation non-residential buildings	/	/	/
District heating pipes	35	i_s	Iron & Steel: basic production and casting
Fridges	41	ome	Machinery and equipment n.e.c.
Dishwashers	41	ome	Machinery and equipment n.e.c.
Washing machines	41	ome	Machinery and equipment n.e.c.
Freezers	41	ome	Machinery and equipment n.e.c.
Dryer	41	ome	Machinery and equipment n.e.c.
TV	40	ele	Electronic equipment
Smartphones	40	ele	Electronic equipment
Computers	41	ome	Machinery and equipment n.e.c.
ICE cars	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
ICE trucks	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
FCV cars	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
FCV trucks	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
EV cars	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
EV trucks	38	mvh	Motor Motor vehicles and parts: cars, lorries, trailers and semi-trailers
Ships	39	otn	Other Transport Equipment: Manufacture of other transport equipment
Trains	39	otn	Other Transport Equipment: Manufacture of other transport equipment
Planes	39	otn	Other Transport Equipment: Manufacture of other transport equipment
Road	/	/	/
Rail	/	/	/
Trolley-cables	41	ome	Machinery and equipment n.e.c.
Fertilizer	33	crp	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
Plastic packaging	33	crp	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
Paper packaging	31	ppp	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
Aluminium packaging	36	nfm	Metals n.e.c.
Glass packaging	34	nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
Paper printing and graphic	31	ppp	Paper & Paper Products: includes publishing, printing and reproduction of recorded media

Paper sanitary and household	31	ppp	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
Steel	35	i_s	Iron & Steel: basic production and casting
Cement	34	nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
Ammonia	33	crp	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
Other chemicals	33	crp	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
Paper	31	ppp	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
Aluminium	36	nfm	Metals n.e.c.
Glass	34	nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
Lime	34	nmm	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
Copper	36	nfm	Metals n.e.c.

The net import ratios of the 2050 baseline scenario correspond to level B. For level A the baseline net import ratios are decreased by 20%, for level C increased by 10%, and for level D increased by 20%.

The projections of net import percentages for the 2050 baseline scenario provided by the Trade module are country specific.

5.3.7.1 Ambition levels

The ambition levels (A, B, C and D) in the table below are referred to the year 2050.

Table 12: Ambition levels for the lever domestic share of product and material production

Name / Unit	A	B	C	D
Product net import [%]	-20%	Baseline scenario	+10%	+20%
Material net import [%]	-20%	Baseline scenario	+10%	+20%

6 Results

This chapter aims to provide an overview of results, generated in the Transition Pathway Explorer for energy intensive industrial sectors including material production, energy demand and emissions until 2050. The levers of the manufacturing industry are set to the most ambitious scenario[4] (level 4). The levers of all the other sectors are set to level 1.

Table 13 shows the material production, the energy demand and the greenhouse gas emissions of the energy intensive industries in 2015 and 2050 (all levers on level 4) as well as the changes in percent.

Table 13: Material production, energy demand and emissions for energy intensive industry sectors in 2050

Industry sectors	Production			Energy demand			GHG emissions		
	2015 [Mt]	2050 [Mt]	% change to 2015	2015 [TWh]	2050 [TWh]	% change to 2015	2015 [Mt]	2050 [Mt]	% change to 2015
Steel	205,7	88,7	- 56,9	466,5	138,9	- 70,2	276,5	67,7	- 75,5
Cement	290,1	39,9	- 86,2	187,7	27,1	- 85,6	190,3	18,4	- 90,3
Pulp & paper	94,1	92,6	- 1,6	236,9	202,1	- 14,7	13,5	4,3	- 68,1
Chemicals	111,4	72,2	- 35,2	633,5	417,0	- 34,2	124,7	46,9	- 62,4
Aluminium	5,9	8,7	+ 47,5	20,6	19,8	- 3,9	5,9	6,0	+ 1,7
Glass	43,5	29,9	- 31,3	76,2	52,4	- 31,2	30,5	18,3	- 40,0
Lime	28,6	9,0	- 68,5	25,4	9,9	- 61,0	18,4	5	- 72,8
Copper	3,1	2,0	- 35,5	8,5	5,3	- 37,6	2,7	1,3	- 51,9

The following figures show the material production, the energy demand and the greenhouse gas emissions for the years 1990 to 2050 per technology or per material under the most ambitious scenario of the manufacturing industry.

[4] Other levers (key behaviours, transport, buildings, …) remaining constant at level 1

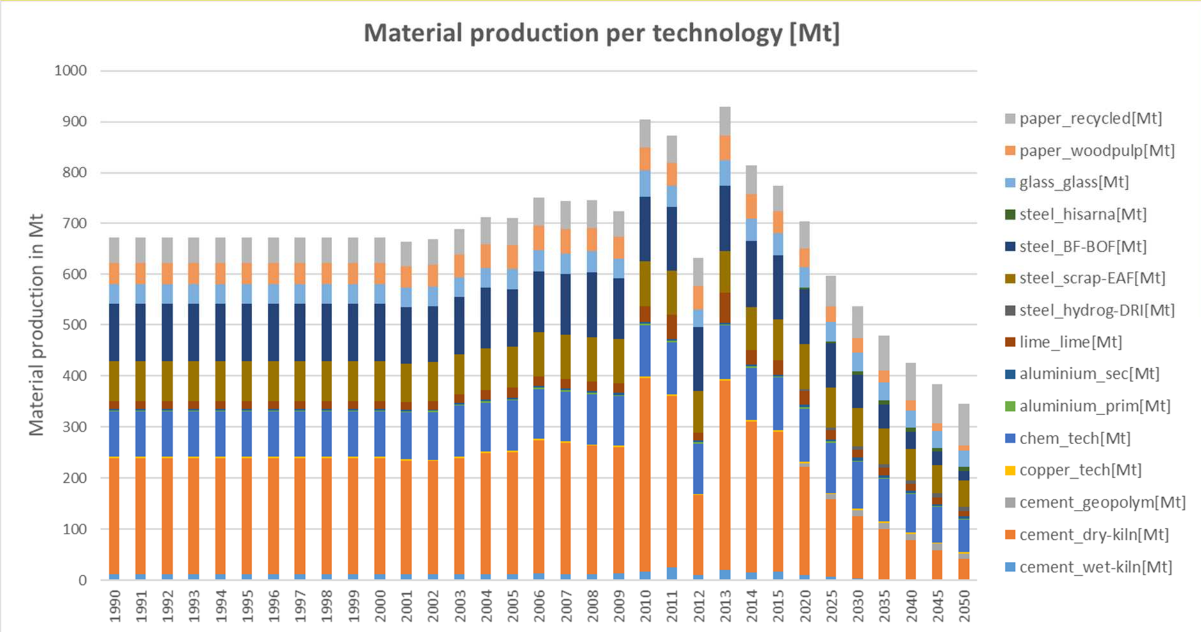

Figure 7: Material production [Mt] per technology until 2050 in the most ambitious industrial scenario (level 4)

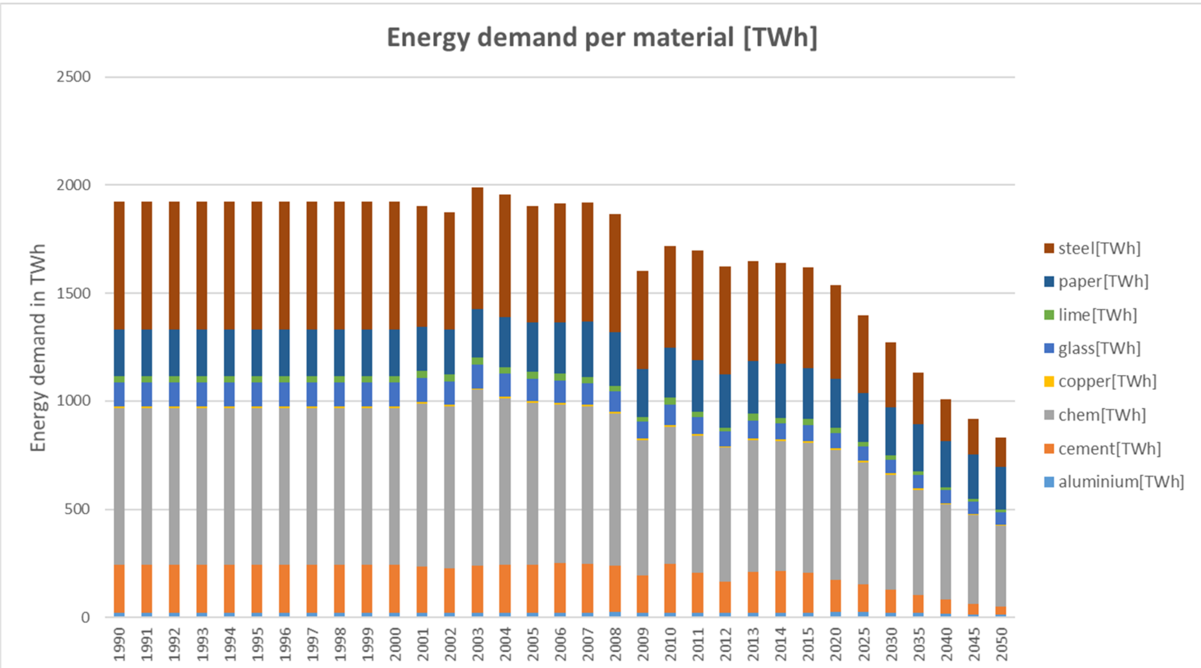

Figure 8: Energy demand [TWh] per material in the most ambitious scenario (level 4)

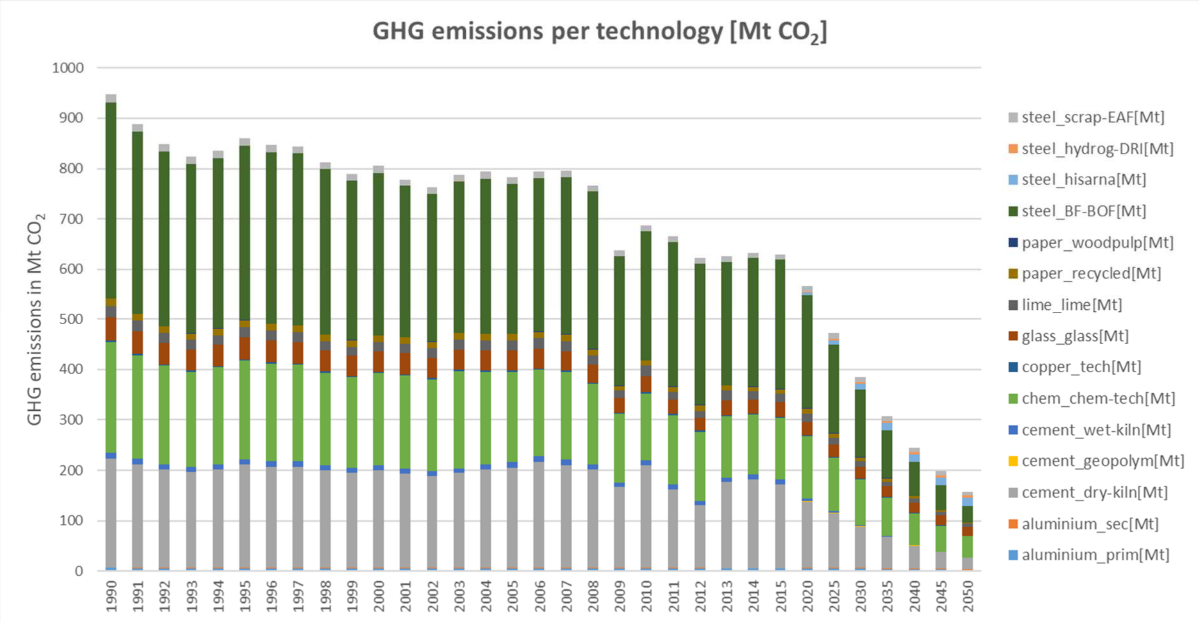

Figure 9: GHG emissions [Mt CO_2] per technology in the most ambitious scenario (level 4)

The extent, to which energy-intensive industries in the European Union will contribute to a decarbonised future, will strongly depend on their ability to implement innovative, new technologies, and the development of new products with an increased material efficiency. The deployment of innovative low-carbon technologies (such as hydrogen-based chemicals, electricity-based steelmaking or low-carbon cement), changes in the product design and materials choice, larger scale in secondary materials industries, and a switch in the energy carrier mix towards renewable electricity or fossil-free hydrogen is required to stay aligned with the EU 2050 carbon mitigation commitments. The analysis also shows, that besides choosing effective decarbonisation scenarios other important impacts such as employment effects and training need to be taken into account so as to ensure a full understanding and political support of the transition effects and trade-offs.

Exploiting the full potential of decarbonisation options may lead to a 90% reduction of greenhouse gas emissions in the industrial sector against a business-as-usual trend, considering the lock-in effects and other limitations such as acceptance and sustainability that come with this transition. To achieve a net-zero greenhouse gas (GHG) emissions objective by 2050 a profound transformation of value chains across the economy, including new products, production technologies, processes and business models, are required. All industrial sectors, including notably energy-intensive ones, have to make very significant contributions to the low-carbon transformation. It is also clear that climate targets are not achievable without a transformative change in the way we use and manage our resources, in particular decision making in the material, energy and climate sector. The European Calculator covers a wide range of technological (> 200 technologies) and knowledge innovation potentials (> 1,000 experts in the co-design phase). Interdisciplinary research is essential to solve these challenges, for its ability to switch from a narrow technical focus to a wider research basis, without sacrificing depth for breadth. The next section provides a higher granularity on the results on a material level.

6.1 Steel

In the most ambitious scenario (level 4) the steel production technologies will change until 2050 from a mix of the primary route (BF-BOF) and the secondary route (scrap-EAF) to a mix with almost the same amount of scrap-EAF, a significantly lower amount of BF-BOF and small amounts of the Hisarna process as well as direct reduction based technology (DRI). The technology shares are shown in Figure 10Table 14 and Figure 10 (left).

Table 14: Technology share and material production of steel in 2015 and 2050

Steel				
	BF-BOF [Mt]	Scrap-EAF [Mt]	HIsarna [Mt]	DRI [Mt]
2015	126,7	79	0	0
2050	19,2	52,3	8,6	8,6

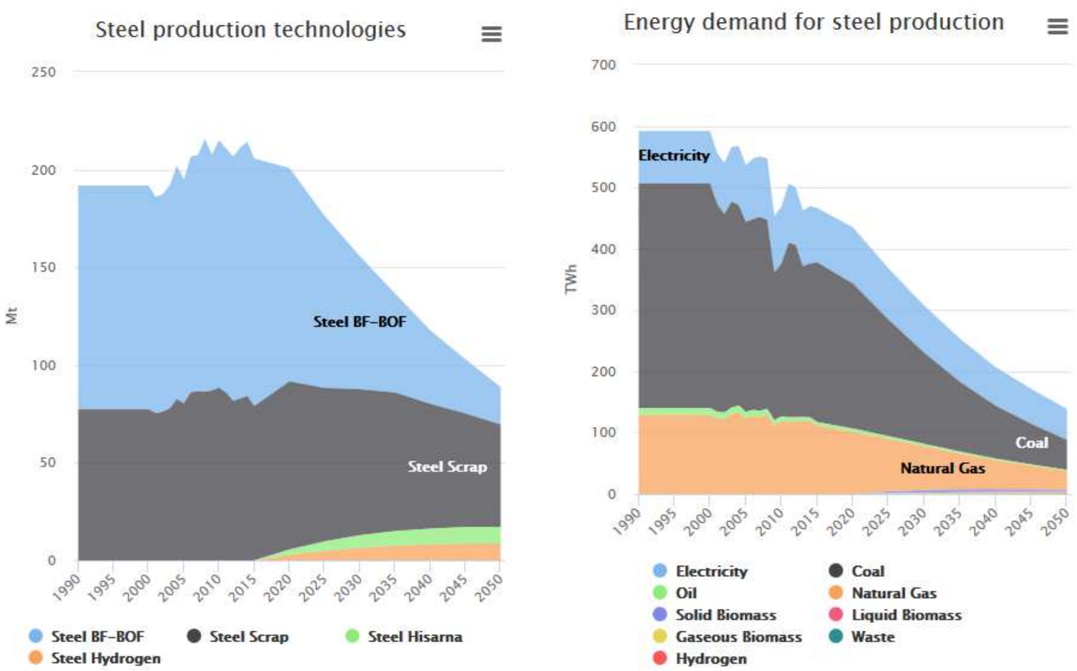

Figure 10: Production technologies and energy demand for steel production in the most ambitious scenario (level 4)

The electricity demand for steel production is expected to decrease to a total of 50 TWh (36 % of the energy carrier mix) in 2050, while fossil fuels such as coal, oil and natural gas are reduced drastically. The energy carriers solid biomass (share of 3 %) and biogas (share of 1 %) will increase, as shown in Figure 10 (right). Coal and natural gas are still expected to provide 57 % in 2050.

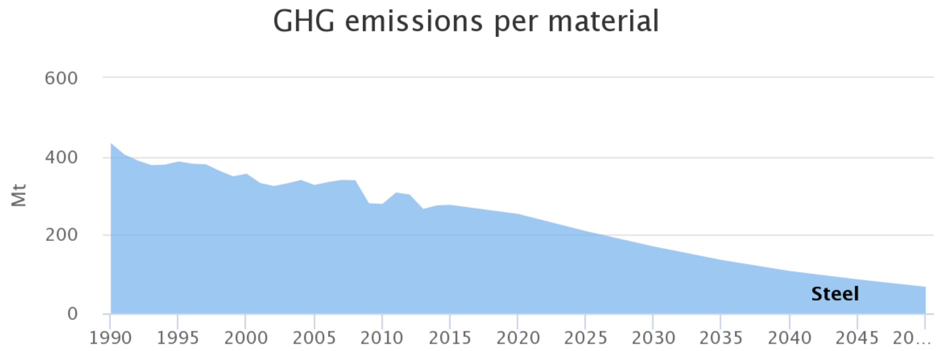

Figure 11: Greenhouse gas emissions for steel production in the most ambitious scenario (level 4)

Figure 11 shows the greenhouse gas emissions for the manufacturing of steel, which will decrease significantly from 276.5 Mt in 2015 to 67.7 Mt in 2050, due to the changes of the technology share and the decarbonisation of the energy carrier mix. This means a reduction of about 76 %.

6.2 Cement

The change in the technology mix of cement production in the most ambitious scenario (level 4) until 2050 is determined by reducing dry-kiln and wet-kiln processes and using geopolymer technology instead. The total production share of cement per technology is given in Figure 10

Table 15 and Figure 12 (left).

Table 15: Technology share and material production of cement in 2015 and 2050

Cement			
	Dry-kiln [Mt]	Wet-kiln [Mt]	Geopolymer [Mt]
2015	274,1	16,0	0
2050	31,9	0	8,0

The wet-kiln process is fully replaced until 2050 in the most ambitious scenario.

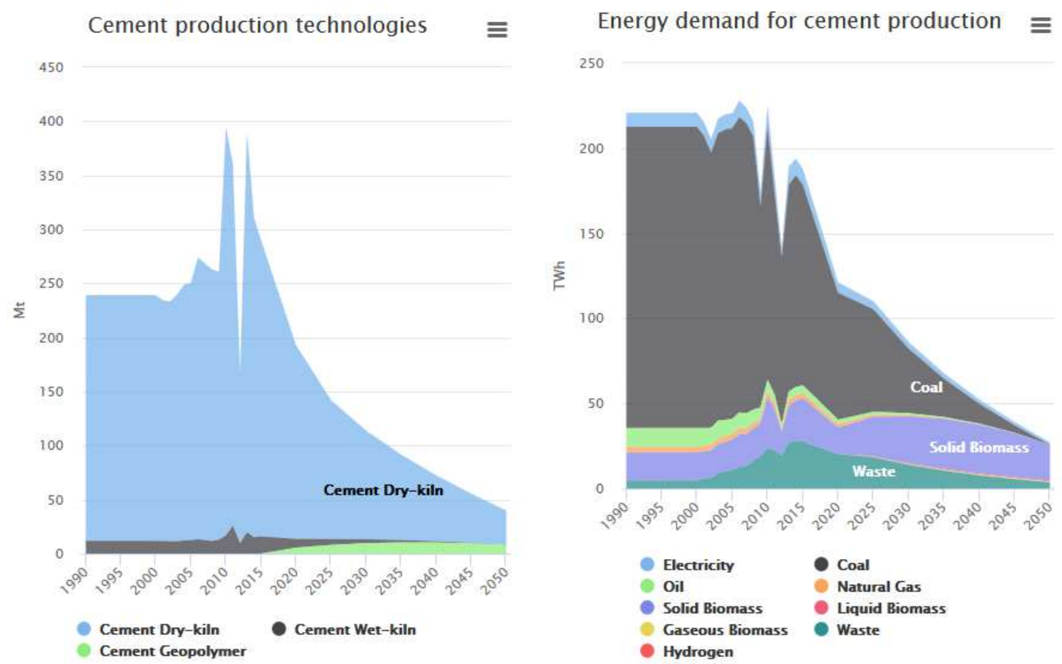

Figure 12: Production technologies and energy demand for cement production in the most ambitious scenario (level 4)

Given the technological change in the cement sector, the share of coal, oil and natural gas are reaching zero until 2050 (Figure 12, right). The demand of solid biomass and biogas is increasing, under the provision of ambitious energy efficiency improvements. The total energy demand for cement production in 2050 will be 27.1 TWh compared to a demand of 188 TWh in 2015, with a share of solid biomass of about 78 %. The reduction of the energy demand is about 86 %.

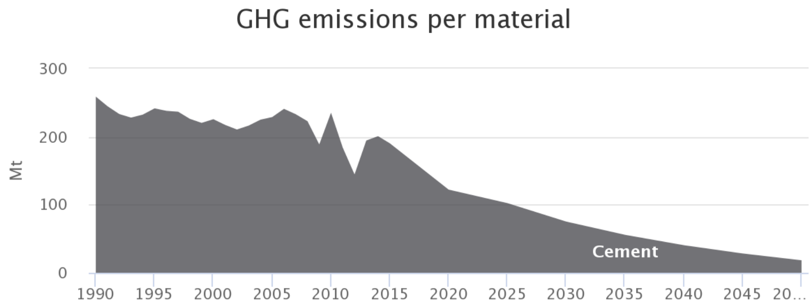

Figure 13: Greenhouse gas emissions for cement production in the most ambitious scenario (level 4)

Figure 13 shows the greenhouse gas emissions for the cement production, which will decrease significantly from 190.3 Mt in 2015 to 18.4 Mt in 2050, due to the changes of the technology share and the energy carrier mix. This means a reduction of about 90 %.

6.3 Paper

Currently, paper is produced by two processes: the production from wood pulp (primary production) and recycling. Until 2050, in the most ambitious scenario (level 4) the ratio will change towards a significantly higher share of the recycling route, which needs less energy than the production from wood pulp. The amounts of produced paper per technology are shown in Figure 10Table 16 and Figure 14 (left).

Table 16: Technology share and material production of paper in 2015 and 2050

Paper		
	woodpulp [Mt]	recycled [Mt]
2015	43,3	50,8
2050	9,3	83,3

Paper recycling route is expected to be of about 90 % in 2050 compared to approximately 54 % in 2015.

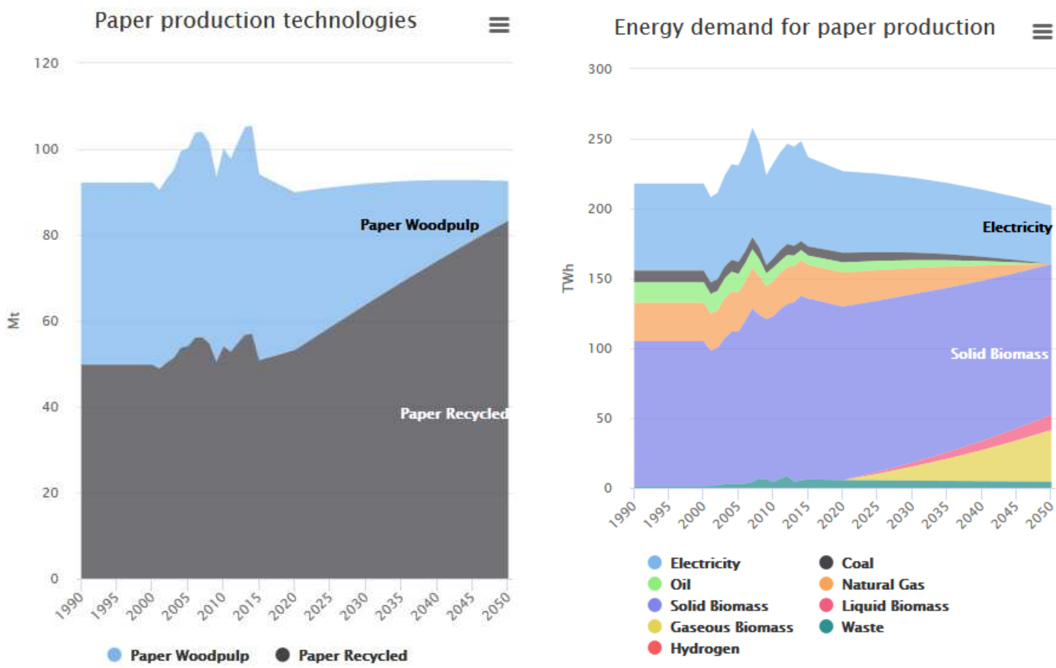

Figure 14: Production technologies and energy demand for paper production in the most ambitious scenario (level 4)

Figure 14 (right) shows the energy demand for paper production until 2050. Coal, oil and natural gas demand are approaching zero. Electricity and solid biomass demands are decreasing, while the demands of liquid biomass and biogas increase from zero to a total amount of 48 TWh in 2050. The total energy demand for the paper production in 2050 will be 202 TWh, where more than half of the demand is provided by solid biomass.

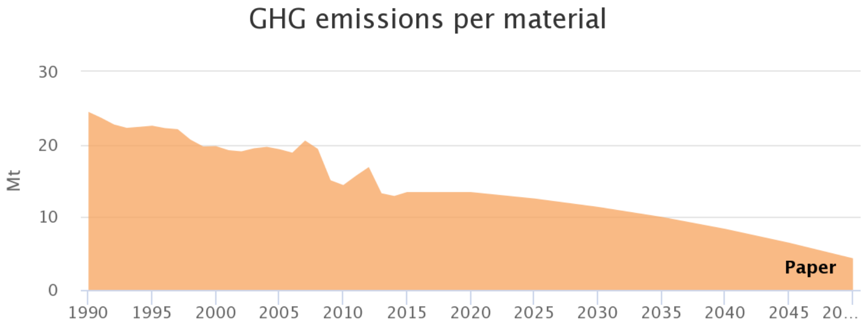

Figure 15: Greenhouse gas emissions for paper production in the most ambitious scenario (level 4)

Figure 15 shows the greenhouse gas emissions for the paper production until 2050. The emissions will decrease significantly from 13.5 Mt in 2015 to 4.3 Mt in 2050 by 68 %, due to the changes of the technology share and the energy carrier mix.

6.4 Chemicals

The transition until 2050 in the most ambitious scenario for the manufacturing of chemicals (including ammonia) is described in this chapter. For the production of chemicals there is only one technology considered in the manufacturing module, therefore no detailed technology share is shown. The production amount of 111.4 Mt in 2015 decreases to 81.9 Mt in 2050.

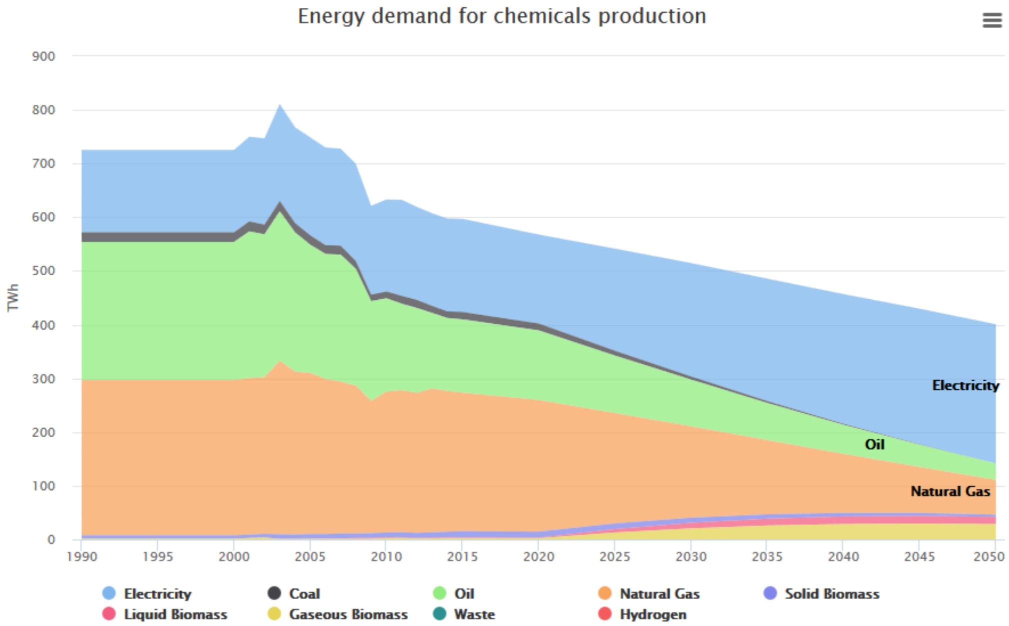

Figure 16: Energy demand for chemicals production in the most ambitious scenario (level 4)

In Figure 16, the energy demand for the production of chemicals until 2050 is shown. In 2015 the demand is mainly supplied by electricity, oil and natural gas. The ratios vary strongly until 2050, when coal, natural gas and oil are decreasing and electricity, liquid biomass and biogas demands are increasing to a total amount of about 75 %. The total energy demand is reduced from 633.5 TWh in 2015 to 417 TWh in 2050.

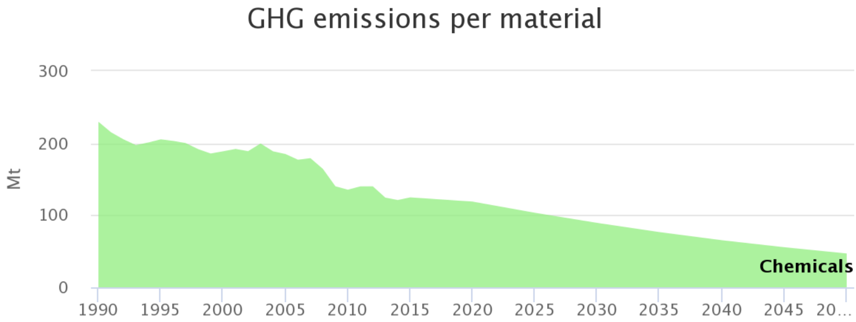

Figure 17: Greenhouse gas emissions for production of chemicals in the most ambitious scenario (level 4)

Figure 17 shows the greenhouse gas emissions for the production of chemicals until 2050. The emissions will decrease from 125 Mt in 2015 to 47 Mt in 2050 by 62 %, due to the decrease of material production and the change of the energy carrier mix.

6.5 Aluminium

Aluminium production will increase until 2050 because of an increasing usage in lightweight mobility, buildings and packaging. Additionally, aluminium is predominantly used in renewable energy products and components like solar or wind power plants. The share of secondary aluminium, which requires approximately 5-10 % of the energy used to produce primary aluminium, will rise in the most ambitious scenario. The amounts of material production are shown in Table 17 and Figure 18 (left).

Table 17: Technology share and material production of aluminium in 2015 and 2050

Aluminium		
	primary [Mt]	secondary [Mt]
2015	2,85	3,02
2050	2,26	6,42

While in 2015 the recycling route produces around 51 % of aluminium in Europe, it increases to a rate of 74 % in 2050.

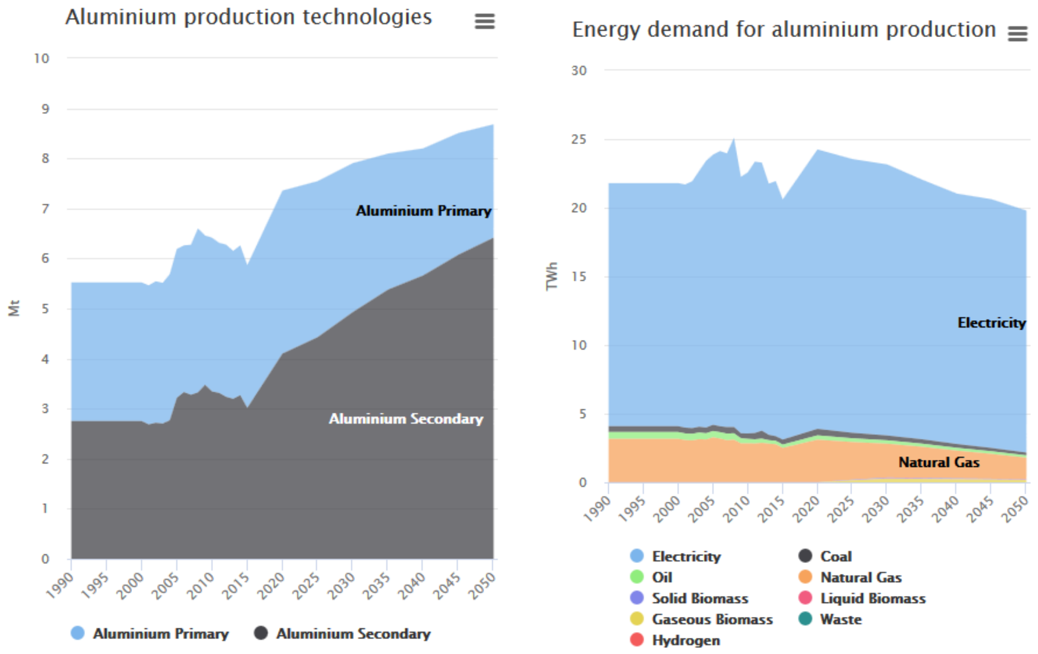

Figure 18: Production technologies and energy demand for aluminium production in the most ambitious scenario (level 4)

Figure 18 (right) shows the energy demand for the aluminium production until 2050. Electricity has the highest share in 2015 and in 2050, with a total value of 17.6 TWh. The demands of coal and oil are about to approach zero. The use of natural gas is decreasing to 1.6 TWh in 2050. The total energy demand for the aluminium production in 2050 will be 19.8 TWh, where about 90 % of the demand is provided by electricity. Compared to the increased production of aluminium from 5.9 to 8.7 Mt, the energy demand slightly decreases by about 4 %, due to the higher share of secondary aluminium, which needs less energy for production than the primary route.

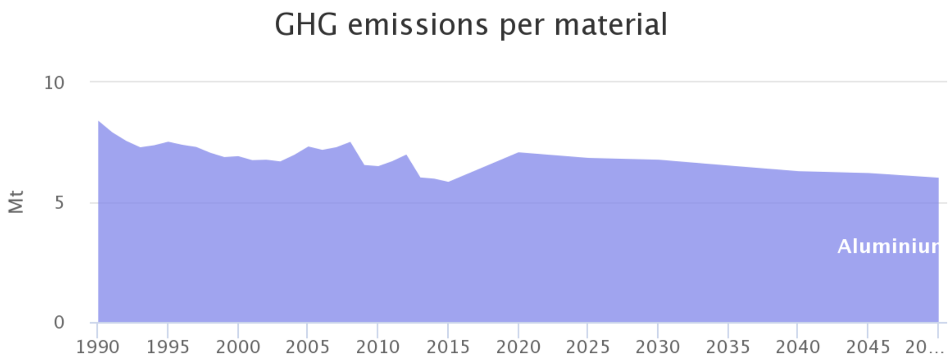

Figure 19: Greenhouse gas emissions for aluminium production in the most ambitious scenario (level 4)

Figure 19 shows the greenhouse gas emissions for the aluminium production until 2050. The emissions will increase from 5.9 Mt in 2015 to 6.0 Mt in 2050 by around 2 %, due to a higher material production.

6.6 Glass

The transition pathway of the glass industry for the most ambitious scenario shows an increased amount of production in 2050 (29.9 Mt) compared to 2015 (43.5 Mt). The manufacturing of glass is described by only one technology in the manufacturing module.

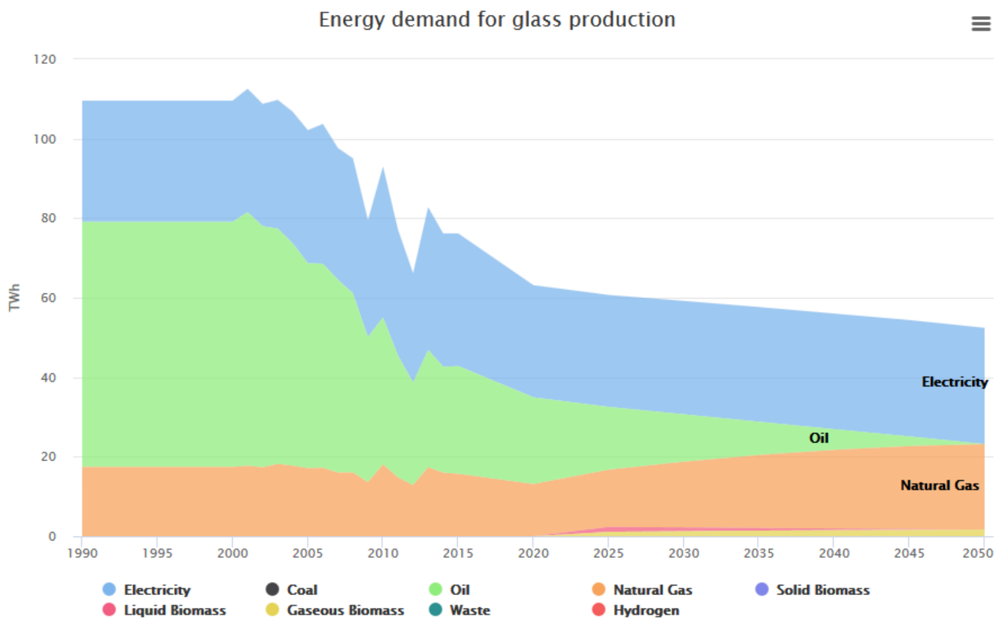

Figure 20: Energy demand for glass production in the most ambitious scenario (level 4)

Figure 20 shows the energy demand for the manufacturing of glass until 2050. In 2015 the demand is supplied by electricity (33 TWh), oil (27 TWh) and natural gas (16 TWh). This composition changes to a share of 29 TWh electricity (56%) and 21.5 TWh natural gas (41 %). Small amounts are provided by biogas (3 %). The total energy demand decreases from 76.2 to 52.4 TWh, which is a reduction of about 32 % compared to 2015, according to the most ambitious scenario of the manufacturing module. The high amount of oil in 2015 is approaching zero in 2050.

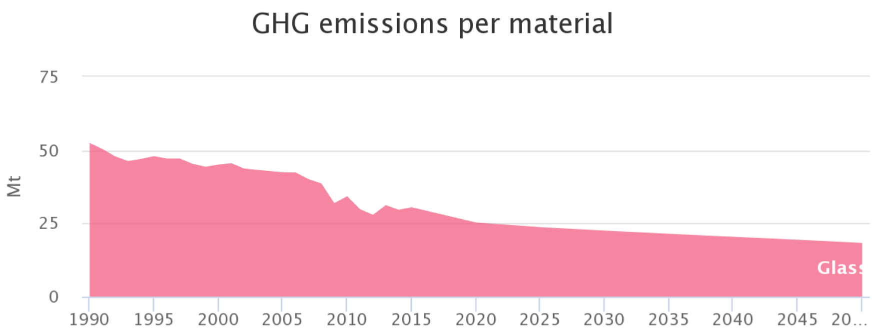

Figure 21: Greenhouse gas emissions for glass production in the most ambitious scenario (level 4)

Figure 21 shows the greenhouse gas emissions for the glass production until 2050. The emissions will slowly decrease from 30.5 Mt in 2015 to 18.3 Mt in 2050 by around 40 % due to the decreasing energy demand and the change of the energy carrier mix to a higher share of electricity, which is provided by renewable energy sources.

6.7 Lime

The production of lime shows a strong decrease of about 69 % until 2050 according to the transition pathway of the most ambitious scenario. In 2015 the production is 28.6 Mt and in 2050 it decreases to 9.0 Mt. For the manufacturing of lime, only one technology is considered in the manufacturing module.

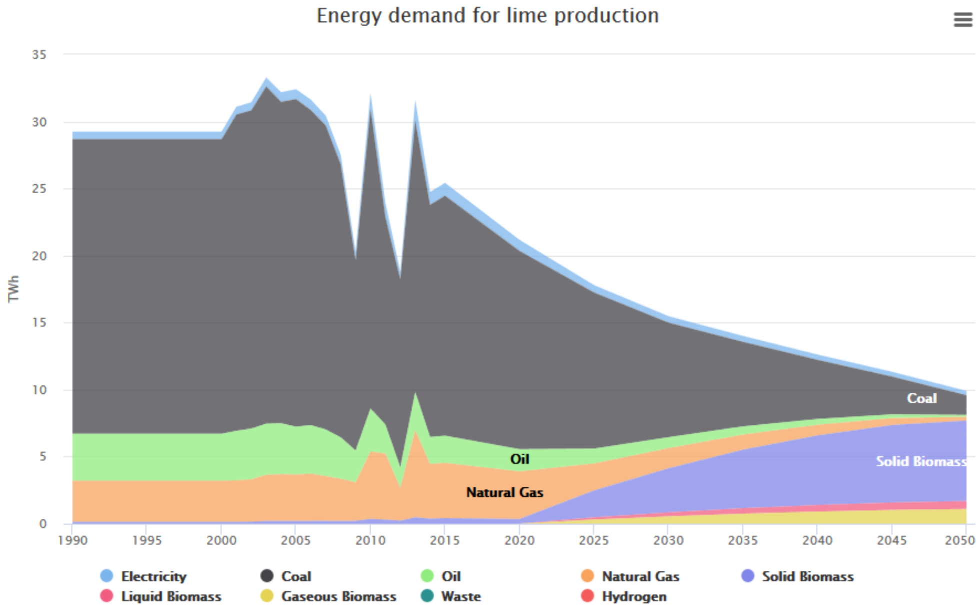

Figure 22: Energy demand for lime production in the most ambitious scenario (level 4)

As can be seen in Figure 22, the composition of the energy demand for the manufacturing of lime changes significantly from 2015 until 2050. In 2015, the demand is supplied by 18 TWh coal, 4.1 TWh natural gas, 2 TWh oil, 1 TWh electricity and small amounts of solid biomass. Until 2050, the usage of coal in the energy supply mix decreases significantly, as well as the usage of oil and natural gas. The highest share in 2050 is solid biomass (6 TWh), which accounts for 60 % of the energy carrier mix. Biogas (1.1 TWh, 11 %) and liquid biomass (0.6 TWh, 6 %) are increasing in the energy carrier mix. The total energy demand decreases from 25.4 TWh in 2015 to 10 TWh in 2050 by about 39 %.

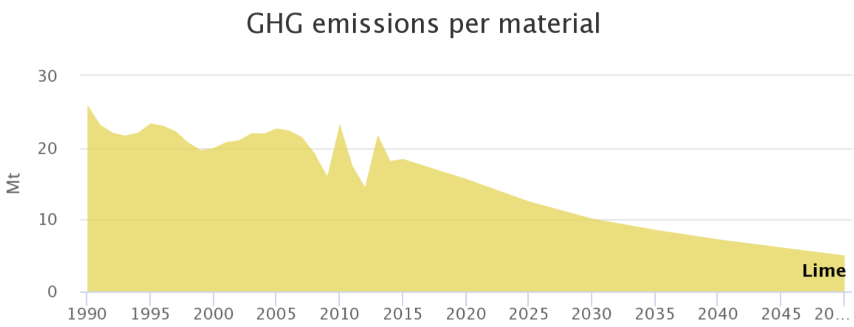

Figure 23: Greenhouse gas emissions for lime production in the most ambitious scenario (level 4)

Figure 23 shows the greenhouse gas emissions for the lime production until 2050. The emissions are decreasing from 18.4 Mt in 2015 to 5.0 Mt in 2050 by around 73 %. The reduction of the emissions can be related to the decreasing material production and energy demand and the decarbonisation of the energy carrier mix.

7 References

Axelson, M., Robson, I., Wyns, T., Khandekar, G. (2018). Breaking Through - Industrial Low-CO2 Technologies on the Horizon. Institute for European Studies, Vrije Universiteit Brussel. Published 13.07.2018

BCG and VDEh (2013), Steel's contribution to a low-carbon Europe 2050

Boustead (2015), Eco-profiles of the European Plastics Industry AMMONIA (PlasticsEurope)

Cantuche et al. (2016), The EU28 GTAP Input-Output Tables, Conference paper presented at the 19th Annual Conference on Global Economic Analysis, Washington DC, USA

Cement Sustainability Initiative of the World Business Council for Sustainable Development (WBCSD) http://www.wbcsdcement.org/GNR-2015/index.html (GRN project)

CEPI (2017), Investing in Europe for Industry Transformation, 2050 Roadmap to a low-carbon bioeconomy

CEPI (2018) Key statistics, European pulp and paper industry

DECHEMA (2017), Low carbon energy and feedstock for the European chemical industry p-148-156

De Vita A. et al. (2018), Technology pathways in decarbonisation scenarios, asset, PRIMES

Ducker Worldwide (2017), Aluminium content in North American light vehicles 2016 to 2028

EC (European Commission, 2011), Energy Roadmpa 2050. Impact Assessment and Scenario analysis.

EFMA (2000), Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry. In: Booklet No.1: Production of Ammonia. European Fertilizer Manufacturers Association, Brussels.

Energy Transition Commission (2018), Reaching zero carbon emissions from Cement, Consultation Paper

Energy Transition Commission (2018), Reaching zero carbon emissions from Steel, Consultation Paper

EU CTI 2050 Roadmap Tool (2018) webpage: https://europeanclimate.org/wp-content/uploads/2018/09/EU-2050-CTI-Industry-sector.pdf

EuLA (2014), A competitive and efficient lime industry, Technical report

Eurofer (2013), A steel roadmap for a low carbon Europe 2050

European Aluminium (2016), Aluminium Innovation Hub: Mapping key objectives and R&D challenges along the aluminium value chain

European Commission (2019), Statistical Pocketbook 2018, https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2018_en

European Copper Institute (2014), Copper's contribution to a low-carbon future

Eurostat (2019), webpage: https://ec.europa.eu/eurostat/web/energy/data/energy-balances

Favier et al. (2018), A sustainable future for the European cement and concrete industry, ETH EPFL

Gilbert et al (2014) Assessing economically viable carbon reductions for the production of ammonia from biomass gasification. Journal of Cleaner Production 64 581-589

Griffin et al. (2018), Industrial decarbonisation of the pulp and paper sector: A UK perspective. Applied Thermal Engineering. 134 152-162 fig.8

Groot H.L. F.de et al. (2012), Mapping resource prices: the past and the future, European Comission

Gustavsson L. and Sathre R. (2011), Energy and CO2 analysis of wood substitution in construction. Climatic Change 105 – 129

IEA (2016), 20 years of Carbon Capture and Storage

IEA (2017), 2017 Energy Technologies Perspectives

International Copper Association (2017), Copper Applications Technology Roadmap

John, S., Nebel, B., Perez, N., Buchanan, A. (2009) Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials. Research Report 2008-02. Christchurch, New Zealand. Department of Civil and Natural Resources Engineering, University of Canterbury.

JRC (2013), Technology Map of the European Strategic Energy Technology Plan

JRC (2018), Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry

Kulczycka et al. (2017), Environmental Impacts of Energy-Efficient Pyrometallurgical Copper Smelting Technologies

Mantzos, Leonidas; Matei, Nicoleta Anca; Mulholland, Eamonn; Rózsai, Máté; Tamba, Marie; Wiesenthal, Tobias (2018): JRC-IDEES 2015. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/jrc-10110-10001

McKinsey (2018), Decarbonization of industrial sectors: the next frontier

Modaresi et al. (2014), Global Carbon Benefits of Material Substitution in Passenger Cars, Environ. Sci. Technol. 48, 10776−10784

Mova J.A. et al. (2015), Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry

OECD/IEA (2019, upcoming), Exploring different clean energy pathways: the case of material efficiency, IEA Publishing

Roth et al. (2016), The pulp and paper overview paper, Sector analysis for the Climate Strategies Project on Inclusion of Consumption in Carbon Pricing. Climate Strategies tab.8

Sathre R. and O'Connor J. (2010), Meta-analysis of greenhouse gas displacement factors of wood product substitution, Environmental Science & Policy, 13, 2, 104-114

Upton B, Miner R, Spinney M, Heath LS (2008), The greenhouse gas and energy impacts of using wood instead of alternatives in residential construction in the United States. Biomass Bioenergy 32:1-10.

Voet et al. (2014), Topical paper 10: Assessment of historical resource efficiency improvements in the aluminium industry

Werner F. et al. (2005), Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: first estimates. Annals of Forest Science, 62 (8), 889-902.

Worldsteel Association (2016), Fact Sheet - Advanced steel applications