EUCALC

Explore sustainable European futures

Raw materials module and manufacturing and secondary raw-materials module for EUCalc

D3.1

February 2020

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Short Description
This report describes the integration of the manufacturing and production module within the overall architecture of the EU Calculator (EU Calc), the input data and levers definition, as well as level setting for material conversion routes as input for modelling. Critical – in terms of GHG emissions, economic importance and supply risk – materials are integrated into the EU Calculator accordingly. The deliverable transparently covers an inventory of input data and levers definition, as well as levels setting for technologies improving energy efficiency of manufacturing processes as input for modelling.

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Name of reviewer	**Date**
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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This deliverable contains original unpublished work except where clearly indicated otherwise.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.

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List of abbreviations

GTAP – Global Trade Analysis Project

LULUCF – Land Use, Land-Use Change and Forestry

TRL – Technology Readiness Level

BF-BOF – Blast furnace - basic oxygen furnace

BAT – Best available technologies

CAPEX – Capital expenditure

OPEX – Operational expenditure

CC – Carbon capture

CCS – Carbon capture and storage

CCU – Carbon capture and usage

CHP - Combined heat and power

FCV – Fuel cell vehicles

EAF – Electric arc furnace

EV – Electric vehicles

EE – Energy efficiency

DRI – Direct reduced iron

DSM – Demand side management

GHG – Greenhouse gases

ICE – Internal combustion engine

1 Disclaimer of the type of document and limitations

This document has been prepared by the EUCalc consortium as an account of work carried out within the framework of the project. The document

- reflects on the module implementation of the "manufacturing and production" module in the overall system architecture
- includes a comprehensive overview of the model logic, interactions with other sub-modules, and assumptions
- contains a detailed explanation on the approach, including the trajectories for each lever and level of ambition (quantified)
- does not contain an analysis of transition pathways for the manufacturing and production sector (see Deliverable 3.2[1])
- does not reflect on combined decarbonisation mitigation options, rather than providing a detailed documentation on assumption on levers and levels of ambition

2 Introduction

In 2015, the European manufacturing sector accounted for 750 million tonnes of CO_2 equivalent emissions or 19 % of the total emissions (including LULUCF) according to the European Energy Agency. CO_2 is the most significant greenhouse gas emitted from industrial processes with 720 million tonnes of direct emissions in 2015. Less than 5 % of the industrial emissions (calculated in CO_2 equivalent) consist of other GHGs like e.g. CH_4 and N_2O. 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 the EU tries to achieve the deep emission reductions required for its climate commitments. In the European Commissions "Roadmap 2050" one-quarter of the CO_2 emissions remaining mid-century is expected to come from industry, especially from energy-intensive sectors producing basic materials.

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

[1] Note: Deliverable 3.2 (Report) provides a structured, documented and transparent view on and analysis of decarbonisation pathways for the manufacturing and production sector of the European Union until 2050. Partly overlapping with this deliverable, the model logic and assumptions are made clear for the eventual reader.

technologies are required; a field where European industries historically have a strong pioneering record.

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 and document the integration of the manufacturing and production module within the overall architecture of the EU Calculator (EU Calc), the input data and levers definition, as well as level setting for material 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 the integration of the manufacturing module within the general model architecture of EUCalc leading to decarbonisation pathway for the manufacturing and production sector of the European Union until 2050. Relevant drivers 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.

The four ambition levels are:

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

For the description of each lever and ambition level, an intensive literature research was carried out. The assumptions, background literature of historic trends as well as relevant works and studies are documented. The integration of the sub-module and the interfaces to other modules from both the demand and supply side are transparently described.

3 Raw Materials, Manufacturing and Production module

3.1 Overall logic

The debate on decarbonizing Europe evolved over time from being the concern of national governments to encompassing a cross-border heterogeneity of economic sectors, businesses, regional decision makers and individuals. 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, EU Calculator (EUCalc) comprises a user interface, the Transition Pathway Explorer, where users can define their own pathways using ambition levers and a temporal horizon of 2050. A lever offers the possibility to choose among different options regarding one question, e.g. the degree of refurbishment in old buildings or the deployment ambitions for district heating networks. This tool has identified as potential users mainly European policymakers, businesses, NGOs amongst other societal actors. Its goal is to equip these potential users with the means to create their own low-carbon transformation pathways at the European and its member states 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 activities in terms of lifestyle, technology availability and climate context, 2) the consumption and production of energy to fulfil the lifestyle, 3) the socio economic impacts, 4) the environment and resource impacts. This is all performed in an economic context, reflecting national productions, consumptions, imports and exports and with a related policy narrative. This wide analysis scope also integrates trade-offs like the impact of eating habits on land-use, of consumers goods purchases on resources, or of buildings renovation on material demand.

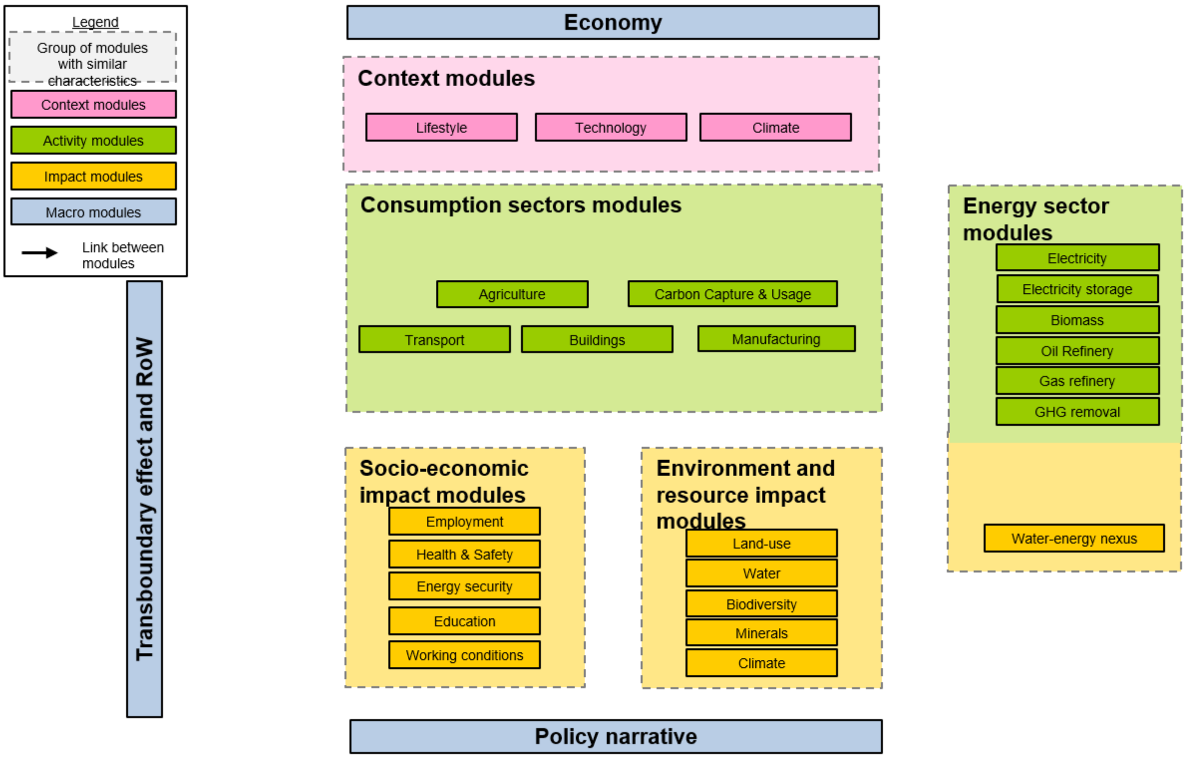


Figure 1: Modular structure of the EUCalc model

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

3.2 Scope definition

The scope 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. 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 2 and 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.

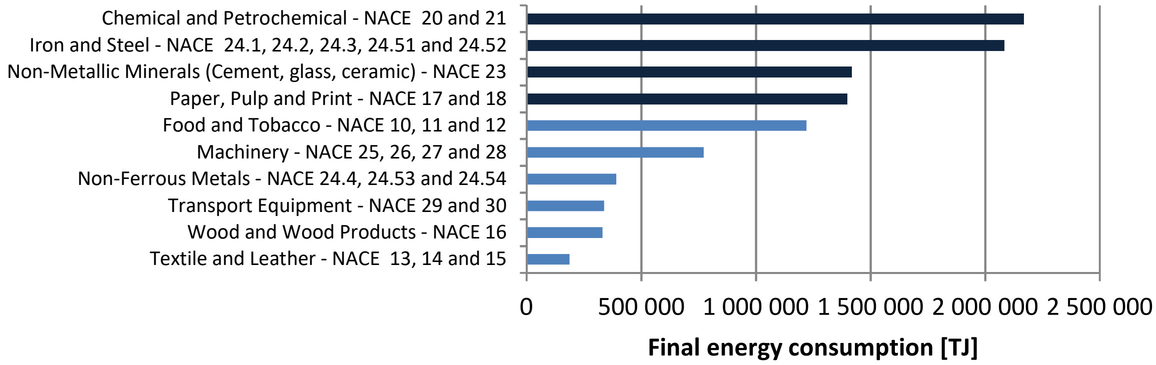


Figure 2: Total energy consumption in 2015 in EU28, the industries modelled in the manufacturing and production module are in dark blue (ÖGUT based on Eurostat data – complete energy balance nrg_110a)

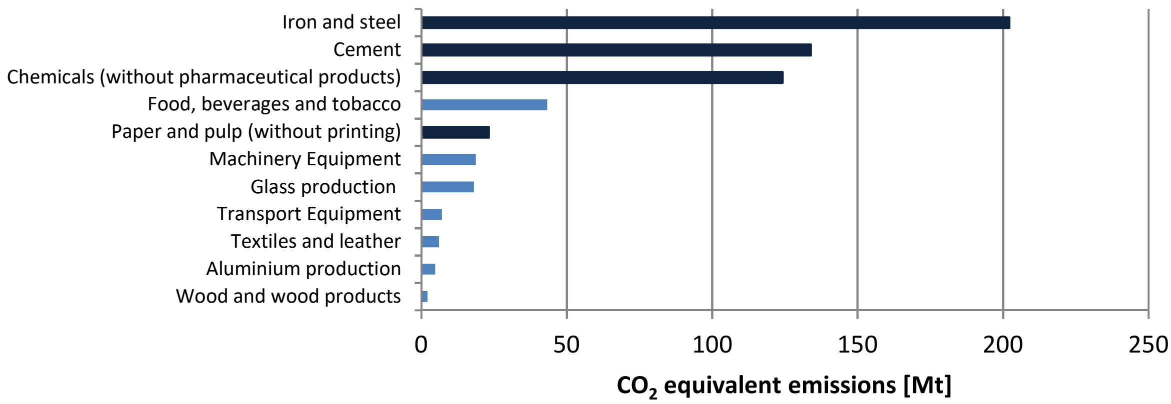


Figure 3: CO_2 equivalent emissions in 2015 in EU28, the industries modelled in the manufacturing and production module are in dark blue (JRC-IDEES- Mantzos et al., 2018)

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 manufacturing and production module

Theme	Information/Question	
What are the types of impacts we want to take into account in the model?	• Products & materials	• Material demand for each product
	• Resources	• Resources demand for certain material and technology
		• Water demand (Blue, Green, Grey)
	• Energy	• Energy consumption by energy carrier and industrial sector
	• Emissions	• Direct GHG emissions of each industrial sector
	• Economy	• Economic impact of the different scenarios (e.g. jobs)
	• Other	• Biodiversity, health, land use
What is the impact of existing solutions to	• Product design	• Impact of material efficiency (use of better materials, smart design, 3D printing, and reuse of components on material production)
		• Impact of material switch to less carbon-intensive materials on energy and GHG emissions (e.g. substitution of concrete with timber in buildings)

decarbonize the sector?	• Materials manufacturing	• Impact of the switch from primary route to recycling route on energy and emissions
		• Impact of energy efficiency increase of each technology on energy consumption
		• Impact of the switch from fossil fuel to biomass, hydrogen, and electricity on GHG emissions
What is the impact of potential breakthrough (technologies or societal)?	• Impact of the deployment of novel technologies on energy, emissions	
	• Impact of CCS deployment on reducing emissions, DSM contribution	
What are the impacts of the sector on the others?	• Energy consumption impact on Supply (WP5)	
	• Biomass demand (feedstock and energy) impact on Agriculture (WP4)	
What are the impacts of other sectors on this one?	• Several other sectors impact manufacturing through its product demand: Lifestyle (WP1) through packaging demand, Transport (WP2) through vehicles and infrastructure, Buildings (WP2) through the construction and renovation of buildings, and appliances, and Agriculture (WP4) through fertilizer demand.	
What are the limitations of the sector model?	• Only a limited number of products (45) and materials (10) covered. A more refined decomposition of products and materials would allow a deeper analysis on dematerialisation scenarios. • No detailed representation of the European industrial plant stock and lifetime. No decommissioning. • Limitations regarding the technical/engineering implementation of the module and economic detail. Indirect representation by GTAP-EUCalc however. • Intangible effects are not modelled explicitly.	

A comprehensive list of products, manufacturing sectors, production technologies and energy carriers taken into account in the Manufacturing module (see Table 2).

Table 2: Scope of the manufacturing and production module

NEW PRODUCT DEMAND

From Lifestyle Module (WP1)
- Plastic packaging [t]
- Paper packaging [t]
- Aluminium packaging [t]
- Glass packaging [t]
- Paper printing and graphic [t]
- Paper sanitary and household [t]

From Transport Module (WP2.2)
- Int. combustion engine cars [num]
- Int. combustion engine trucks [num]
- *Int. combustion engine buses [num]*
- *Int. combustion engine motorcycles [num]*
- Fuel cell cars [num]
- Fuel cell trucks [num]
- *Fuel cell buses [num]*
- *Fuel cell motorcycles [num]*
- Electric cars [num]
- Electric trucks [num]
- *Electric buses [num]*
- *Electric motorcycles [num]*
- *Plug-in hybrid cars [num]*
- Planes [num]
- Trolley-cables [km]
- Roads [km]
- Rails [km]
- *Streetlights [km]*

From Building Module (WP2.1)
- Residential buildings [m^2]
- Non-residential buildings [m^2]
- Insulation residential buildings [m^2]
- Insulation non-residential buildings [m^2]
- Fridges [num]
- Washing machines [num]
- Dishwashers [num]
- Freezers [num]
- Dryers [num]
- TVs [num]
- Smartphones [num]
- Computers [num]
- District heating pipes [km]

- *Plug-in hybrid trucks [num]* - *Plug-in hybrid buses [num]* - *Plug-in hybrid motorcycles [num]* - Ships [num] - Trains [num]	**From Agriculture Module (WP4.3)** - N-fertilizers [t]
INDUSTRIES AND TECHNOLOGIES	**ENERGY CARRIERS**
• **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 [-]	- Coal [TWh] - Oil [TWh] - Natural gas [TWh] - Solid biomass [TWh] - Liquid biomass [TWh] - Gaseous biomass [TWh] - Electricity [TWh] - Hydrogen [TWh] - Waste [TWh]

The production projections for non-energy intensive manufacturing sectors (transport equipment, food, beverages and tobacco, textiles and leather, machinery equipment, wood and wood products and the products from other industries) until 2050 are not based on activities performed in other modules. The prospective production values hence are calculated by projecting historic production volumes (production indices) from 2000 to 2015 for each country. As an example, the trend for "other industries" for all countries is shown in Figure 4. In this case, a logarithmic trend is assumed for the approximation to the actual statistical data. The formula of the trend line is used to estimate the future production index until 2050. This means that for these sectors, the production evolution is fixed.

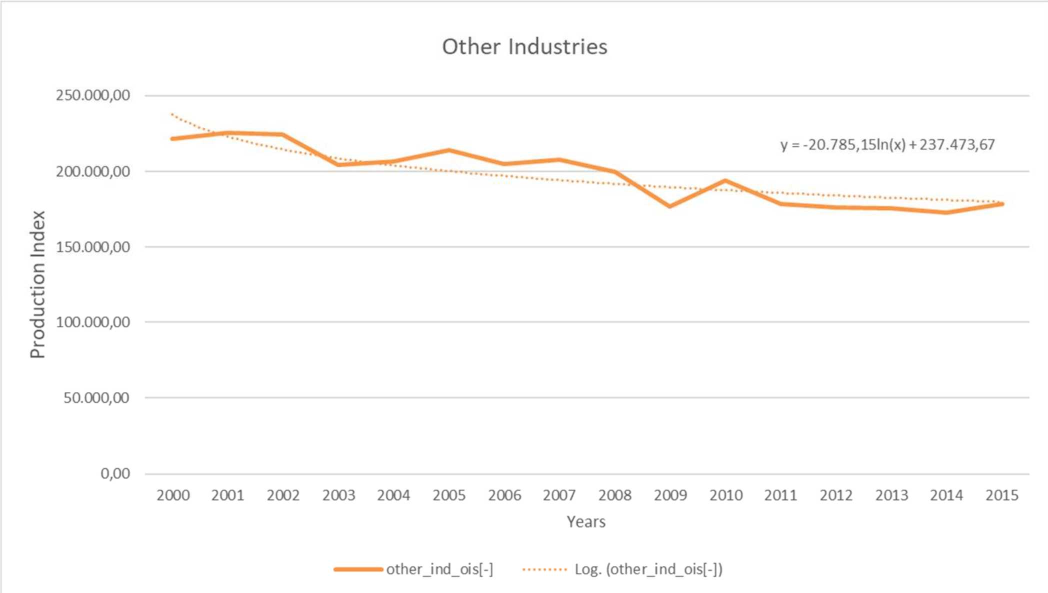


Figure 4: Trend line of the production index of "other industries" for EU28+Switzerland

The calculations are divided into four subsequent steps (product, material, energy and feedstock and emission level), shown in the calculation tree (Figure 5). Additionally, raw materials to produce e.g. iron are provided by the non-core module “Minerals” (WP4).

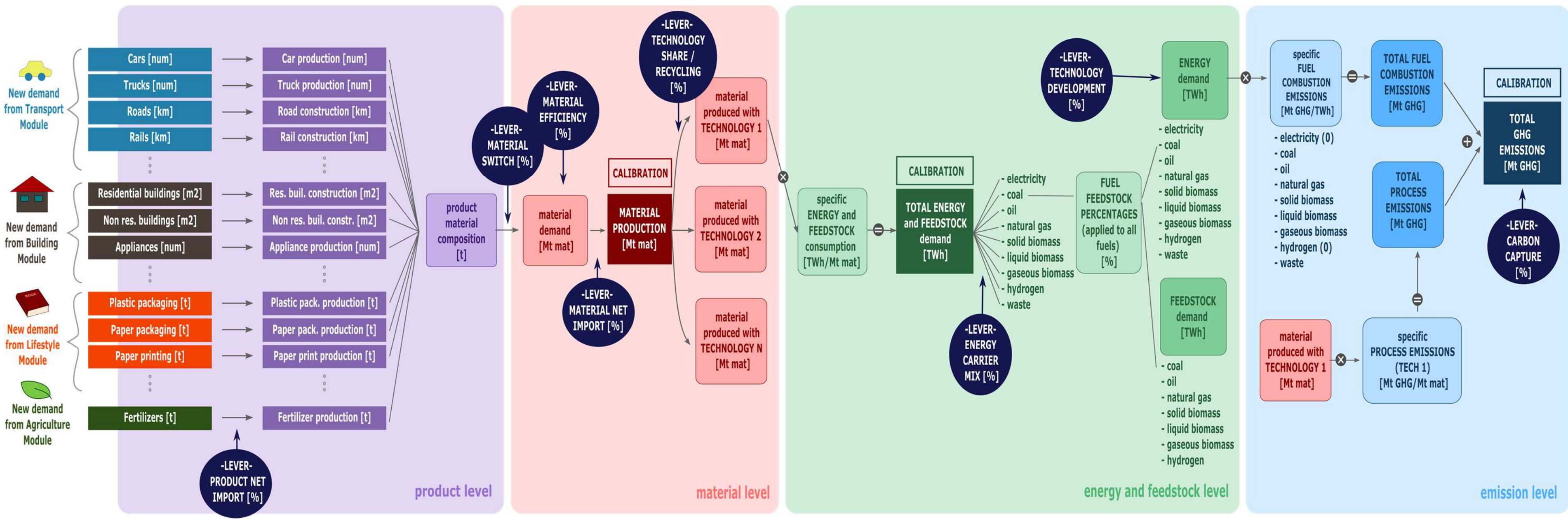


Figure 5: Manufacturing and production calculation tree for one industrial sector. Analogous calculation trees are used for each energy-intensive sector considered (steel, cement, chemicals (split in ammonia and other chemicals), paper, aluminium, glass, lime and copper). For non-energy intensive sectors, material demand is based on historic trends and the calculation tree performed for energy and emissions only.

4 Interfaces with other modules

This section provides an overview of the interface with other modules within the overall model architecture, including input and output data used for the Production and Manufacturing module.

4.1 Inputs from other modules

Technology

The Technology module specifies specific energy consumption and specific process emissions per technology. It includes the material intensities per product, as laid down in the material decomposition table, and material switch ratios. The technology architecture is shown in Figure 6.

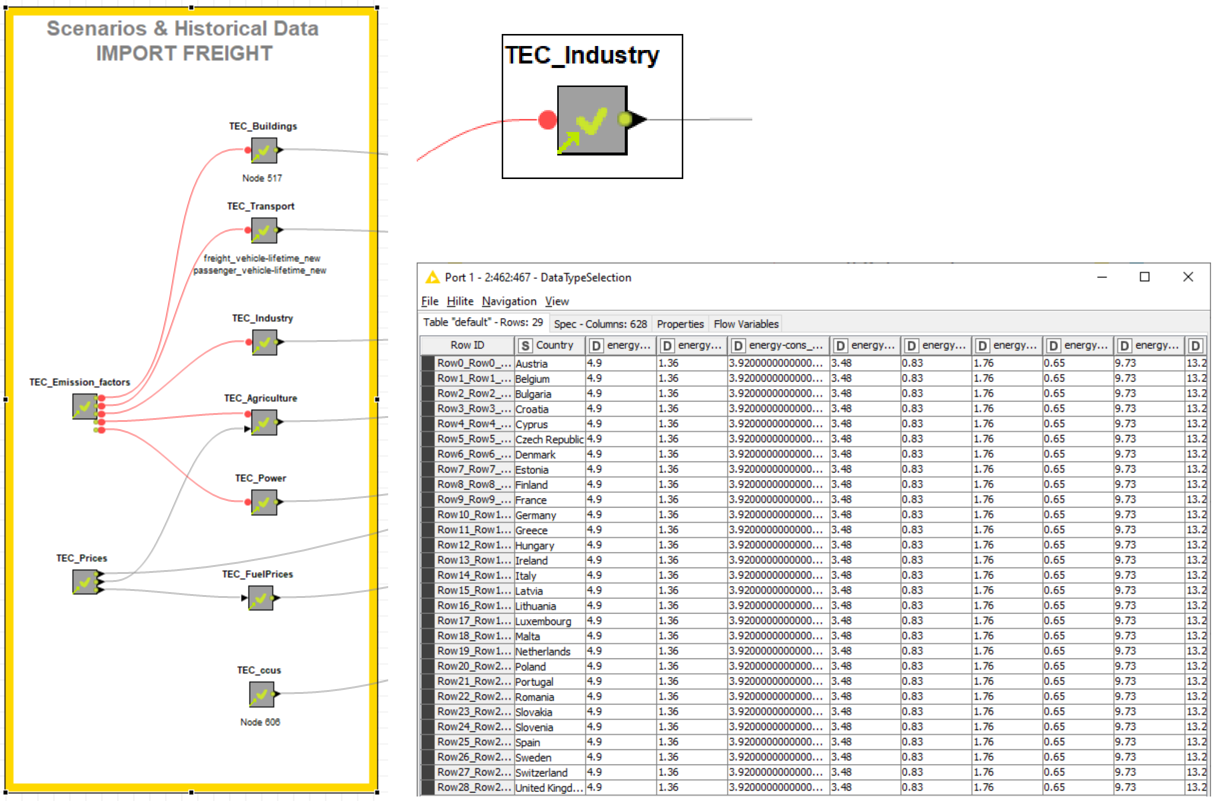


Figure 6: Interface TEC_IND

Inputs from demand sectors

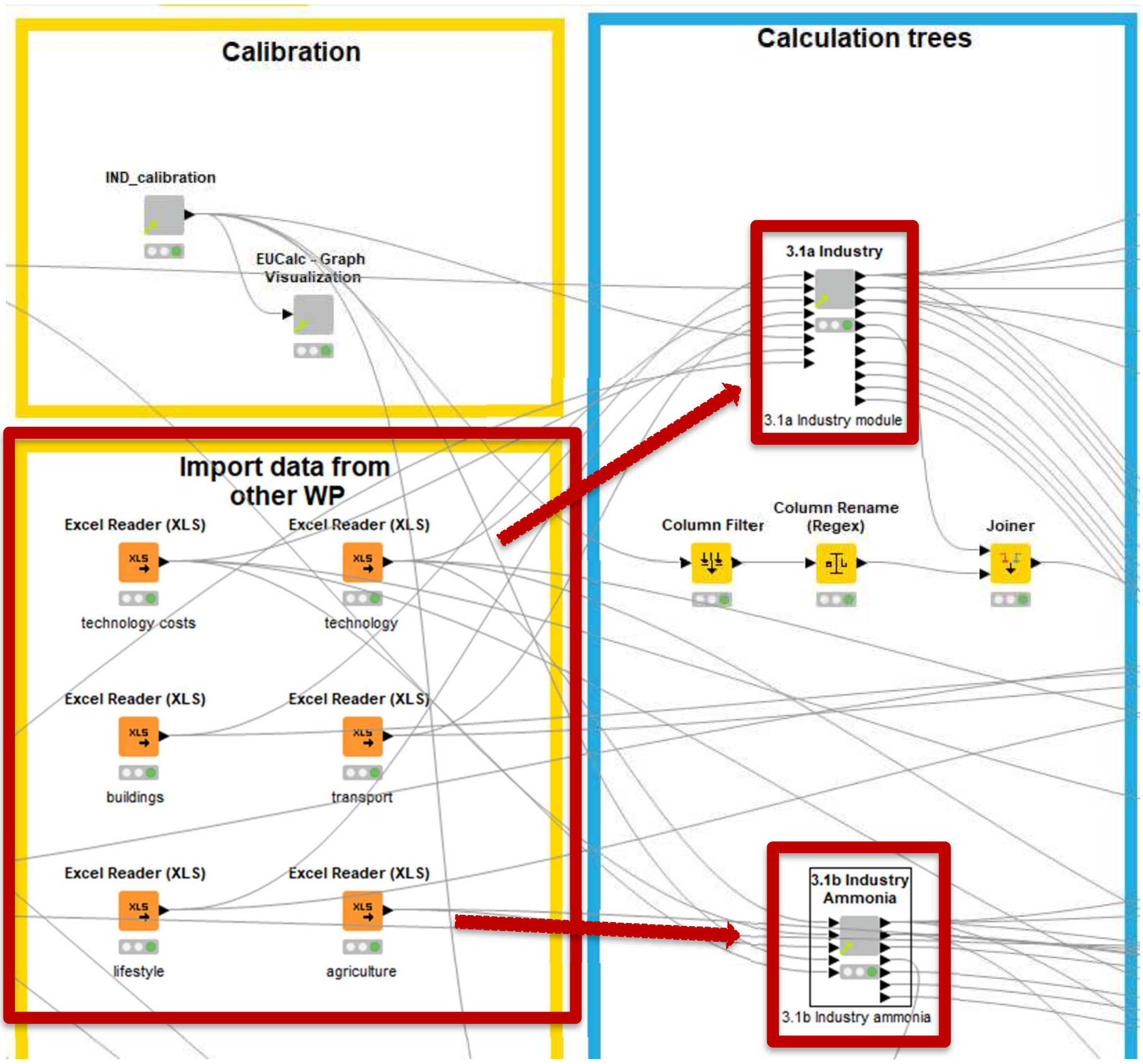


Figure 7: Interface for inputs from demand sectors (Lifestyle, Buildings, Transport, Agriculture)

Lifestyles

The Lifestyle module 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 2). 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.

Buildings

The Building module 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 2). 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 2).

Accounting of the net imports of these products, the Manufacturing module assesses how much materials will be required for their manufacturing.

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 2). 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.

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.

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).

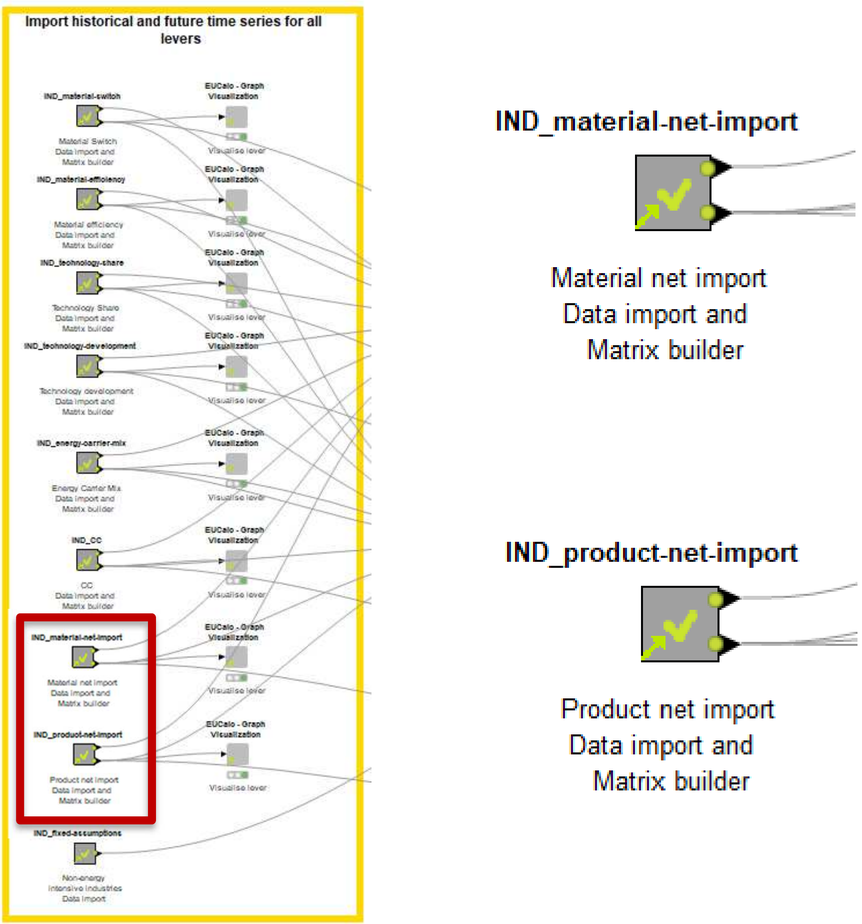


Figure 8: Interface for material and product net import (GTAP)

4.2 Data from literature (historical database)

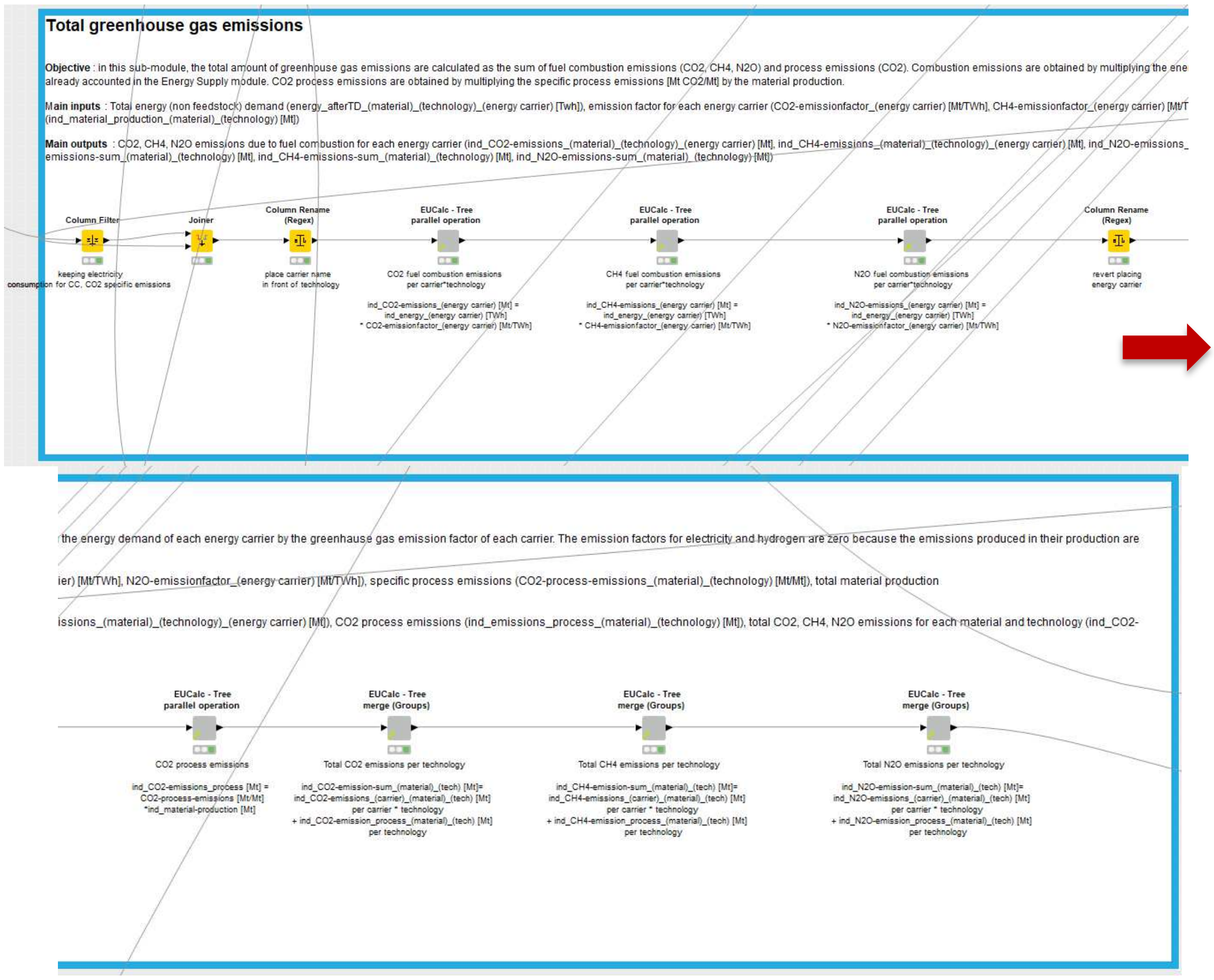
The main source used for the calibration of material production, energy consumption and emissions of the Manufacturing module is JRC-IDEES (Mantzos et al., 2018). The database was published in 2018 and is maintained by the European Commission's Joint Research Centre.

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

4.3 Outputs to other modules

Climate emissions

Within the Manufacturing module total greenhouse gas emissions (CO_2, CH_4 and N_2O) from fuel combustion and processes are calculated based on the technologies in place and the annual material demand. The results are calibrated within the manufacturing module against official EUROSTAT statistics for historic values and provided to the Climate Emissions module, which then calculates CO_2 equivalents.



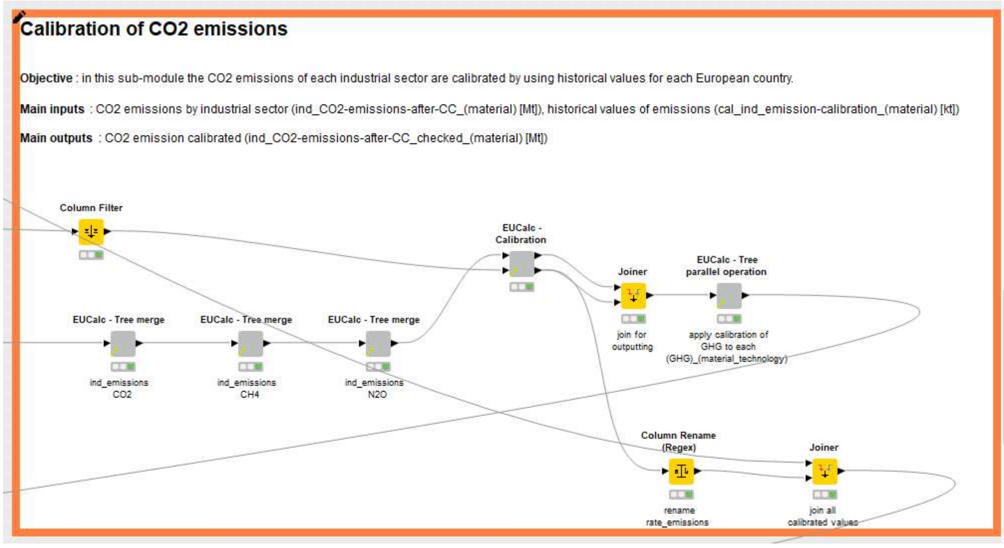


Figure 9: Calculation and calibration of total greenhouse gas (GHG) emissions to provide for climate module

Interfaces to supply sectors and trade

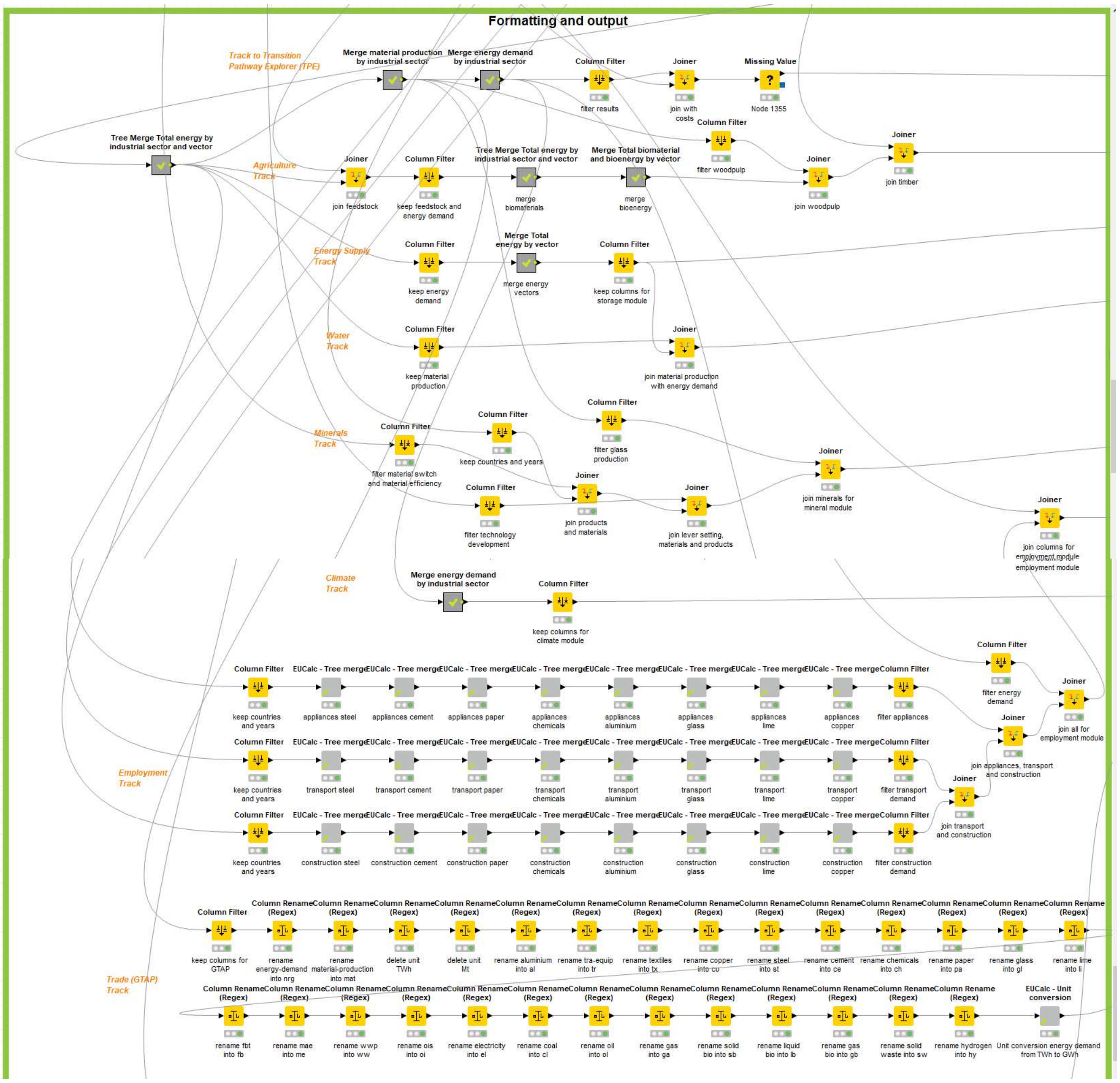


Figure 10: Output to other modules provided by the manufacturing and production module

Water

The water extraction and use (e.g. pollution) along industrial production chains is part of this sub module focusing on water consumption in this sector. The material production divided into technologies is provided to this sub-module in order to perform the quantification of the water footprint of materials.

Minerals

The minerals and raw materials module (as in the product composition) decomposes the materials into the required raw materials needed to produce one equivalent. For example, the input of the Transport module is the yearly demand of new vehicles (cars, trucks, ships, trains, and planes as detailed list in Table 2). 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 decomposes the materials that will be required for the construction of roads and railways and for the manufacturing of cars, trucks, etc. The minerals module decomposes on a material level (e.g. iron ore for steel, bauxite for aluminium).

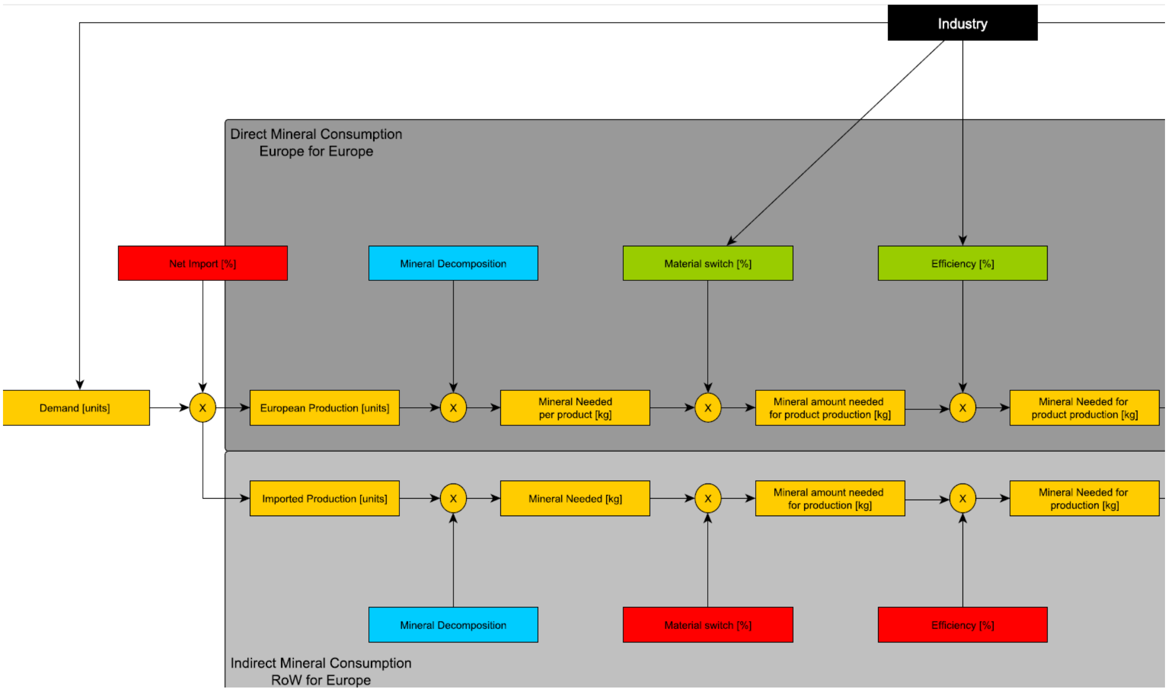


Figure 11: Interface logic manufacturing and minerals (Raffray 2019)

Agriculture

The Manufacturing module calculates the amount of biomass (both for feedstock and for energy uses) and waste (for energy use) that will be required in the future years for the materials manufacturing. This output is provided to the Agriculture module. The Manufacturing module receives the fertilizer demand from the Agriculture module and in turns provides back the biomass demand. The fertilizer demand increases the biomass demand (e.g. biogas needed to produce ammonia), which increases the fertilizer demand for growing biomass. <u>To avoid this loop, the Manufacturing module is split in two: industry and industry-ammonia</u>. The first one includes all industries except for ammonia and calculates the biomass demand for the materials manufacturing (excluding ammonia). The second one includes only ammonia production. It receives the fertilizer demand from Agriculture as an input but does not provide back the biomass demand for ammonia production (which is a marginal value compared to the total industrial biomass demand).

Energy supply and storage

The future energy demand per energy carrier and per manufacturing material is an output of the Manufacturing module provided to the Energy Supply module.

Carbon Capture Use and Storage (CCUS)

The emissions from emission-intensive manufacturing sectors are provided to the Carbon Capture Storage and Use module.

Employment

The employment module receives the annual energy (TWh by energy carrier) and material demand (Mt) for each manufacturing sector, aggregated by appliances, construction and transport.

Trade (GTAP)

Annual energy and material demand are provided to the Trade module (by the GTAP node). The output send to the Trade module consists of the annual energy (TWh by energy carrier) and material demand (Mt) for each manufacturing sector excluding the non-energy intensive sectors. The output is used to compute a number of pathways in GTAP.

Naming convention: I=Industry; nrg=energy-demand; mat=material production

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 3 summarizes all the proposed levers. The calculation tree in Figure 5 shows, where the levers are applied in the calculations.

Table 3: List of levers for the Manufacturing module

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

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

3.	Technology share/Recycling [%]	Percentage of material produced with a given technology in each industry (see the list of industries and technologies in Table 2). 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).
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- **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 does 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 4: Ambition levels for the lever material switch

Name / Unit	2015	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

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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 analysis performed by Material Economics (2018) shows that demand-side measures could reduce EU industrial emissions by 56% by 2050 (see Figure 12). These abatement opportunities have been calculated accounting for material recirculation (recycling), product material efficiency (use of high-strength materials, smart design, reduction of over-specification, reduction of production waste) and new circular business models (higher utilisation rate of vehicles and buildings).

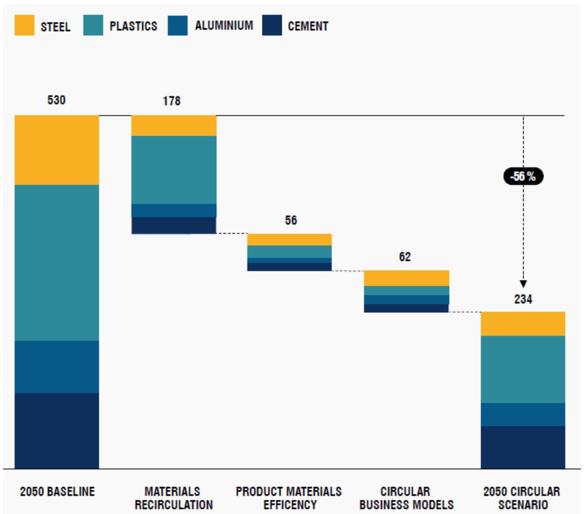

Figure 12: EU emissions reductions potential from a more circular economy, 2050 [Mt of carbon dioxide per year] (Material Economics, 2018)

Material efficiency alone could reduce industrial emissions by 56 Mt per year in steel, plastics, aluminium and cement production (see Figure 12). The lever ‘material efficiency’ focuses on the options to reduce the material input required for products. This can be achieved following a number of strategies.

One strategy is to reduce the waste of materials in the manufacturing and construction processes (e.g. currently about 15% of buildings materials are wasted in construction). While some losses in manufacturing yields may be unavoidable, there is potential for more tailored production processes to reduce losses. For example, the use of additive manufacturing such as 3D printing could almost eliminate scrap production. GE Aviation was able to reduce the weight of its jet engines by approximately 25% through additive manufacturing (Geissbauer et al., 2017).

Another approach for saving materials is to reduce over-specification. According to Material Economics (2018), an estimate of 50% of the steel used in buildings is in excess to what is strictly necessary to meet structural needs. Regarding cement, on-site contractors often use more cement (and clinker) than required in the specified concrete mix, either due to lack of training or because of additional but unnecessary safety factors. Better training and the use of ready-mix concrete could reduce these cement losses.

Another way to increase material efficiency is the use of more advanced materials. For example, the use of high-strength steel enables carmakers to reduce vehicle weight by 25-39% compared to conventional steel (World steel association, 2016).

A recent study of OECD/IEA (2019, upcoming) performed a systematic analysis of the impact of material efficiency strategies on global material demand for cement and steel. In this study, the material efficiency strategies are analysed across the value chain, from design and construction until the end of life. As can be seen in Figure 13 and Figure 14, three different scenarios are explored: the Reference Technology Scenario (RTS), the Clean Technology Scenario (CTS), and the Material Efficiency Scenario (MEF), which investigates, what would occur, if material efficiency is pushed to its practical limit beyond what is already occurring in the CTS.

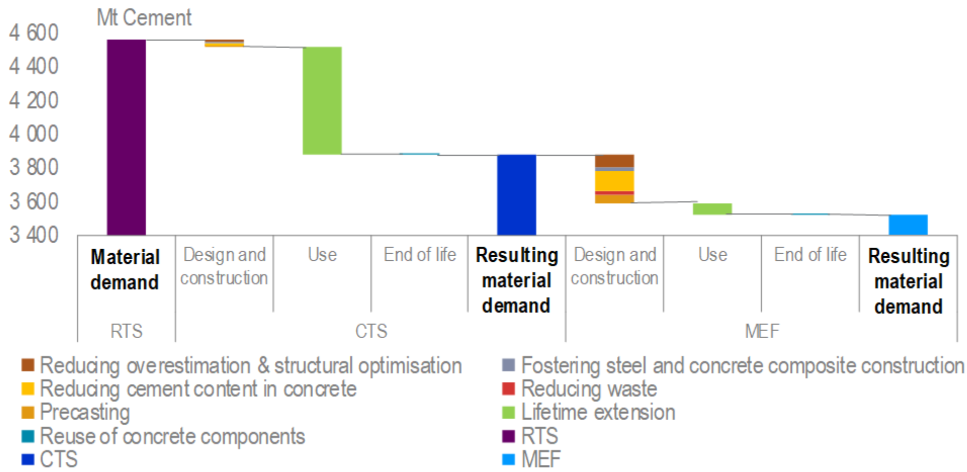

Figure 13: Impact of material efficiency strategies on cement demand (OECD/IEA, 2019, Exploring different clean energy pathways: the case of material efficiency, IEA Publishing. Licence: www.iea.org/t&c). RTS is the Reference Technology Scenario, CTS the Clean Technology Scenario, and MEF the Material Efficiency Scenario.

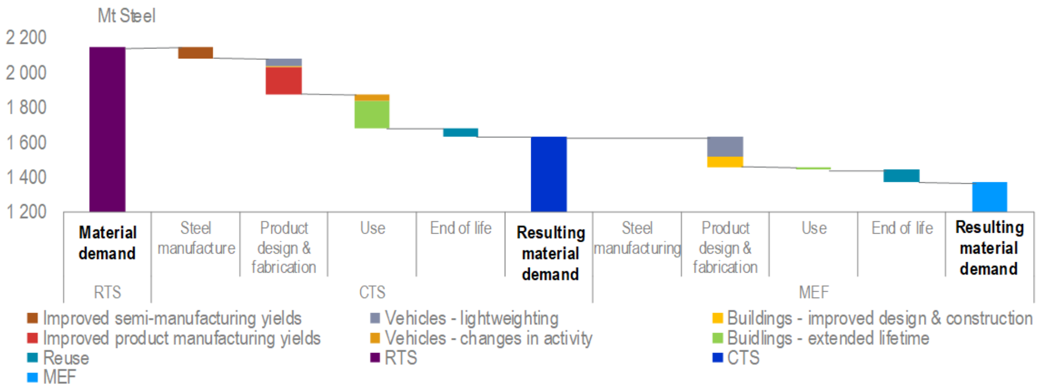

Figure 14: Impact of material efficiency strategies on steel demand (OECD/IEA, 2019, Exploring different clean energy pathways: the case of material efficiency, IEA Publishing. Licence: www.iea.org/t&c). RTS is the Reference Technology Scenario, CTS the Clean Technology Scenario, and MEF the Material Efficiency Scenario.

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[3], which is not considered in the lever material efficiency). 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.

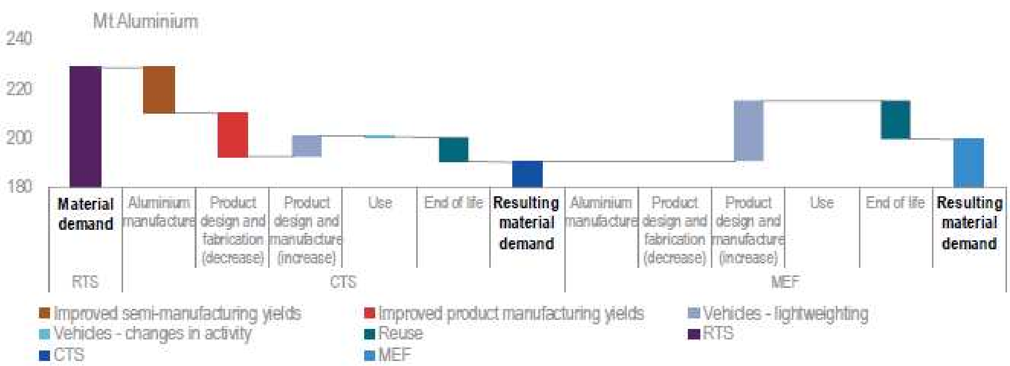

Figure 15: Impact of material efficiency strategies on aluminium demand (OECD/IEA, 2019, Exploring different clean energy pathways: the case of material efficiency, IEA Publishing. Licence: www.iea.org/t&c). RTS is the Reference Technology Scenario, CTS the Clean Technology Scenario, and MEF the Material Efficiency Scenario.

[3] Lifetime of products is currently not addressed, but part of the final version

Some container **glass** and flat glass manufacturers have the potential to use more recycled glass (cullet) on the condition that it is available at the right quality. The utilisation of cullet saves energy and reduces the requirement for the use of virgin raw materials, which release CO_2 during the glass melting process.

Material efficiency in the **lime** industry can be achieved by using low-lime cement or by material substitution. 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).

Disaggregation methodology rational

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.

Feedback from stakeholder consultations

In the expert consultation, it was asked if the lower consumption of fuel of lighter vehicles (due for example to the substitution of steel with high strength steel) was considered in the model. The lower fuel consumption of lighter vehicles can be modelled with a scenario, in which both the material switch lever of the Manufacturing module and the vehicle consumption lever of the Transport module are set to their maximum ambition level.

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 5: Ambition levels for the lever material efficiency

Name Unit	2015	2050			
		1	2	3	4
Steel [%]	0	8	16	25	33
Cement [%]	0	6	10	15	20
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	4	7	10	14

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Expert consultation (for details see EUCalc deliverable 3.4, Expert consultation on manufacturing, material use and raw materials)

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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 6: 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 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 7: Ambition levels for the lever technology share

Name / Unit	TRL	2015	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

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Expert consultation (for details see EUCalc deliverable 3.4, Expert consultation on manufacturing, material use and raw materials)

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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 consists of a combination of electricity, coal, oil, gas, solid biomass, liquid biomass, gaseous biomass, waste and hydrogen and changes from fossil fuels to electricity, hydrogen, (bio) gas, and biomass. Within the scope various non-fossil fuel decarbonisation options for the industry sector, such as electrification or hydrogen-based processes[4] are compared.

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.

Within a determined technology, one important decarbonisation option for the European manufacturing and production sectors is the substitution of fossil fuels used for energy and for feedstock. There are several possibilities to reach this goal. The first one is the electrification of heat, which can be obtained by replacing furnaces, boilers, heat pumps running on fossil fuels with electric ones. A second possibility is the use of zero-carbon hydrogen to replace certain fuels used for energy or feedstock. Furthermore, the switch to sustainable biomass or zero-carbon hydrogen can reduce carbon emissions in the manufacturing sector.

The availability of low-cost zero-carbon electricity and biomass will influence the feasibility of these decarbonisation options. Availability can vary considerably

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

among locations. Countries with high electricity prices and without biomass resources will have to rely on renewable electricity transmitted over long distances or imported biomass and zero-carbon hydrogen.

The decarbonisation options for the energy carrier mix vary considerably from one sector to another. Figure 16 shows the decarbonisation options in term of energy carrier switch for some industrial sectors according to McKinsey (2018).

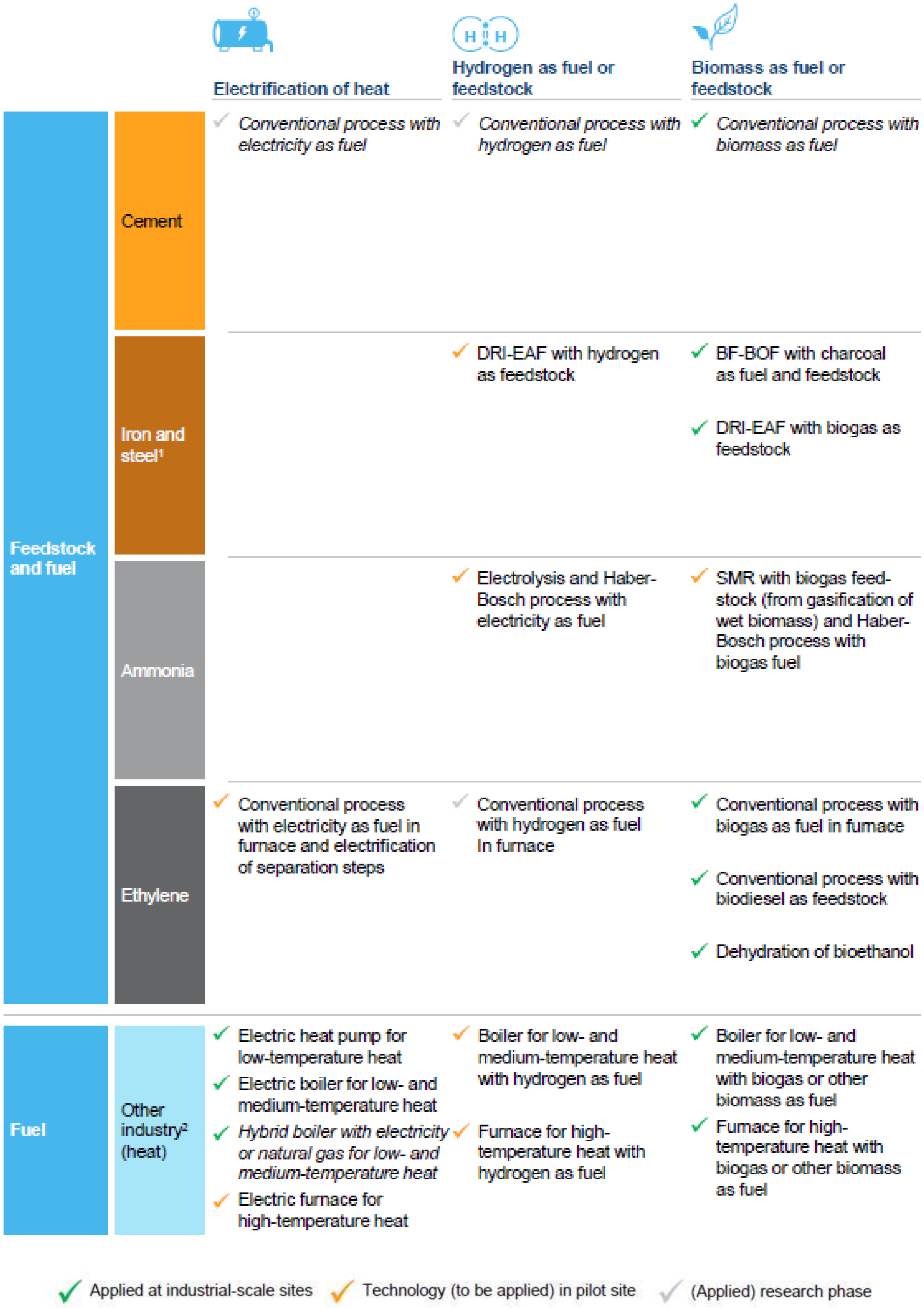

Figure 16: Decarbonisation options for the energy carrier mix (McKinsey, 2018)

The ambition levels of the energy carrier mix of each technology and industrial subsector are based on the previous literature review.

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 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 Figure 17). 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).

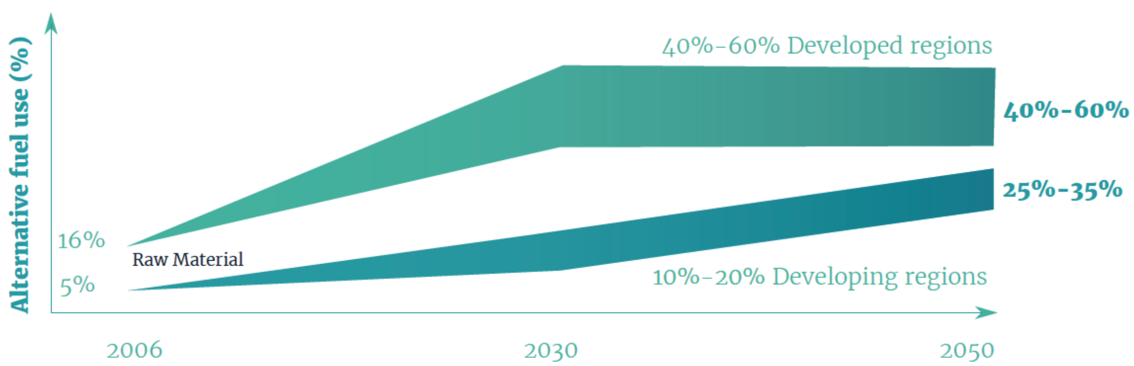

Figure 17: Forecast of alternative fuel use in cement industry by region. Europe is part of the developed region (Favier et al., 2018)

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, to produce 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).

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 now often used to make urea, a type of fertilizer based on ammonia and CO_2. The switch to hydrogen in ammonia production together with the use of nitrate-based fertilizers instead of urea would allow eliminating these emissions provided that the power sector is fully decarbonised (McKinsey, 2018). The low-carbon ammonia route has a two times higher CAPEX and three times higher OPEX than conventional production, at a current TRL level of 7 (Axelson et al., 2018).

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 (see Figure 18). 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).

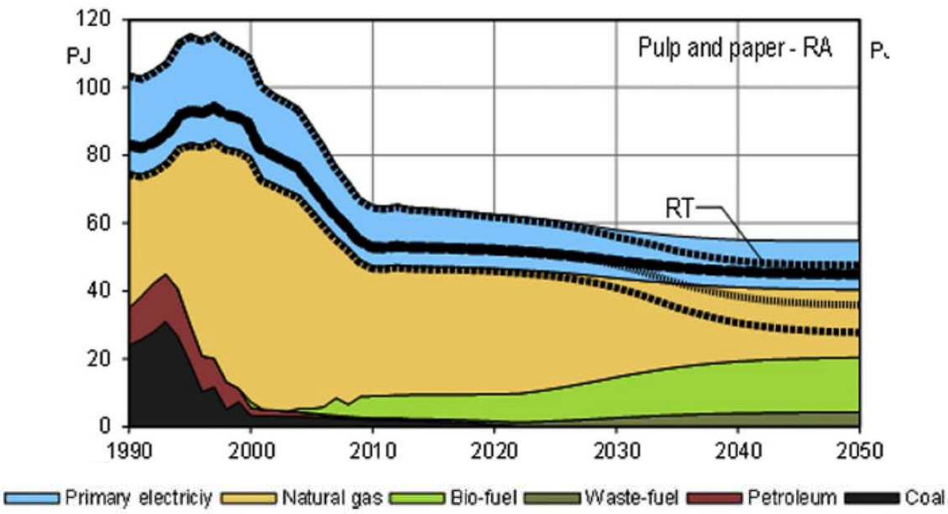

Figure 18: Energy carrier mix under the Reasonable Action scenario (RA) and Radical Transition scenario (RT) for the UK paper and pulp industry (Griffin et al., 2018)

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 these technologies. Although electric melting is available for small furnaces (< 150 tpd), it still needs to be demonstrated for large furnaces such as those used in flat or container glass production. For certain glass compositions (e.g. E-glass for reinforcement fibres) there are technical aspects (associated with the electrical conductivity), which limit the proportion of electrical energy for melting. 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. However, any alternative fuel (especially hydrogen) must be modified in such a way, that the radiation from the flame is effectively transferring energy to the glass. This will still require quite some coordinated research. The efficiency of oxyfuel combustion can be improved by preheating of the gas and oxygen using the waste heat from the furnace [IES 2018].

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.

For the manufacturing of **copper,** the energy carrier mix consists of electricity, and hydrocarbon fuels. The energy demand and energy carrier mix heavily depend 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.

The manufacturing of **transport equipment** will change its energy carrier mix towards an increased use of biomass.

The main processing operations of the **food, beverages and tobacco** industry include materials reception and treatment, size reduction, mixing and forming, separation techniques, product processing techniques, heat processing and post-processing operations. Currently, the high heat demand of several processes causes high amounts of gas in the energy carrier mix followed by electricity. The decarbonisation of the energy carrier mix can be achieved by the electrification of heat and by using gas turbine CHPs, fuelled by biogas for heat supply (Gowreesunker et al., 2018). Furthermore, the usage of biomass can contribute highly to emission reduction in the food, beverage and tobacco industry.

The **textile and leather** industry currently uses high amounts of gas and electricity for the production processes. The dyeing sector is a considerable energy consumer, since its manufacturing process requires a substantial quantity of steam. The use of biomass as substitution for gas to provide thermal energy is considered in literature (Nunes et al., 2019). Also, the change to electricity provides a possibility to reduce carbon emissions.

At the manufacturing process of **machinery equipment** mainly electricity is used as energy carrier followed by gas. For the future energy carrier mix, an increasing amount of electricity and a partial substitution of gas by biomass is assumed.

The current energy carrier mix of **wood and wood products** consists of biomass, electricity and small amounts of gas, oil and coal. Under the assumption of a total substitution of fossil fuels in 2050, a future fuel mix comprising biomass and electricity is estimated.

The manufacturing processes as well as the produced products from **other industries** are very heterogeneous, so no unified trend for the future energy carrier mix could be found in literature. It is assumed, that the future energy carrier mix will be strongly dominated by biomass and electricity.

Disaggregation methodology rational

From 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.

Feedback from stakeholder consultations

At the stakeholder consultation, it was pointed out that in some cases level 4 was not ambitious enough. This suggestion was taken into account and the total share of fossil fuel for level 4 is kept below 15% for all the technologies considered. We decided not to have the fossil share at 0% (as suggested by some expert stakeholders) because for some technologies, like steel BF-BOF, it is not realistic.

Another feedback concerned the limited availability of biomass and how this is taken into account in the model. In the EUCalc model, the availability of biomass at national level is determined by the Agriculture module (WP4) based on the demand of transport, building, industry, and power sectors. If the biomass demand cannot be satisfied a warning in the pathway explorer will signal it to the user.

A suggestion from an expert stakeholder was to add heat as an energy carrier.

5.3.4.1 Ambition levels

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

Table 8: Ambition levels for the lever energy carrier mix

Material	Technology	Energy carrier	2015	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
	scrap-EAF	To electricity [%]	0	0	0	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	0	0	0
	HIsarna	To electricity [%]	0	0	0	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	0	0	0
	hydrogen-DRI	To electricity [%]	0	0	0	0	0
		To hydrogen [%]	0	0	0	30	70
		Solid to gas [%]	0	0	2	3	5
		Liquid to gas [%]	0	0	2	3	5
		To biomass [%]	0	0	0	0	0
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
	dry-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
	geopolymers	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
Ammonia	-	To electricity [%]	0	0	0	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	0	0	0
Other chemicals	-	To electricity [%]	0	0	0	25	50
		To hydrogen [%]	0	0	0	0	0
		Solid to gas [%]	0	0	2	50	100
		Liquid to gas [%]	0	0	2	3	5
		To biomass [%]	0	0	10	20	30
Paper	Wood pulp	To electricity [%]	0	0	0	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	33	66	100
	recycled	To electricity [%]	0	0	0	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	33	66	100
Aluminium	primary production	To electricity [%]	0	0	0	0	50
		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
	Secondary production	To electricity [%]	0	0	0	0	50
		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
Glass	-	To electricity [%]	0	0	0	0	20
		To hydrogen [%]	0	0	0	0	0
		Solid to gas [%]	0	0	2	3	5
		Liquid to gas [%]	0	0	100	100	100
		To biomass [%]	0	0	2	6	7
Lime	-	To electricity [%]	0	0	0	0	0
		To hydrogen [%]	0	0	0	0	0
		Solid to gas [%]	0	0	20	35	0
		Liquid to gas [%]	0	0	0	0	0
		To biomass [%]	0	0	5	30	80
Transport equipment	-	To electricity [%]	0	0	0	25	50
		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	20	40	60
Food, beverages and tobacco	-	To electricity [%]	0	0	0	25	50
		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	20	40	60
Textiles and leather	-	To electricity [%]	0	0	0	25	50
		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	20	40	60
Machinery equipment	-	To electricity [%]	0	0	0	25	50
		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	20	40	60
	-	To electricity [%]	0	0	0	25	50

Wood and wood products		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	20	40	60
Other industries	-	To electricity [%]	0	0	0	25	50
		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	20	40	60
Copper	-	To electricity [%]	0	0	0	25	50
		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	20	40	60

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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.

A number of technology improvements can be applied across different sectors. Table 9**Fehler! Verweisquelle konnte nicht gefunden werden.** lists the most important energy efficiency measures of these cross-cutting technologies.

Table 9: Overview of cross-cutting technologies and most important energy efficiency (EE) measures (Henzler et al., 2017)

Technology	Relevant Sectors	Important EE Measures
Steam	Chemicals, Petroleum Refining, Pulp & Paper	▪ Increase boiler efficiency ▪ Employing operating & control techniques ▪ Minimizing blowdown from the boiler ▪ Optimizing steam distribution systems
Motor drives	All industry plants where electricity is available	▪ Use of energy-efficient motors ▪ Use of variable speed drives ▪ Motor repairs / rewinding
Pumps / Pumping systems	Agriculture, Chemicals, Food, Waste	▪ Pumping system control & regulation ▪ Improving pipework system ▪ Optimizing motors & transmission
Compressed air systems (CAS)	All sectors	▪ Assessing actual flow/pressure/quality needs ▪ Reducing compressed air system leaks ▪ Optimizing controls & supply to meet actual needs
Heating	Chemicals, Copper & Aluminum, Food, Glass & Ceramics, Iron & Steel, Pulp & Paper, Textiles	▪ Efficient load management ▪ Use of heat exchangers and heat pumps ▪ Heat recovery & CHP / CCP generation
Cooling	Chemicals, Copper & Aluminum, Food, Glass & Ceramics, Iron & Steel, Pulp & Paper, Textiles	▪ Employing chillers & cooling systems ▪ Improving parts of the compressor ▪ Evaporative cooling
System EE	All sectors	▪ Efficient matching of supply to demand

Some other energy efficiency measures can be applied only to single sectors. These sector-specific energy efficiency measures are listed in Table 10**Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 10: Overview of sector-specific energy efficiency (EE) measures (Henzler et al., 2017)

Sector	Specific EE Measures
Chemicals	▪ Upgrade steam cracking plants to best practice technology ▪ Upgrade all fertilizer production plants to best practice technology
Iron & Steel	▪ Improved Furnace designs ▪ Reduced number of temperature cycles ▪ Coke dry quenching ▪ Top pressure recovery turbines
Cement	▪ Multi-stage preheater systems ▪ Addition of pre-calciner to pre-heater kilns ▪ Dry systems with preheaters & pre-calciner ▪ Fluidized bed advanced kiln systems ▪ Fuel management ▪ High-efficiency mills & classifiers
Pulp & Paper	Use of: ▪ additives, increased dew point, & improved heat recovery for drying ▪ continuous digester, washing presses & pulping aids ▪ vacuum system optimization ▪ advanced dryer controls

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 11: 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).

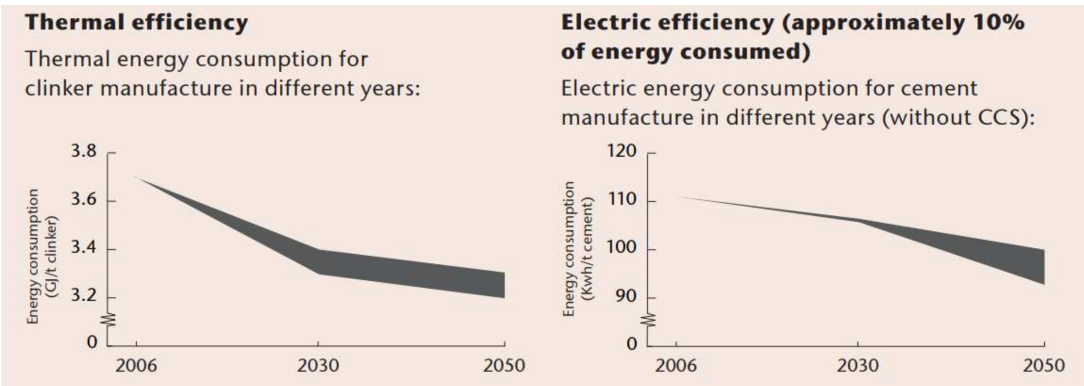

Figure 19: Projected thermal and electric energy consumption for a cement plant using state of the art technology kiln (IEA, 2009)

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).

The production of **transport equipment** shows following possibilities for energy efficiency in literature: high efficiency welding/inverter technology, multi-welding units, frequency modulated DC-welding machines, hydroforming, infrared and UV paint curing and microwave heating.

For the production of **food, beverages and tobacco** the following energy efficiency options are considered: premium efficiency control with adjustable speed drivers for pumps and motors, high efficiency burners, advanced heating and process control (oven), process heat recovery and variable speed drivers on chiller compressors.

In the **textiles and leather** sector, the highest shares of end energy use have motor driven systems and steam. Energy efficiency can be increased by using high-efficiency motors, variable speed drivers, power quality solutions, control systems and optimization software or instrumentation and measurement.

In the **machinery equipment** sector, the following production energy efficiency options are considered: premium efficiency control with adjustable speed drivers (for pumps and motors), advanced heating and process control (furnace), impeller trimming (pump), high efficiency non-packaged HVAC and optimized process re-design.

At the manufacturing of **wood and wood products**, the following technology developments are considered: high efficient CHP systems, efficient motor systems like the replacement of V belts with cogged belts, motor load sizing and using motor maintenance software as well as the usage of efficient compressor systems. Also, efficient lighting systems can contribute to energy efficiency of the production sites.

In the sector **other industries** efficiency measures like energy efficient motor systems, steam processing, drying wood rubber plastics, refrigeration and fire heaters are considered.

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 12: Ambition levels for the lever technology development

Name / Unit	2015	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
Transport equipment [%]	0	3	8	13	18
Food, beverages and tobacco [%]	0	6	16	25	35
Textiles and leather [%]	0	6	10	14	18
Machinery equipment [%]	0	5	8	12	15
Wood and wood products [%]	0	3	5	8	10
Other industries [%]	0	3	9	14	18
Copper [%]	0	8	12	16	20

References

Expert consultation (for details see EUCalc deliverable 3.4, Expert consultation on manufacturing, material use and raw materials)

Brown et al. (2016), The Clean Energy Technology Assessment Methodology - A methodology for assessing renewable energy and energy efficiency technology markets, International Energy Agency

CEPI (2011), Investing in Europe for Industry Transformation, 2050 Roadmap to a low-carbon bioeconomy

CEPI (2016) Key statistics, European pulp and paper industry

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

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

Elshkaki et al. (2016), Copper demand, supply, and associated energy use to 2050

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

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

Henzler M. et al (2017), Industrial Energy Efficiency and Material Substitution in Carbon-Intensive Sectors, Adelphi

ICF (2015), Study on energy efficiency and energy saving potential in industry and on possible policy mechanisms

IEA (2009), Cement Technology Roadmap 2009, Carbon emissions reductions up to 2050

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

van Sluisveld M. et al. (2018), EU decarbonisation scenarios for industry, Deliverable 4.2, REINVENT – PROJECT NR 730053 (fig.25 and fig.44)

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 oxyfuels. 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 is the largest carbon capture and use process currently in existence (DECHEMA, 2017). In addition to urea, several 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.

For the production of **transport equipment**, **food, beverages and tobacco**, **textiles and leather, machinery equipment, wood and wood products** and products from **other industries** no CO_2 reductions by CCS/CCU are assumed. This is because CC is an asset intensive technology and we assume these sectors do not emit enough GHG emissions per plant to fully use the technology.

The ambition levels adopted for CC are mainly based on the projections provided by IEA (2017) shown in Figure 20. 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).

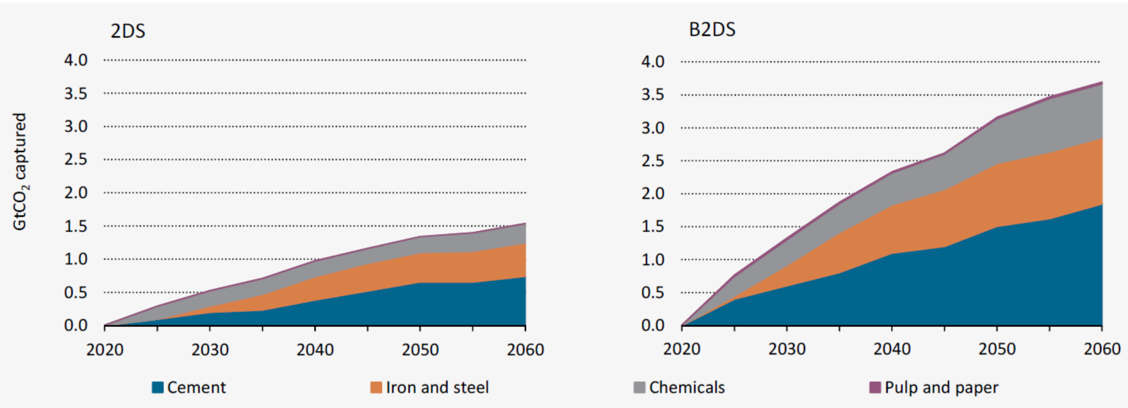

Figure 20: CO_2 captured and stored from industry by subsector in the 2 degrees scenario (2DS) and in the below 2 degrees scenario (B2DS) (IEA, 2017)

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 13: Ambition levels for the lever carbon capture

Name / Unit	2015	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
Aluminium – primary [%]	0	0	0	0	0
Aluminium – secondary [%]	0	0	0	0	0
Glass [%]	0	0	0	0	0
Lime [%]	0	0	10	30	70
Transport equipment [%]	0	0	0	0	0
Food, beverages and tobacco [%]	0	0	0	0	0

Textiles and leather [%]	0	0	0	0	0
Machinery equipment [%]	0	0	0	0	0
Wood and wood products [%]	0	0	0	0	0
Other industries [%]	0	0	0	0	0
Copper [%]	0	0	0	0	0

References

Expert consultation (for details see EUCalc deliverable 3.4, Expert consultation on manufacturing, material use and raw materials)

BCG and VDEh. 2013. Steel's Contribution to a Low-Carbon Europe 2050

Carbon Cure, 2017, Working with waste

Cembureau (2013), The role of CEMENT in the 2050 LOW CARBON ECONOMY p.45

DECHEMA (2017), Low carbon energy and feedstock for the European chemical industry p-148-156Eurofer (2013), A steel roadmap for a low carbon Europe 2050

Easac (2013), Carbon capture and storage in Europe

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

IEA, Technology Roadmap Carbon Capture and Storage

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

IEA (2017), 2017 Energy Technologies Perspectives

Institute for European Studies (2018), A Bridge Towards a Carbon Neutral Europe

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

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

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 14 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 14: 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 15: 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%

References

Rueda Cantuche, Jose Manuel, Tamas Revesz, Antonio F. Amores, Marian Mraz, Emanuele Ferrari, Alfredo Mainar, Letizia Montinari and Bert Saveyn (2016), The EU28 GTAP Input-Output Tables, Conference paper presented at the 19th Annual Conference on Global Economic Analysis, Washington DC, USA

6 Description of constant parameters

6.1 Constants list

6.1.1 Product material composition

The average amount of materials contained in a product is fundamental to estimate the total amount of materials that need to be produced to satisfy the demand for new products. Table 16 shows the material composition of each product and the main source references for this estimate.

Table 16: Product material composition

Product	steel	cement	ammonia	other chemicals	paper	timber	aluminium	glass	lime	copper
Residential buildings [kg/m² floor]	11.00	100.0 0	0.00	1.00	0.00	60.00	0.00	70.00	30.00	2.00
Non-residential buildings [kg/m² floor]	16.00	150.0 0	0.00	2.00	0.00	20.00	40.00	160.0 0	10.00	1.00
Insulation residential buildings [t/m² wall]	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Insulation non-residential buildings [t/m² wall]	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
District heating pipes [t/km]	22.20	0.00	0.00	14.80	0.00	0.00	0.00	0.00	0.00	0.00
Fridges [kg/num]	45.00	0.00	0.00	19.50	0.00	0.00	2.25	0.75	0.00	2.07
Dishwashers [kg/num]	14.00	0.00	0.00	12.00	0.00	0.00	0.00	0.00	0.00	1.00
Washing machines [kg/num]	30.40	20.00	0.00	16.80	0.00	0.00	4.00	1.60	0.00	1.00
Freezers [kg/num]	46.12	0.00	0.00	3.36	0.00	0.00	3.46	0.00	0.00	2.07
Dryer [kg/num]	27.00	0.00	0.00	9.90	0.00	0.00	1.62	0.05	0.00	1.00
TV [kg/num]	1.32	0.00	0.00	3.24	0.00	0.00	0.84	6.00	0.00	0.52
Smartphone [kg/num]	0.02	0.00	0.00	0.05	0.00	0.00	0.03	0.02	0.00	0.00
Computer [kg/num]	0.51	0.00	0.00	0.90	0.00	0.00	0.12	1.11	0.00	8.09
ICE cars [t/num]	1.10	0.00	0.00	0.17	0.00	0.00	0.10	0.05	0.00	0.03
ICE trucks [t/num]	18.31	0.00	0.00	0.28	0.00	0.00	1.6	0.75	0.00	0.48
FCV cars [t/num]	0.95	0.00	0.00	0.18	0.00	0.00	0.09	0.05	0.00	0.02
FCV trucks [t/num]	15.90	0.00	0.00	3.03	0.00	0.00	1.48	0.75	0.0	0.09
EV cars [t/num]	0.83	0.00	0.00	0.16	0.00	0.00	0.14	0.04	0.00	0.05
EV trucks [t/num]	13.83	0.00	0.00	2.60	0.00	0.00	2.33	0.63	0.00	0.25
Ships [t/num]	3870. 88	0.00	0.00	317.5 0	0.00	0.00	635.00	0.00	0.00	75.00
Trains [t/num]	1801. 30	0.00	0.00	83.64	0.00	0.00	278,80	0.00	0.00	4.26
Planes [t/num]	23.00	0.00	0.00	28.75	0.00	0.00	40.25	0.00	0.0	0.66
Road [t/km]	0.00	1108. 80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rail [t/km]	0.06	172.5 0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.76
Trolley-cables [t/km]	0.09	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.89
Fertilizer [t/t]	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Plastic packaging [t/t]	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Paper packaging [t/t]	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00

Aluminium packaging [t/t]	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Glass packaging [t/t]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
Paper printing and graphic [t/t]	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Paper sanitary and household [t/t]	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00

Table 17: Assumptions and source references for the product material composition table

Product	Estimated weight	Source references
Residential buildings	0,530 kg/m²	De Wolf (2018)
Non-residential buildings	0,789 kg/m²	
Insulation residential buildings	13,43 kg/m²	Global calculator, EPS 032 (10cm thickness)
Insulation non-residential buildings	13,43 kg/m²	
District heating pipes	37 kg/m	germanpipe.de
Fridges	75 kg	Magalini et al. (2018)
Dishwashers	40 kg	
Washing machines	80 kg	
Freezers	88,7 kg	
Dryer	45 kg	
TV	12 kg	Mihai (2016)
Smartphone	iPhone 6	
Computer	3 kg	
ICE cars	1.5 t	Dai et al.(2016)
ICE trucks	25 t	
FCV cars	1.5 t	
FCV trucks	25 t	
EV cars	1.5 t	
EV trucks	25 t	
Ships	31750 t	Sullivan (2018)
Trains	2788 t	
Planes	115 t	
Road	-	Matschei (2018)
Rail	-	Chester (2018)
Trolley-cables	880 kg/km	Global calculator, overhead lines (rail) and wires (buses)

References

Chester MV (2018), Rail Concrete and Steel Use form a Life Cycle Lens, IEA Material Demand Workshop, Paris, 8. Mar 2018

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Dai Q., J. Kelly and A. Elgowainy (2016), Material Composition of U.S. Light-duty Vehicles

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Sullivan JL, GM Lewis, GA Keoleian (2018), Effect of mass on multimodal fuel consumption in moving people and freight in the U.S., Transportation Research Part D: Transport and Environment, Vol. 63

6.1.2 Material switch ratios

Material switch ratios are used to calculate the amount of material necessary to replace another material and guarantee the same final functionality of the product. For the material switches in transport the replacement ratios used were proposed by Luk et al. (2017):

- 0.55 kg of aluminium to replace 1 kg of conventional steel in cars and trucks (Fig.1 Luk et al., 2017)
- 0.4 kg of carbon fibres to replace 1 kg of conventional steel in cars and trucks (Fig.1 Luk et al., 2017)

For the material substitution in buildings, no reliable estimates for switch ratios were found in literature. Hence the ratio between specific Young moduli of the materials was used to estimate the material switch ratios (this approach was already used in the Global Calculator). The specific Young modulus indicates the strength property of a material per mass density of the material. Hereafter the adopted material switch ratios:

- 1.08 kg of wood (spruce) to replace 1 kg of steel in buildings (the specific Young modulus of steel is 25 and of spruce 23)
- 5.18 kg of wood (spruce) to replace 1 kg of cement in buildings, assuming 14% of cement per kg of concrete (the specific Young modulus of concrete is 17 and of spruce 23)

This approach could not be used to determine the material switch ratios in insulating materials because the replacement should guarantee the same thermal properties and not the same strength. Due to lack of reliable and robust data in the current model the following material switch ratios are used:

- 1 kg of paper (cellulose) to replace 1 kg of chemicals in renovated surfaces
- 1 kg of natural fibres to replace 1 kg of chemicals in renovated surfaces

References

Specific young modulus: https://en.wikipedia.org/wiki/Specific_modulus

Luk et al. (2017), Review of the Fuel Saving, Life Cycle GHG Emission, and Ownership Cost Impacts of Lightweighting Vehicles with Different Powertrains. Environ. Sci. Technol. 51, 8215−822

6.1.3 Specific energy consumption

The specific energy consumptions represent the amount of energy and feedstock necessary to produce 1 Mt of a certain material using a certain technology. As it was not possible to find a unique database providing the energy consumptions associated to all the technologies analysed in the Manufacturing module, more sources were necessary to estimate these values. The specific energy consumptions for each technology and the relative sources are listed in Table 18.

Table 18: Specific energy consumptions for each technology

Industry – Technology	Specific energy consumption [TWh/Mt]	Source references
Steel - BF-BOF	4.90	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Steel - scrap-EAF	1.36	
Steel - HIsarna	3.92	Tata Steel (2018) *reduction of energy demand of 20% with respect to steel BF-BOF
Steel - hydrogen-DRI	3.48	Vogl et al. (2018)
Cement - dry-kiln	0.83	JRC (2013) p. 137
Cement - wet-kiln	1.76	JRC (2013) p. 137
Cement - geopolymers	0.65	Jamieson et al. (2015)
Ammonia	9.73	DECHEMA (2017) p.57
Other chemicals	13.26	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Paper - woodpulp	6.04	Healy (2011), IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Paper - recycled	3.11	
Aluminium – primary	13.85	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Aluminium – secondary	1.84	
Glass	2.42	
Lime	1.18	A competitive and efficient lime industry (EuLA, 2014)
Copper	4.72	Study on Energy Efficiency and Energy Saving Potential in Industry and on possible Policy Mechanisms (ICF, 2015)
Transport equipment	0.03	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Food, beverages and tobacco	0.11	
Textiles and leather	0.07	
Machinery equipment	0.03	
Wood and wood products	0.25	
Other industries	0.16	

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6.1.4 Feedstock percentages

In most of the industrial sectors fuels are usually used to generate energy (mainly heat), but in a few industries, they are also used as raw materials. The feedstock percentages of Table 19 are used to assess the amount of fuel used for energy purposes (fuel combustion) and the amount used as feedstock (incorporated in the final product). It is important to calculate the amount of fuel used as feedstock because these are emissions avoided, at least until the end-of-life of products.

Fuels are used as a feedstock typically in the chemical industry where oil is one of the main raw materials for chemicals production. Fuels are used as feedstock also in other industries. In the steel industry part of the carbon contained in coal ends up in steel. In ammonia production most of the hydrogen in natural gas is combined with nitrogen to produce ammonia. In the paper industry, the main raw material to produce paper is wood (solid biomass).

The following table shows the feedstock percentages for the technologies modelled. For steel, the coal feedstock percentage is currently zero due to a lack of reliable estimates from literature. For ammonia, the feedstock percentage of gas is based on Boustead (2015) as well as for hydrogen and biogas. For other chemicals, the feedstock percentages of fossil fuels are calculated based on the IDEES database (Mantzos et al., 2018). The same percentages were assumed for biomass, in case of fuel switch from fossil to biobased feedstock for chemical production. In paper production it was assumed that most of the wood (solid biomass) is used as feedstock for the production of pulp and only the residues are used to produce energy.

Table 19: Feedstock percentages of energy carriers for each technology

Industry – Technology	Coal	Oil	Gas	Solid Biomass	Liquid Biomass	Gaseous Biomass	Hydrogen
Steel - BF-BOF	0%	0%	0%	0%	0%	0%	0%
Steel - scrap-EAF	0%	0%	0%	0%	0%	0%	0%
Steel - HIsarna	0%	0%	0%	0%	0%	0%	0%
Steel - hydrogen-DRI	0%	0%	0%	0%	0%	0%	0%
Cement - dry-kiln	0%	0%	0%	0%	0%	0%	0%
Cement - wet-kiln	0%	0%	0%	0%	0%	0%	0%
Cement - geopolymers	0%	0%	0%	0%	0%	0%	0%
Ammonia	0%	0%	94%	0%	0%	94%	94%
Other chemicals	17%	91%	43%	17%	91%	43%	50%
Paper – wood pulp	0%	0%	0%	80%	0%	0%	0%
Paper – recycled	0%	0%	0%	0%	0%	0%	0%
Aluminium – primary	0%	0%	0%	0%	0%	0%	0%
Aluminium – secondary	0%	0%	0%	0%	0%	0%	0%
Glass	0%	0%	0%	0%	0%	0%	0%
Lime	0%	0%	0%	0%	0%	0%	0%
Copper	0%	0%	0%	0%	0%	0%	0%
Transport equipment	0%	0%	0%	0%	0%	0%	0%
Food, beverages and tobacco	0%	0%	0%	0%	0%	0%	0%
Textiles and leather	0%	0%	0%	0%	0%	0%	0%

Machinery equipment	0%	0%	0%	0%	0%	0%	0%
Wood and wood products	0%	0%	0%	0%	0%	0%	0%
Other industries	0%	0%	0%	0%	0%	0%	0%

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6.1.5 Specific combustion emissions

The specific combustion emissions of CO_2, CH_4, and N_2O are specified for each energy carrier and correspond to the emissions produced during the fuel combustion per unit of fuel used [Mt/TWh fuel]. The emission factors used in the model are those proposed by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The emission factor for biomass will be provided by the Agriculture module (WP4) and it will account for CO_2 absorbed during the biomass growth. The emission factors for electricity and hydrogen are zero because the emissions generated in their production are calculated in the Energy Supply module (WP5).

Table 20: Emission factors per energy carrier

Energy carrier	CO_2 [Mt/TWh]	CH_4 [Mt/TWh]	N_2O [Mt/TWh]
Electricity	0	0	0
Coal	0.364	3.61E-05	5.42E-06
Oil	0.3	1.08E-05	2.17E-06
Gas	0.203	1.08E-06	1.08E-07
Solid Biomass	0	0	0
Liquid Biomass	0	0	0
Gaseous Biomass	0	0	0
Waste	0.403	1.08E-04	1.44E-05
Hydrogen	0	0	0

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6.1.6 Specific process emissions

Industrial process emissions are generated as a by-product of the conversion of raw materials to the final product material and exclude energy-related emissions due to direct combustion. These emissions are particularly hard to abate. The only way is a change in raw materials or the use of carbon capture. For some industries, these emissions are particularly relevant. For example, 60% of emissions in the cement industry are process emissions from the calcination process.

The specific process emissions [Mt CO_2/Mt of material] used in the Manufacturing module to calculate the total process emissions based on the total material production are shown in Table 21 with the relative sources. Most of the specific process emissions are based on the IPCC Guidelines for National Greenhouse Gas Inventories (2006).

Table 21: Specific process emissions for manufacturing technologies

Industry – Technology	Specific process emissions [Mt CO_2/Mt of material]	Source references
Steel - BF-BOF	1.46	IPCC Guidelines for National Greenhouse Gas Inventories (2006) p.4.25
Steel - scrap-EAF	0.08	
Steel - HIsarna	1.17	Tata Steel (2018) *reduction of carbon emissions by 20% with respect to steel BF-BOF
Steel - hydrogen-DRI	0.70	IPCC Guidelines for National Greenhouse Gas Inventories (2006) p.4.25
Cement - dry-kiln	0.52	
Cement - wet-kiln	0.52	
Cement - geopolymers	0	-
Ammonia	2.10	IPCC Guidelines for National Greenhouse Gas Inventories (2006) p.3.15 (table 3.1 European average value)
Other chemicals	0.45	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Paper – wood pulp	0.00	-
Paper – recycled	0.00	-
Aluminium – primary	1.60	IDEES database 2015 EU28 Industry (Mantzos et al., 2018)
Aluminium – secondary	0.30	
Glass	0.20	
Lime	0.85	A competitive and efficient lime industry (EuLA, 2014)
Copper	0.60	Nilsson et al. (2017)
Transport equipment	0	-
Food, beverages and tobacco	0	-
Textiles and leather	0	-
Machinery equipment	0	-
Wood and wood products	0	-
Other industries	0	-

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