Explore sustainable European futures

Integration of the resource's modules "Land allocation, biodiversity impact & forestry", "Water scarcity" and "Minerals" modules

D8.4

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Short Description

This report describes how the resources modules are integrated in the EUCalculator framework. The resource modules include agriculture, land-use, land-use change and forestry, minerals, water and biodiversity modules. The report details the modules' scope, input-output interaction and calculation trees.

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List of abbreviations

Aichi Targets – The biodiversity targets set by the CBD members for 2020 at the CBD meeting in Aichi

APS - Alternative Protein Sources

BMI - Body Mass Index

BSM – Biosourced Material

CBD – Convention on Biological Diversity

CBF - Crop-Based Food groups

CSA – Climate-Smart Agriculture

CSF – Climate-Smart Forestry

DDGS - Dried Distillers Grains

EU – European Union

ICE - Internal Combustion Engine

FAO - Food and Agriculture Organization

FTS – Future Time Series

GHG – Greenhouse gases

GVA - Gross Value Added

INDC - Intended Nationally Determined Contributions

IPCC - Intergovernmental Panel on Climate Change

LSU – Livestock Unit

LULUCF – Land-Use, Land-Use Change and Forestry

Mtoe – Mega ton oil equivalent

OTS- Original Time Series

RESEDA - Réseau pour la sécurité et la qualité des denrées animales

RCP - Representative Concentration Pathway

RoW – Rest of the World

SDG – Sustainable Development Goals

TPE – Transition Pathway Explorer

TWh – Terawatt per hour

UCO – Used Cooking Oil

UNFCCC - United Nations Framework Convention on Climate Change

WEI - Water Exploitation Index

WP – Work Package

1 Introduction

Moving towards a low carbon society will affect multiple dimensions and sectors through various non-linear interlinkages. To develop coherent and sustainable decarbonization strategies, decision-makers need to understand and capture those effects, and the extent of how they will affect the different sectors. The European Calculator (EUCalc) strives to offer a scientifically sound exploratory tool, namely the Transition Pathway Explorer (TPE) in order to broaden societal discussion and scientific debate to accelerate the transition towards a low-carbon society via close user involvement and education.

EUCalc uses a modular approach to address inter-disciplinary and multi-dimensional issues. This report aims to describe how the resource related modules have been integrated in the modelling framework. In the present report, the resource modules refer to the agriculture, land-use, land use change and forestry; water; biodiversity and minerals modules. Resource modules are at the crossroads of the lifestyles and technology deployment patterns (e.g. food, transport, building demand):

> The agriculture, land-use, land-use change and forestry sectors have significant sustainability impacts (Strapasson et al., 2016), such as land-use, deforestation, GHG and other atmospheric pollutant emissions. Consequently, this module first aims at integrating in the framework how changes in diets, agricultural practices, and forestry management may affect GHG emissions, land-demand, water-demand and biodiversity impacts. Given the inherent interactions between food, bio-sourced materials and bioenergy sectors, a systemic approach that considers the interlinkages between food, bioenergy, and biomass is required to assess the sustainability of a bio-based economy (Rafiaani et al., 2018). The module considers the interplay between these sectors and how they may affect the sustainability of the Calculator pathways.
>
> The biodiversity module aims to quantify the impact of land restoration for biodiversity conservation on source sinks and GHG emissions in the EU. The module shows how the EU's ambition to halt biodiversity loss might affect future land-use.
>
> The water module aims at quantifying the impacts of the EU28+1 (including Switzerland) water demands on the local water resources in different scenarios. The water module considers different types of water impacts: water withdrawal, water consumption and water stress. This module delivers a visual representation of possible trends in water flows for different sectors, namely lifestyle, production & manufacturing, energy supply and agriculture & land-use. Water scarcity is addressed by calculating water stress values for each region in 2050 and by indicating these values on a map of Europe.
>
> The mineral module visually represents the impact of the EU's current digital and energy transitions on metallic mineral resources. Mineral depletion is addressed through processed data from the industry module for metallic minerals: Iron (from steel), Bauxite (from Aluminium), and Copper. The EU demand per capita for these minerals is compared with the world demand per

capita. In addition, medium worldwide demand projections are computed to show the global demand impact on reserves, reserve bases, and resources.

The objective of the deliverable is to present how the resource modules are integrated in the overall EUCalc framework. Section 2 presents the overall module logic; Section 3 presents their scope, and Section 4 details how the modules interact with each other. Section 5 describes the modules' inputs and outputs. Finally, Section 6 presents the calculation trees of each resource module.

2 Overall Logic

EUCalc considers historical data from 1990 to 2015, and computes projections until 2050 based on various ambition levels that drive the demand for resources. These ambition levels and levers have been identified in the literature and through expert workshops (see Deliverable 4.2, 4.3) as influencing relevant dimension of agriculture and lulucf, water, biodiversity and mineral sectors.

2.1 The agriculture, land-use, land-use change and forestry (lulucf) modules

The modules are based on a bottom-up approach. They compute the impacts of food, feed, bioenergy, and biomaterial demand in terms of energy, GHG emissions, and land-use.

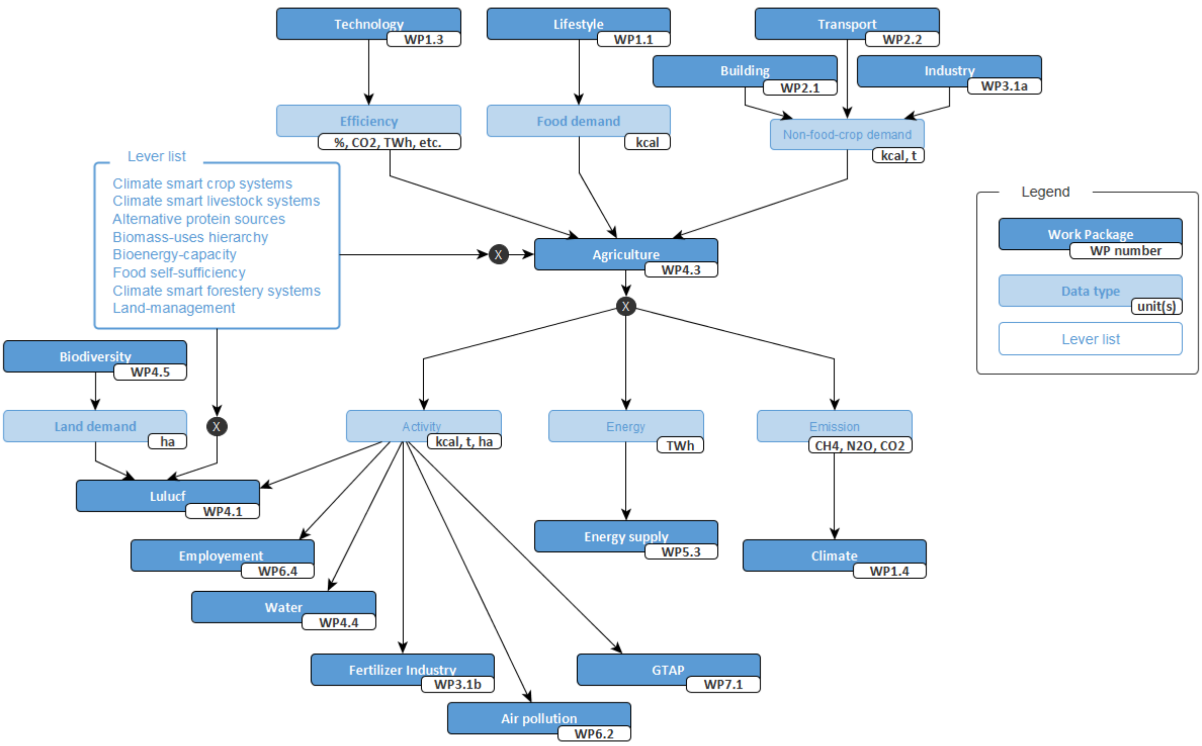

Figure 1 – Overview of the agriculture and land-use sectors

Figure 1 presents the simplified logic of the agriculture and the lulucf module. In brief, the lifestyle, building, transport and industry modules are computing a demand for food, non-food (including biosourced materials and energy), sent to the agriculture module. The later includes crop, livestock, beverages, biorefinery production patterns, driven by the lever setting, that are computing the resource demand (e.g. energy); resource supply (e.g. wood for electricity); the GHG emissions (CO_2, CH_4, N_2O); and finally, activity data (e.g. crop production by type). The energy and emission data are driven towards the energy supply and climate emission modules respectively, while the activity data enables other modules to compute the sustainability impacts such as employment and water-use. Lulucf module uses biodiversity and agriculture activity data to compute the land demand and land and carbon dynamics.

2.2 Biodiversity

The biodiversity module serves to quantifiably link biodiversity protection to GHG emissions. It uses a bottom-up approach to calculate the demand on agriculture and forestry in terms of land-use. The module uses historical data for land use and protected areas for the years 1990-2015, and determines values until 2050 based on lever settings.

The main outputs of the biodiversity module are:

- The direct negative GHG emissions from land conservation for biodiversity.
- The amount of land either needing to be protected and/or restored in order to meet the targets, and the negative emissions tied to this.

The basic calculation logic adopted here is (1) derive the annual land needed to reach the target; (2) restore agricultural areas within protected areas until either the target is met or no further land is available; (3) restore agricultural or natural land until either the target is met or no further land is available. Thereafter, GHG emissions are calculated based on the annual total amount of protected area.

2.3Water

The water module is based on a bottom-up approach to compute the water demands from the different water intensive sectors, as well as the water resources by region.

The main outputs of the water module are:

- The water demand for each main sector in each country.
- The local surface and groundwater resources available in each country based on specific climate scenarios.
- The water stress (or Water Exploitation Index normal) derived from water demand and water resources, based on specific climate scenarios.

The fundamental calculation logic consists in: (1) estimating water flows from each sector (households & services, livestock, irrigation, electricity supply, industrial manufacturing); (2) computing the water resources available. Thereafter, the Water Exploitation Index normal (WEI-normal) in each region is derived by dividing water consumption by water availability. Figure 2 presents the general calculation logic of the water module.

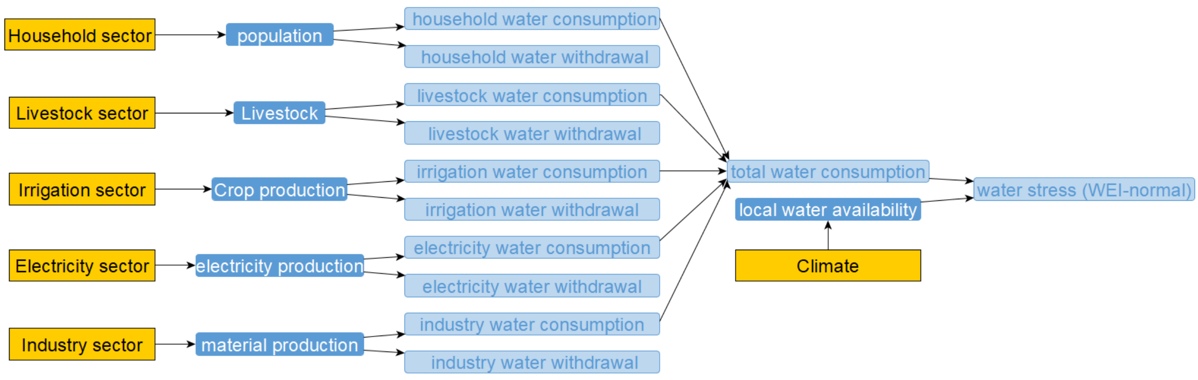

Figure 2 – Overall calculation logic of the water module

As water issues are due to an uneven distribution of water resources across space and time (Postel et al., 1996), water stress values might vary within a country and at yearly temporal scale. Thus, a finer granularity is implemented to highlight regions where risks of water shortage are the highest:

- 6 countries are divided in sub-regions to capture the spatial variability of water shortage, namely Spain, Italy, Greece, France, UK, Germany. The decision to regionally discriminate these six countries came from a discussion with JRC experts. It was suggested that those countries would show relevant and stark discrepancies between regional areas (e.g. North vs South) (Bisselink et al, 2018).
- Two semesters are distinguished each year to capture the temporal variability of water shortage: "winter" which spans from October to March, and "summer" which spans from April to September.

Overall, this choice in regional and temporal granularity is the result of a trade-off between appropriately representing water issues while ensuring a fast computation time, which is a key objective of the model to ensure users' friendliness. The decision was made thanks to expert consultation, in particular during a workshop on resource use, and feedback from the Joint Research Center (JRC).

2.4 Minerals

The mineral module serves to represent the mineral demand from the transport, agriculture, building, energy, and industry modules. The overall logic is first to obtain the production from outside Europe thanks to the *Industry* lever *Product net import*, which provides the amount produced in and exported from the EU, the amount imported, and the amount of material directly exported. Then, there is product decomposition into materials. The *material switch* and the *material efficiency* levers from the *Industry* module are applied to obtain the amount of material necessary to manufacture the products. The calibration is then applied onto the material amounts needed for production and exportation at the EU28 plus Switzerland scale. The calibration rates are then applied to each country for the demand in export +

production, export and import. This is followed by the mineral amounts for exports being subtracted from production and export amounts to obtain the mineral amounts needed for material production. The *technology development* lever from the *Industry* module is also applied since it has a direct link on the recycled amounts of material coming into the production. Finally, the European demand produced in Europe is added to the European demand produced in the rest of the world in order to get the total – direct and indirect – resource impacts of the European demand. In comparison to the reserves in 2015, the module also addresses the relative reserve left in 2050. The main outputs are as follows:

- Mineral Demand segregated for each sector [Mt]
- Mineral availability in percentage of 2015 reserves [%]

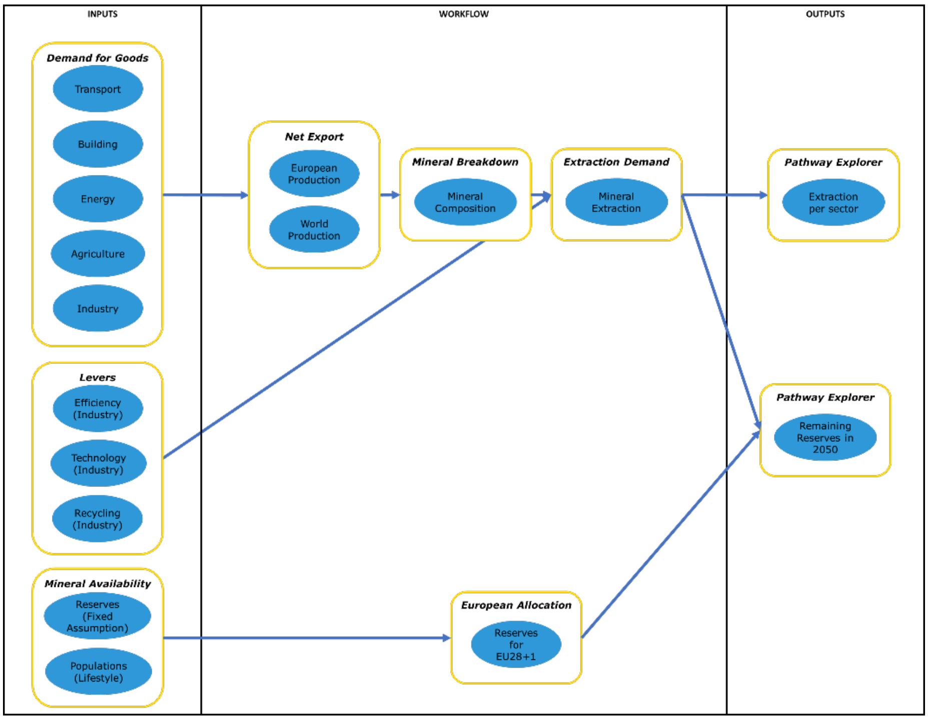

Figure 3 - Overall model logic scheme introducing the parameters introduced during each step

Almost all sectors require minerals for their activities. All these areas stem from mining and primary mineral refining at the industry level. The raw refined material is then utilized by other sectors to make finished products. As an example, a car, is made using steel, aluminium, and copper (among others). The raw minerals are refined and extracted by the mineral industry. As such, it seems like the main inputs for mineral demand comes from the industry module, which already has the levers of interest.

3 Scope Definition

3.1 Agriculture

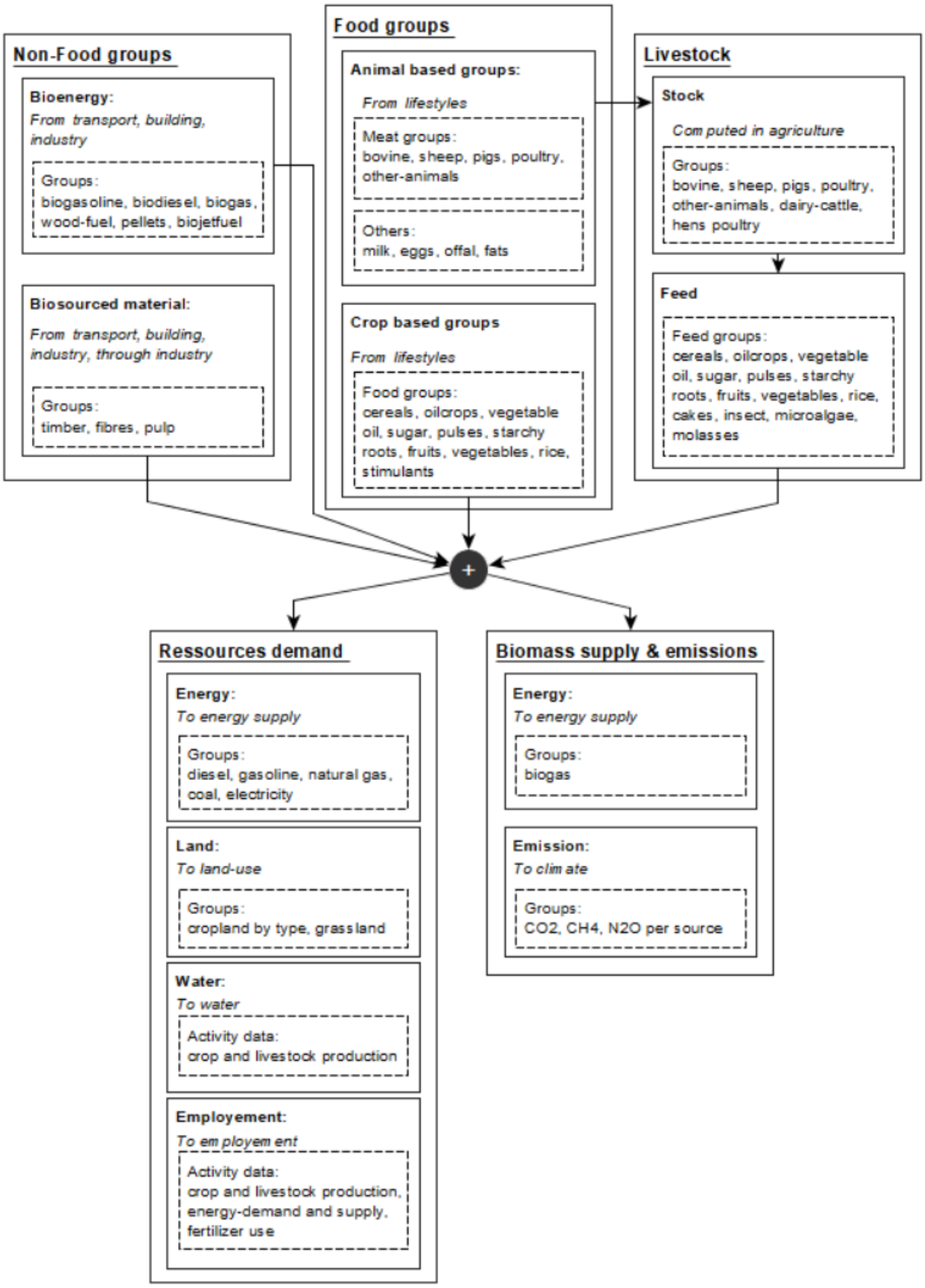

Figure 4 – Agriculture scope

As shown by Figure 4, the agriculture module considers biomass demand for food, feed, non-food and energy. The agriculture module modelling framework basically provides the highest level of details that data availability enables us to consider at the level of the 28 European Member States and Switzerland. Food and non-food data are mainly based on FAOSTAT, while bioenergy data are based on both FAOSTAT and EUROSTAT. The module provides a similar and possibly higher level of details compared to other state of the art models such as FAO's (FAO, 2018) and TYFA-IDDRI (Poux and Aubert, 2018) models but while being connected to an overall modelling framework that considers extra-dimensions such as transportation, building and industry sectors. In other words, it allows us to explore a wider range of possible scenarios, not only for agriculture settings but also for the indirect factors that are affecting lifestyles, resource-use and technology patterns.

The agriculture module enables to assess the impact of moving towards a "climate-smart" approach, or *CSA for Climate Smart Agriculture*. According to the FAO (Food and Agriculture Organisation), CSA can be defined as approaches:[1]

> *"needed to transform and reorient agricultural systems (…) to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible."*

CSA includes practices for crop, livestock, forestry, and fishery systems. As recommended by the experts and stakeholders consulted in London in September 2019 (see (Baudry et al., 2018)).

3.2 Land-use, land-use change and forestry (lulucf)

[1] FAO, CSA (direct link: www.fao.org/climate-smart-agriculture/en/)

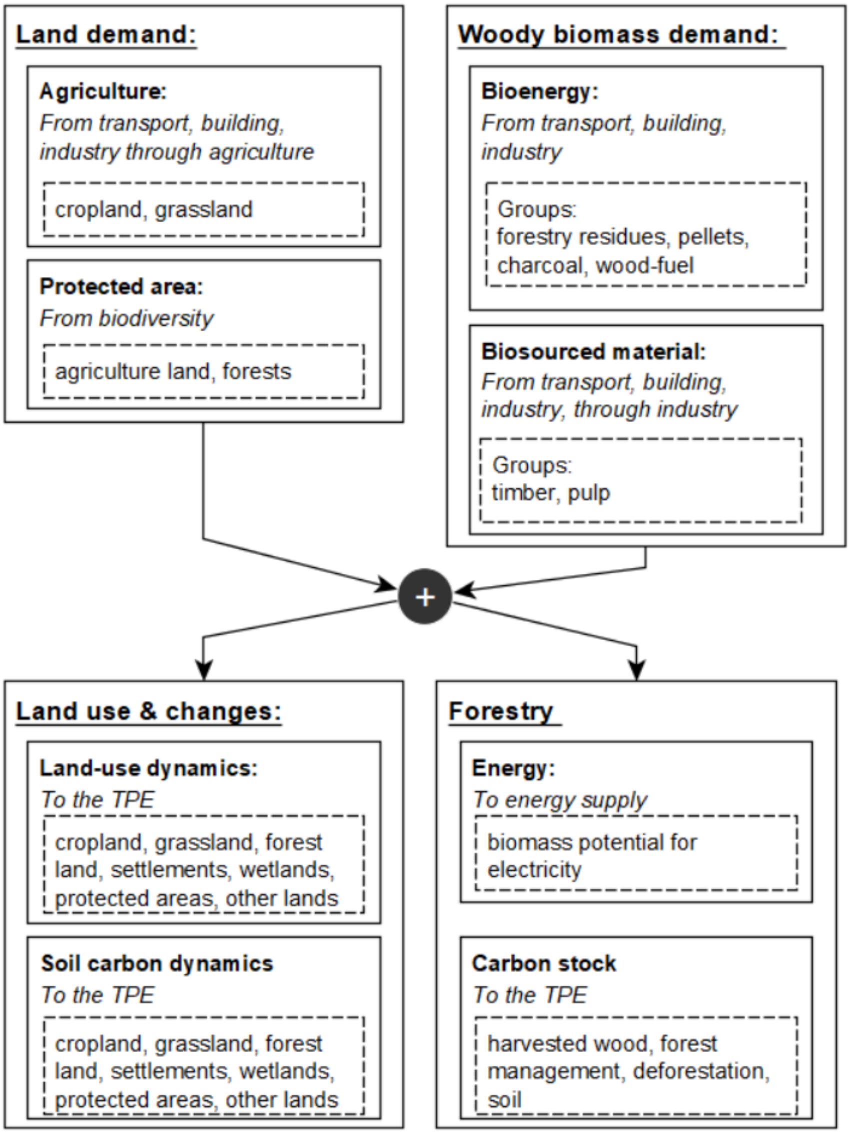

Figure 5 – Lulucf module scope

The lulucf module includes land-use, land-use change and forestry features. It enables to compute the impacts on land resources, including land-use, biodiversity, and the land carbon dynamics. In brief, the lulucf module computes the land availability given the resource demand patterns, leading to free and reallocate land-use (e.g. natural prairies, forest), or leading to crop on forest whenever resource demand overtakes land availability. The land-use related data are based on FAOSTAT while carbon dynamics is based on the UNFCCC official national GHG emissions inventories.

The forestry feature computes the forest dynamics, including the natural fellings, harvest, losses, forest density, tree species and age, etc. Forestry data is mostly based on FAOSTAT and EFI (EFI & FAO, 2015), which are offering an homogeneous level of details for the 28 Member states and Switzerland. Such as agriculture, the forestry module follows a 'climate-smart approach' (Baudry et al., 2019; Nabuurs et al., 2017).

3.3 Biodiversity

Globally, species numbers are in decline, resulting in lower levels of plant and animal life (biodiversity) and threatening the functioning of complex ecosystems. The establishment of protected areas is generally seen as an efficient means to reduce biodiversity loss and to contribute to the global conservation effort. Indeed, this is one of the approaches taken by the Convention on Biological Diversity (CBD) to help deal with biodiversity declines, as well as the approach taken by many national governments and civil society. The CBD and EU committed to an ambitious conservation strategy, aiming to halt biodiversity loss and setting aside at least 17% of terrestrial land managed for the protection of species (CBD, 2010). Protection of biodiversity thus creates a demand on land which is in direct competition with land demands for food production and forestry. This module also takes into account the potential direct impacts of climate change on biodiversity by identifying land preservation targets that are modelled as potentially being the most resilient to climate change. The biodiversity module enables the user to assess the impacts of protecting countries' natural capital, specifically its biodiversity, through land conservation.

Biodiversity dynamics under a changing climate are complex and happen on a spatially explicit scale. For the module to fit into the spatially non-explicit EUCalc framework we make the assumption that the land to be protected is required to remain a refugia under 2°C of global warming (that is 75% of species are still viable to persist in these areas in a 2°C warmer world; Warren et al., 2018) and that the percentage is that of the country as a whole, which tracks the CBD Aichi 2020 policy targets

These lands are then 'frozen' in terms of land-use such that their emissions (positive or negative) are assigned to the biodiversity portion of the module. This avoids the risk of double-counting of emissions between the biodiversity, forestry and agriculture portions of the modules.

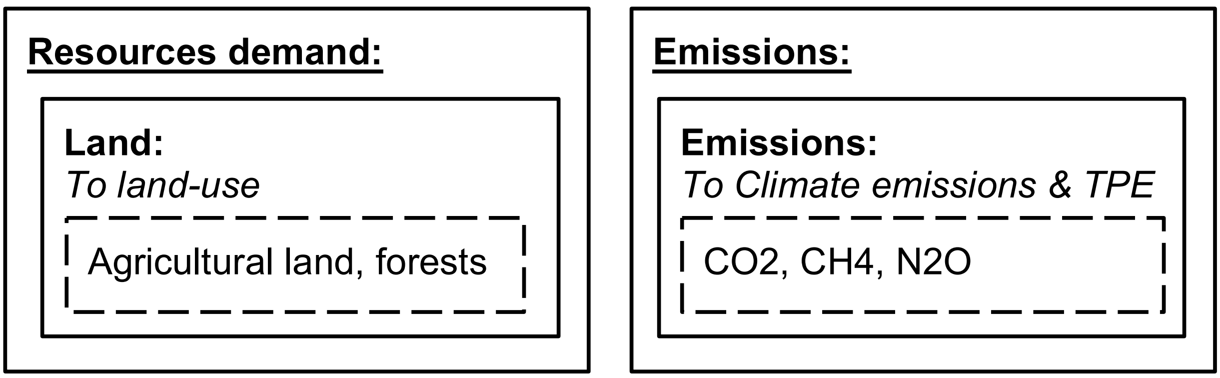

Figure 6 – Biodiversity module overview

3.4 Water

3.4.1 Water resources (supply)

Water resources are mostly driven by precipitation which is dependent on climate (Bisselink et al., 2018). In EUCalc, climate scenarios are determined by a lever that allows the user to set climate ambition for the World. We obtain water availability scenarios thanks to the JRC team. They simulated the local water availability for all relevant European regions with a monthly time-step. The historical datasets cover the period 1981-2010, while the projections run up to 2100, for both the RCP 4.5 and RCP 8.5 scenarios.

The data received is then aggregated to obtain the granularity defined in Section 2 - Overall logic, and matched to the levels given by the Climate lever (see Table 1).

Table 1 – Description of datasets used for future water resources according to the level of the Climate lever

Climate lever	Water resources data description
Level 1	RCP 8.5 dataset
Level 2	RCP 4.5 dataset
Level 3	RCP 4.5 dataset with static value from 2048 to 2050
Level 4	RCP 4.5 dataset with static value from 2030 to 2050

3.4.2 Water demand

According to the data granularity provided by other modules, water demand per sector is disaggregated into the main water intensive industries and products, as detailed in Figure 7. In this model, we exclusively focus on domestic water demands.

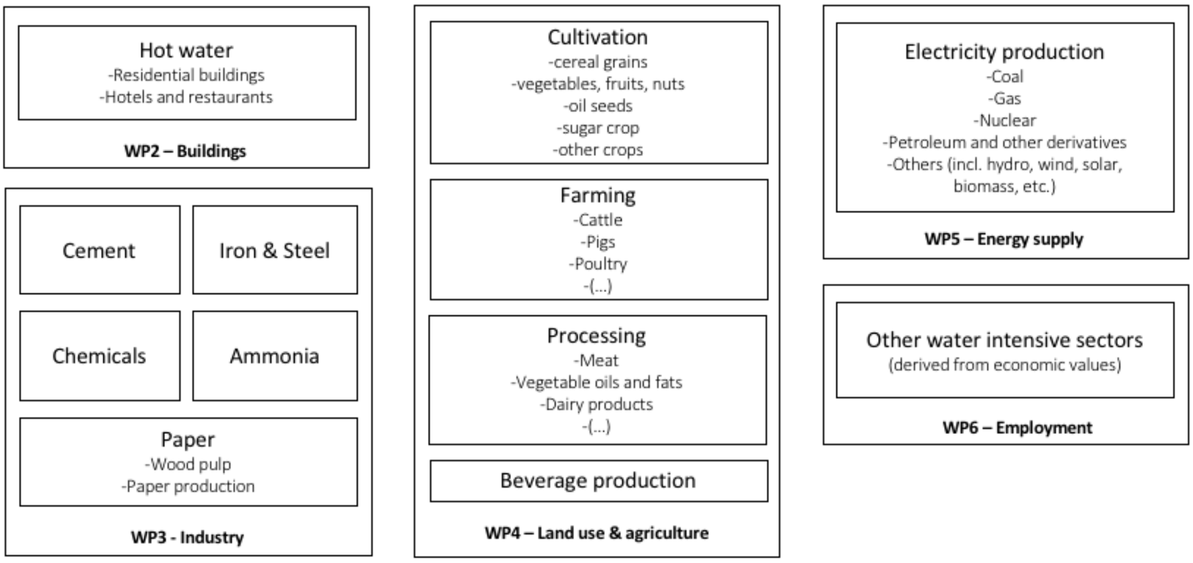

Figure 7 – Sectors and products considered in the water module

3.5 Minerals

3.5.1 Mineral demand

The resource demand within the mineral module has been segregated into two types of demand: demand for mineral and extraction demand for mineral. The latter could vary heavily depending on recycling technologies as well as current stocks of the material close to the manufacture. Inherently, in the future, extraction demand will depend on two things: further development of recycling technologies and geographic proximity to these recycling plants and product manufactures. In the mineral module, mineral demand is calculated using mineral decomposition and then the application of *material switch* and *material efficiency* levers from the Industry module. The recycle rate, represented here by the percentage of recycled material entering the manufacturing process, is calculated but not given as an output.

Thus, only mineral demand is demonstrated by the module and not mineral demand for extraction. Figure 8 below shows the width of product decomposed, which comprises the majority of European demand.

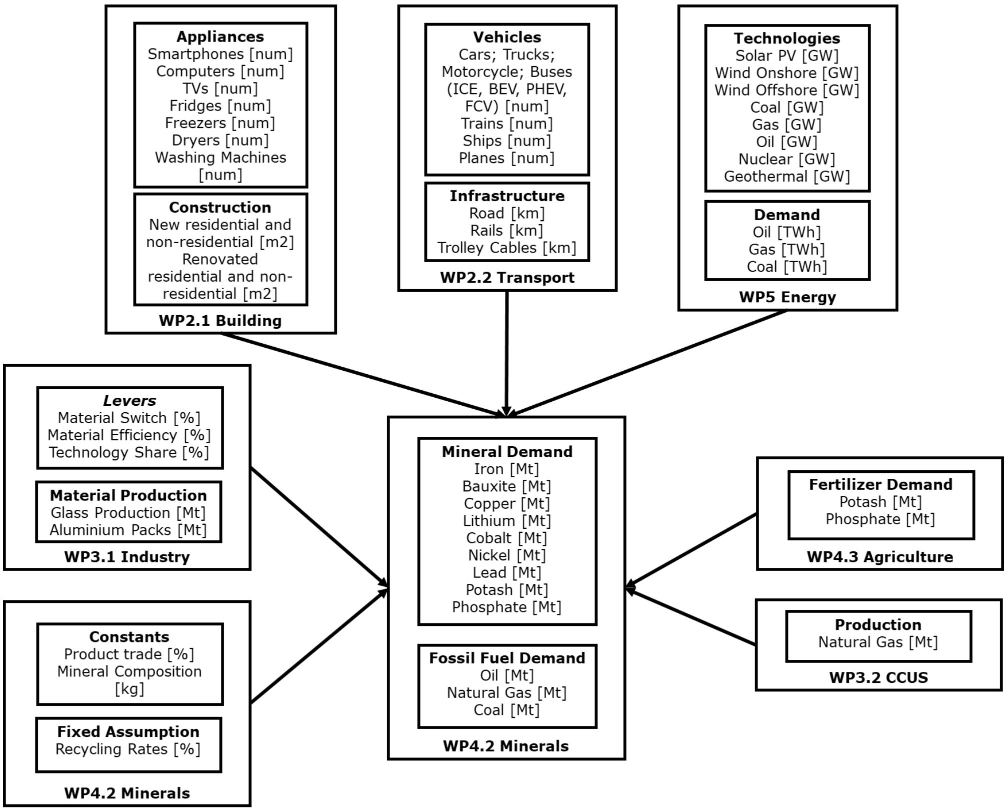

Figure 8 - Pathway to obtain the mineral demand with what is modelled for the release 1.8 and what is envisioned for the final version

3.5.2 Mineral availability

The mineral reserves were taken from the United States Geological Survey (USGS) database in 2015. The database establishes the reserves left in the world for extraction (see appendix I for definition). They are imported as constants and transformed into *European allocated* reserves by dividing the global reserves in 2015 by the global population and multiplying by the EU28+1 country populations. This comes from the fairness approach that each person in the world has the exact same amount of resource available. Using the demand for extraction determined by computing the mineral demand by a scrap ratio, the module computes the percentage of the EU reserves used in the pathway. This aims to provide the reserve left and allocated to Europe in 2050.

Figure 9 below shows the general scope of how mineral availability is computed by associating population and the reserves. This fairness approach determines the impact of the EU demand and not the production, which could be exported, therefore, ought to be accounted in other countries resource inventories.

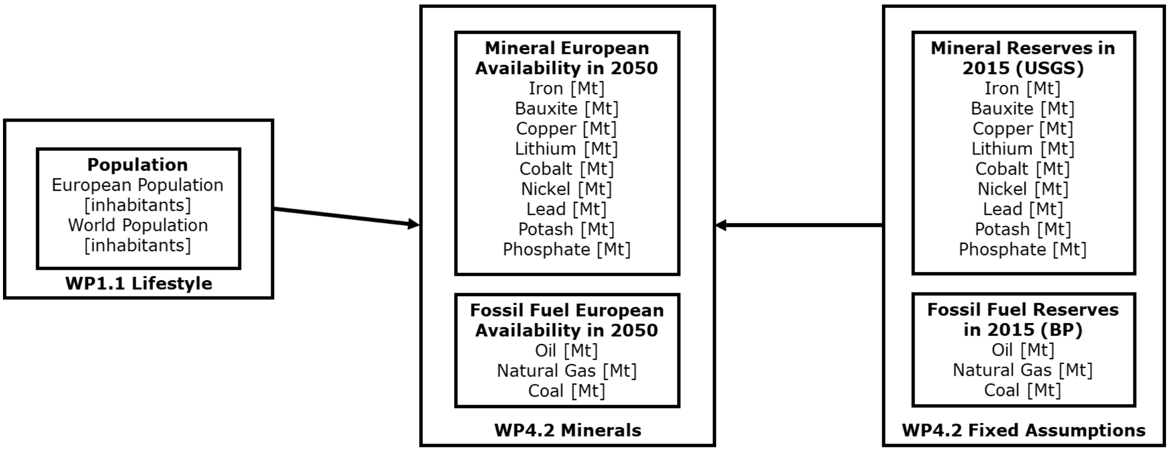

Figure 9 - Pathway to obtain the mineral demand with what is modelled for the release 1.8 and what is envisioned for the final version

4 Interactions with other modules

4.1 Agriculture

The agriculture module is mostly demand-driven and enables the modelling framework to compute the resources requirement to supply food, bioenergy, and biosourced materials (Figure 10).

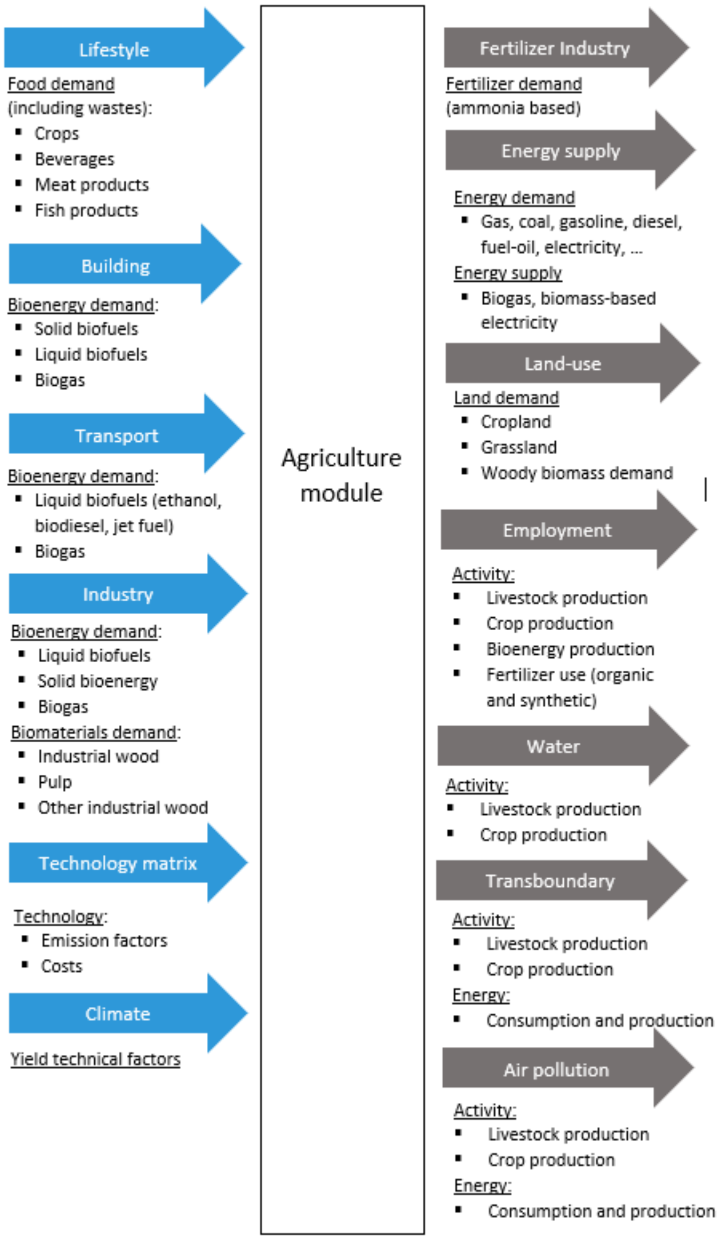

Figure 10 – Agriculture module in brief

Inputs: For each country and each year, the module is gathering the food demand (kcal) from the lifestyle module and the demand for biomass from the transport (TWh), building (TWh), and industry sectors (TWh, t). The climate module also feed agriculture with climate factors that either increase or decrease the crop yields depending on the temperature, crop type, country and year. The technology module feed agriculture with the emission factors regarding energy combustion.

Outputs: the agriculture module then feeds: the fertilizer module (as an industry sub-module) with the demand for synthetic fertilizers (t); the energy supply with the energy demand and supply (Mtoe/TWh); the land demand (ha); the employment module with the biomass production by type and use (e.g. feed, bioenergy), the energy consumption by type (TWh), the self-sufficiency ratio per food group (%), the demand for fertilizer (t) by type (e.g. mineral, organic); the water module with agriculture production (kcal), the livestock population (lsu); the air pollution module with livestock population (lsu), input-use (t, TWh); the GTAP module with commodity production (kcal), livestock population (lsu), input-use (t, TWh); and finally feeds the TPE with the activity, energy and emission data.

Levers (directly) associated to agriculture module: As presented in the EUCalc Deliverable D4.1, the lever associated with the agriculture module includes: the food self-sufficiency, climate-smart crop production system, climate smart livestock production systems, alternative protein sources (livestock), the biomass-uses hierarchy and bioenergy capacity.

A more detailed description of the module interactions is presented in Section 5.

4.2 Land-use, land-use change and forestry (lulucf)

The land-use, land-use change, and forestry module aims at computing the land associated impacts of the explored pathways. Such as its name indicates, it computes the land-use, land-use changes and associated GHG emissions and carbon storage in the soil.

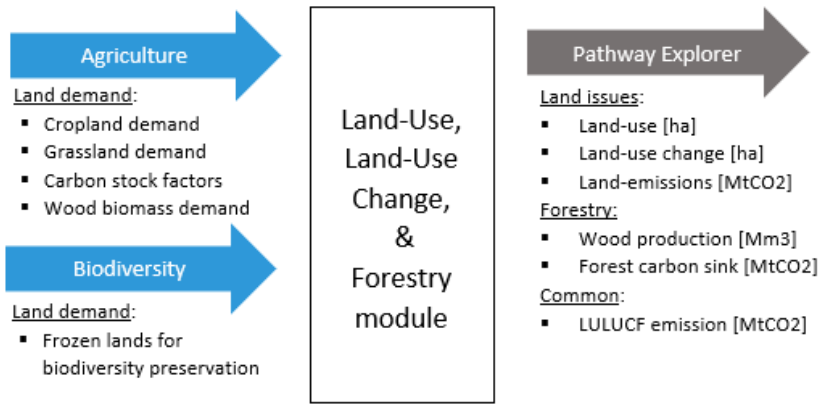

Figure 11 – Land-use, land-use change & forestry module

Inputs: The agriculture and biodiversity modules feed the lulucf with the demand for lands (ha), including agriculture lands (grasslands, cropland expressed in ha) and the amount of protected lands (ha). Finally, the wood biomass demand is provided by the agriculture module, including the demand of the other sectors.

Outputs: the land-use module then feeds: the energy supply module with the forestry biomass supply (TWh) and feeds the TPE with the demand for lands and associated lulucf emission per source (e.g. forests soil and biomass carbon storage).

Levers (directly) associated to the land-use module: As presented in the EUCalc Deliverable D4.1, the lever associated with the land-use module includes: the land-management and climate smart forestry levers.

A more detailed description of the module interactions is presented in Section 5.

4.3 Biodiversity

The biodiversity module takes no inputs from any other modules. It calculates land-demand (ha) based on the lever settings (see EUCalc Deliverable D4.1) and feeds it to the land-use module. The biodiversity module also estimates the GHG emissions from protected and restored areas and feeds them to the climate emissions module as well as the pathway explorer. As mentioned above, lands set aside (frozen) for biodiversity protection are excluded from the GHG emissions calculation in the LULUCF module to avoid double counting.

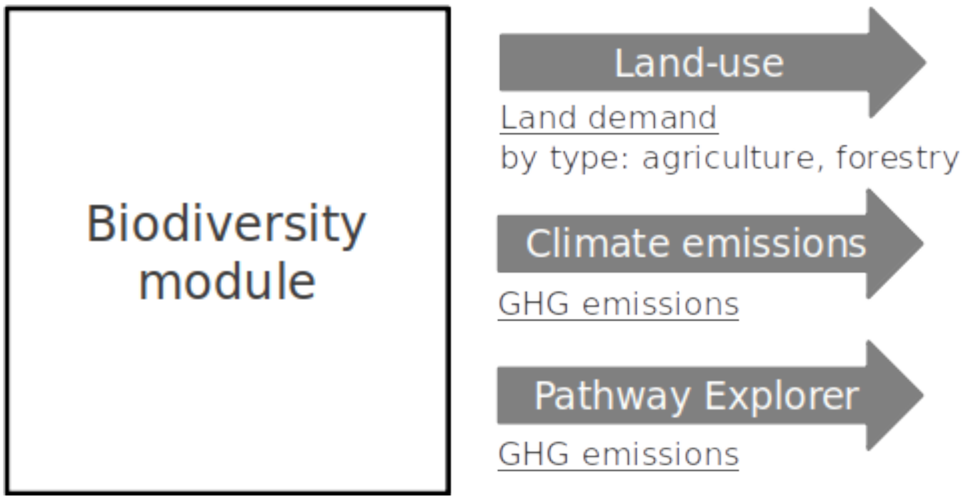

Figure 12 – Biodiversity module in brief

4.4 Water

The water module takes as inputs from other modules several production values demands in their original unit (tons, kWh, etc.). These values are then converted into water demand using water intensities (See section 6, Detailed calculation trees/water). The subsequent outputs are the water withdrawal and water consumption by sector, as well as the water stress by region and semester. The outputs are then shown in the TPE. Interactions with the water module are summarized in Figure 13.

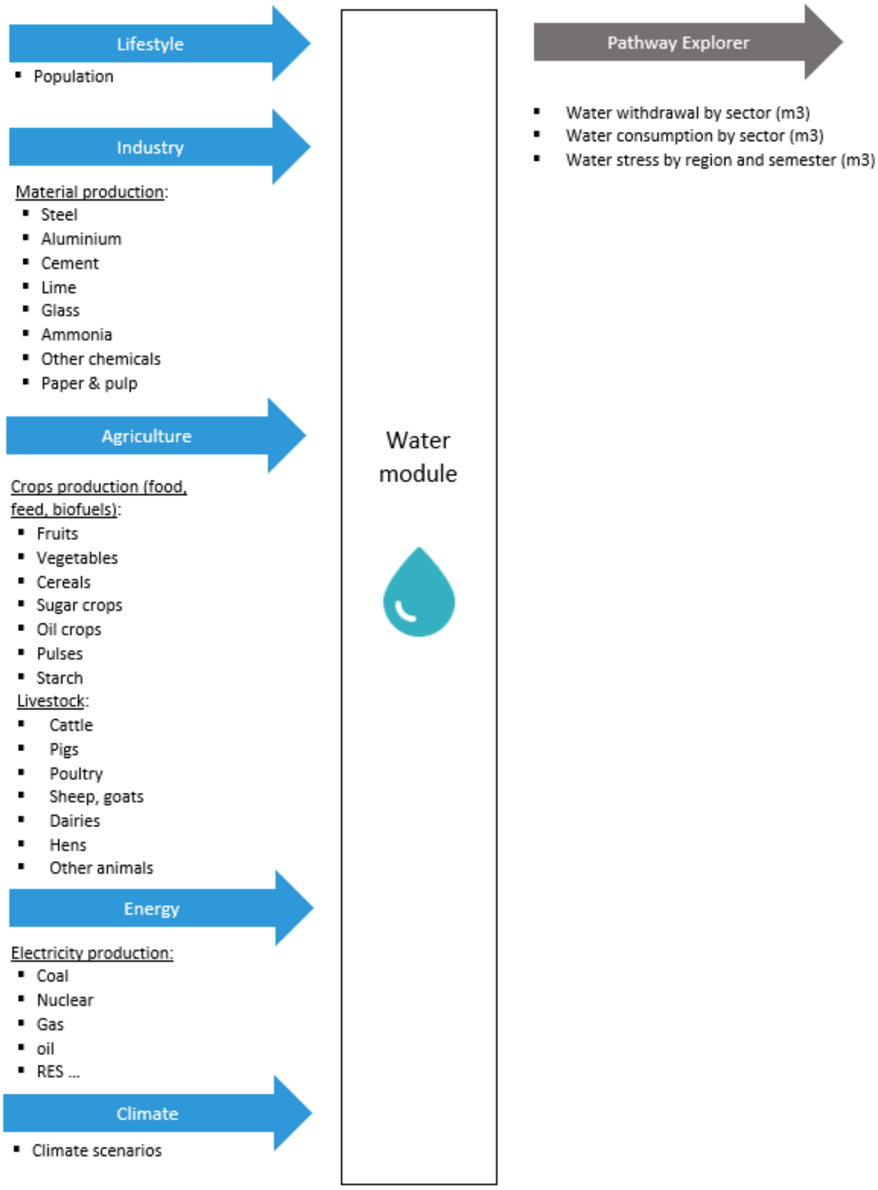

Figure 13 – Overview of the water module interactions

4.5 Minerals

Product demand redefines the main demand sector in material: transport, building, energy, and agriculture. The demand in transport comes under the form of individual vehicles (cars and motorcycles), passenger vehicles (buses), freight vehicles (low, medium and heavy trucks). The demand for transport comes also under the form of large vehicles for either freight or passenger, or both (planes, ships, tramways, trains). The demand in building represents the demand for not only construction materials (residential and non-residential) but also for user consumables (phones, TVs, computers, dryers, fridges, etc.). The technological demand in the energy sector is not accounted for in the industrial sector which accounts for new electricity generation technologies (mainly photovoltaic and wind turbines). Finally, the industry module provides mostly the levers – material switch, material efficiency, product net import, and technology development that are linked to recycling capacity. In the case of agriculture, most of the modelling work have been achieved within the concerned module. Therefore, it is only computed as demand within the mineral module. Finally, the impact on fossil fuel reserves is also demonstrated, though no computation is considered on the inputs.

The outputs are entirely integrated to the Pathway Explorer (TPE). These are associated with both mineral demand in Europe per sector (transport, building, industry, agriculture, electronics, domestic appliance, energy) and mineral availability based on EU allocated reserves.

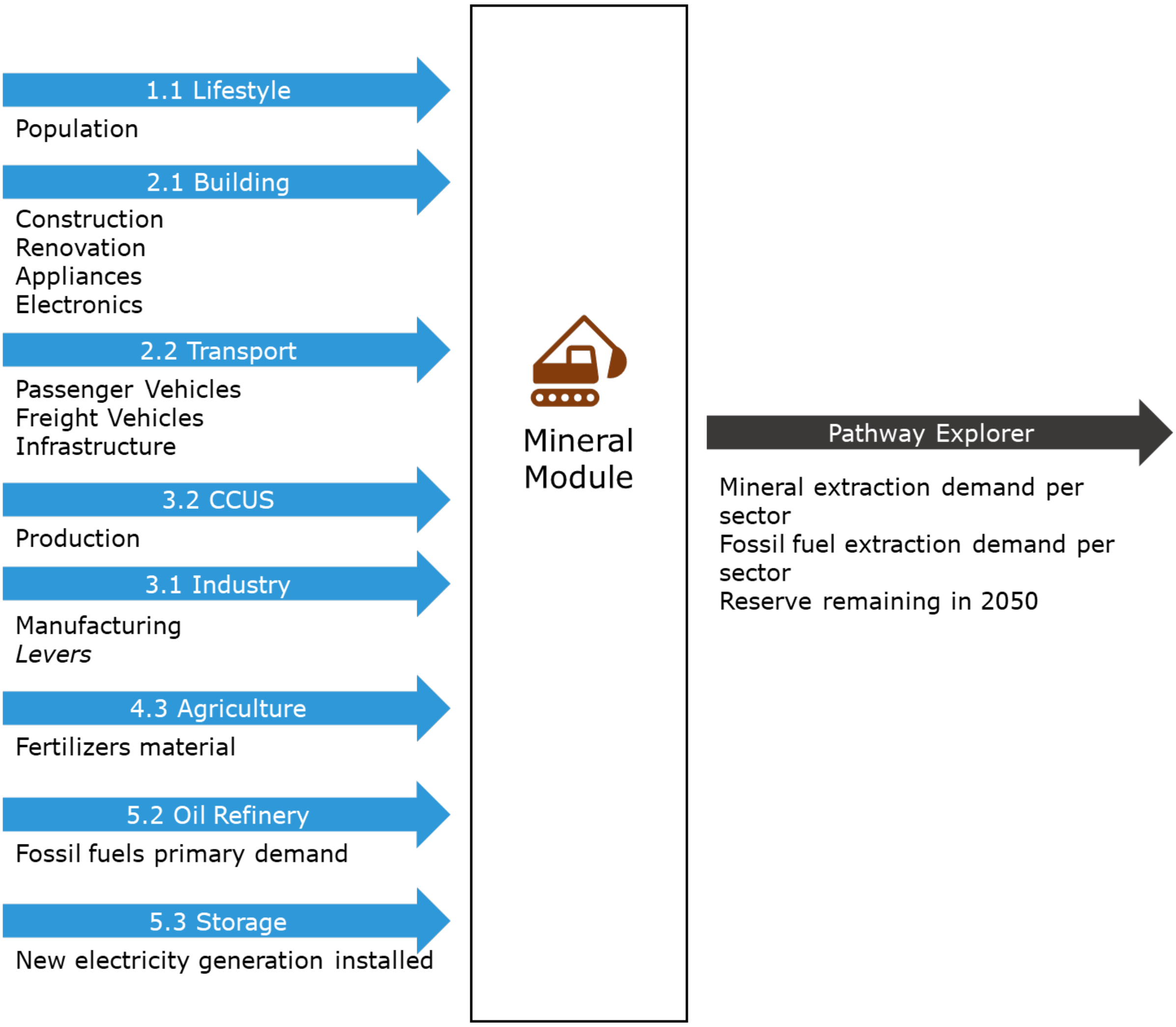

Figure 14 - Scheme showing the relationship with the other modules

5 Inputs and outputs

5.1 Agriculture

5.1.1 Description of the agriculture module inputs

5.1.1.1 Lifestyle's inputs

The lifestyle module provides agriculture with the calorie requirement aggregated by country and by food group, accounting for the wastes of consumers and distributors, expressed in kcal/year (Costa, n.d.)

The calorie requirement is computed from the amount of daily calories demand for an individual to maintain its metabolic rates and comes expressed in kcal/cap/day. The total calorie requirement is based on FAOSTAT database for the period 1990-2015,[2] and the possible range of calorie demand for future scenarios is determined by extending the country-specific Body Mass Index (BMI) & income dependence observed between 1990 and 2013 for each country. The calorie requirements for the higher ambition levels are assumed to be those resulting from a decline in BMI so that overweight levels of a country are, respectively, a quarter of that observed in 2015 and half of that observed in 2015.[3]

The specific diet composition is expressed in kcal/year and is computed from the daily calories demand shared in 26 food groups. The lowest ambition levels are considering a continuation of the current trends, based on FAOSTAT observed data, keeping the country heterogeneous diet composition trends. The higher ambition levels assume health-oriented scenarios which implies the diet composition to converge to typical rations in which all meat does not go over 90g/day; sugars & sweeteners are kept below 10% of calorie consumption; fruits & vegetables consumption represent at least 400g/day. For the most ambition level, a general improvement of all the above calories is assumed so that countries meet the best dietary standards (Springmann et al., 2018). This implies red meat to be kept at no more than 42g/day; sugars & sweeteners at below 5% of calorie intake; and fruits & vegetables consumption to be over 600g/day. The 26 food groups are aggregated by the lifestyle modules following the patterns presented in the following Tables:

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[2] Food and Agriculture Organization (FAO), FAOSTAT, Food Supply - Crops Primary Equivalent / Livestock Primary Equivalent;

Direct link: *http://www.fao.org/faostat/en/#data/CC* / *http://www.fao.org/faostat/en/#data/CL*

[3] See: EUCalc Lifestyle documentation; Direct link : *https://drive.google.com/open?id=1OftuGqv2ML3WM09qGRQNkltaSrGkhoUo*

Table 2 – Meat demand categories in EU28+1

EUCalc	FAOSTAT category	Aggregation rationales in brief
Meat, bovine	Meat, non-dairy cattle Meat, buffalo	Cattle meat represents nearly 17% of the overall meat production in the EU28+1. Cattle is a significant GHG emitter and requires large amount of feed and lands. Buffalos are aggregated with cattle as they only represent 0.04% of meat production.
Meat, poultry	Meat, chicken Meat, duck Meat, goose and guinea fowl Meat, turkey Meat, bird nes	Poultry meat represents nearly 30% of the meat production, including 82% of chicken meat. Added up together, the other poultry represent 5% of the meat production Thus, the other poultry have been aggregated with chicken in a unique poultry meat category.
Meat, pig	Meat, pig	Pig is the most produced and consumed meat in the EU28+1, representing half of the meat production.
Meat, sheep & goat	Meat, sheep Meat, goat	Sheep and goats are only representing 2% of the overall meat production, but as small ruminants, they are using pastureland and are thus considered as a dedicated meat category.
Meat, other animals	Meat, rabbit Meat, game Meat, horse Meat, mule Meat, ass Meat, nes	Added up together, the other meat types represent less than 2% of meat production in tons in EU28+1. Thus, they have been gathered together as a unique meat category other animal.
Milk, dairy (all)	Milk, dairy-cow Milk, dairy-goat	The level of data for milk consumption and production is not homogeneous in FAOSTAT. Thus, EUCalc only considers an aggregated category 'milk dairy' in the agriculture model. Nevertheless, the split of dairy-

	Milk, dairy-sheep Milk, dairy-buffalo	animals is considered in the yields in terms of kcal/animal.
Eggs hens	Eggs, laying hens	No aggregation required, EUCalc uses the FAOSTAT most important level of detail.
Animal fats	Animal fats	No aggregation required, EUCalc uses the FAOSTAT most important level of detail.
Offal	Offal	No aggregation required, EUCalc uses the FAOSTAT most important level of detail.

The animal-based food products are aggregated in 9 groups including bovine, sheep, pig, poultry and other animals, which basically corresponds to the typical aggregation level used by EUROSTAT[4] and FAOSTAT[5]. Adding higher levels of details would have been possible although the implied complexity would not have added significant result improvement. Nevertheless, the FAOSTAT level of details is preserved at the production side, i.e. in the agriculture module considers the split of animal types through the pre-processing of the data. For instance, the bovine yields have been computed given the population of non-dairy cattle and buffaloes.

Table 3 – Food crop-based products demand categories in EU28+1

	EUCalc	FAOSTAT category	Aggregation rationales in brief
Food crop-based	Cereal	Wheat, Maize, Barley, Rye, Oats, Sorghum, Brans, Millet, Other cereals	Cereals are aggregated into a unique food group (excluding rice) for simplification and to meet the objective of real-time computation.
	Rice	Rice	Rice is considered separately as its cultivation involves direct and significant CH4 emissions.

4 Eurostat, statistics explained, Agricultural production - livestock and meat (2018); Direct link: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_livestock_and_meat&oldid=427096

5 Food and Agriculture Organization (FAO), FAOSTAT, Food Supply - Crops Primary Equivalent / Livestock Primary Equivalent;

Direct link: http://www.fao.org/faostat/en/#data/CC / http://www.fao.org/faostat/en/#data/CL

	Oil crops	Rapeseed, Olives, Sunflower, Soya beans, Groundnuts, Cottonseed, Sesame, Other oil crops	Oil crops are aggregated into a unique food group for simplification and to meet the objective of real-time computation.
	Pulses	Beans Peas Other pulses	Pulses are aggregated into a unique food group. We considered a better compromise to gain in computation time rather than maintaining a higher level of information in the present case.
	Starchy roots	Cassava, Potatoes Sweet potatoes, Yams Other roots	Starchy roots are aggregated into a unique food group. We considered a better compromise to gain in computation time rather than maintaining a higher level of information in the present case.
	Vegetable oil	Rapeseed, Olives Sunflower, Palm Soybean, Maize germ, Groundnuts, Cottonseed, Sesame Coconut, Palm, Other oils	Vegetable oil are aggregated into a unique food group for simplification and computation time issues. We considered a better compromise to gain in computation time rather than maintaining a higher level of information in the present case.
	Sugar & Sweeteners	Sugar & Sweeteners	No aggregation required
	Fruits	Multiple fruit variety	FAOSTAT offers a two-aggregation level for fruits and vegetables, a detailed one, and an aggregated one. We selected the most aggregated to gain in computation time.
	Vegetable	Onions Tomatoes and products Vegetables, Other	FAOSTAT offers a two-aggregation level for fruits and vegetables, a detailed one, and an aggregated one. We selected the most aggregated to gain in computation time.

	(Stimulants) Tea Coffee Cocoa	(Stimulants) Tea Coffee Cocoa	Although stimulants are mainly imported from outside of Europe, the agriculture module will estimate the embedded GHG emissions associated with the stimulant's consumption.

The crop-based food products are aggregated into 13 groups including cereals, rice, oil crops, pulses, starchy roots, sugar, sweeteners, vegetable oil, fruits, vegetables and stimulants (coffee, tea, cocoa). Alcoholic beverages accounts for another 4 extra food groups that includes wine, beer, distilled and fermented alcohol. Adding higher levels of details would have been possible although the implied complexity would not have added significant result improvement. Such as the livestock-based products, the highest level of detail is preserved at the production side, i.e. the agriculture module considers the split of crop types in all computation for the period 1990-2015 and assumes fixed split by 2050.

Alcoholic beverages are taken separately in order to properly modelling the possible by-products supply that can be used as bioenergy, animal feed, fertilizer and other aggregated uses (Table 4).

Table 4 – Alcoholic beverages demand categories in EU28+1

	FAOSTAT category	EUCalc	Aggregation rationales in brief
Alcoholic beverages	Wine	Wine	Wine requires large land areas and yields significant number of by-products such as marc and lees that can be used as bioenergy and agronomy feedstock.
	Beer	Beer	Beer requires lots of cereals and yields significant number of by-products such as cereal meals and yeast that can be used as animal feed.
	Distilled alcohol	Distilled alcohol	No aggregation required, EUCalc uses the FAOSTAT most important level of detail.
	Fermented alcohol	Fermented alcohol	No aggregation required, EUCalc uses the FAOSTAT most important level of detail.

Finally, the lifestyle module is providing the assumed amount of food waste that is coming from the consumers and distribution, for each food group, also expressed in kcal/year. The average fraction of food waste in Europe per food group are taken from Gustafsson et al. (2013) and are assumed to be the same across the EU members, given the lack of a more detailed database. Thus, the absolute value of waste varies from country to country given the different dietary compositions and population.

For the least ambition level, food waste at the consumer level evolves following historical patterns of more food demand leading to more food waste. This implies an average increase of 25% in relation to the food waste in 2015 in the EU28+1. For the third ambitious levels, it is assumed that countries achieve food waste reductions at the consumer level of 50% by 2050, which means complying with the SDG target 12.3 (originally set by 2030). This translates to an average food waste for EU28+Switzerland of 410 kcal. For the highest ambition level countries achieve food waste reductions at the consumer level of 75% by 2050, thus overcoming the SDG target 12.3 by 2030. This translates to an average food waste for EU28+Switzerland of 200 kcal.

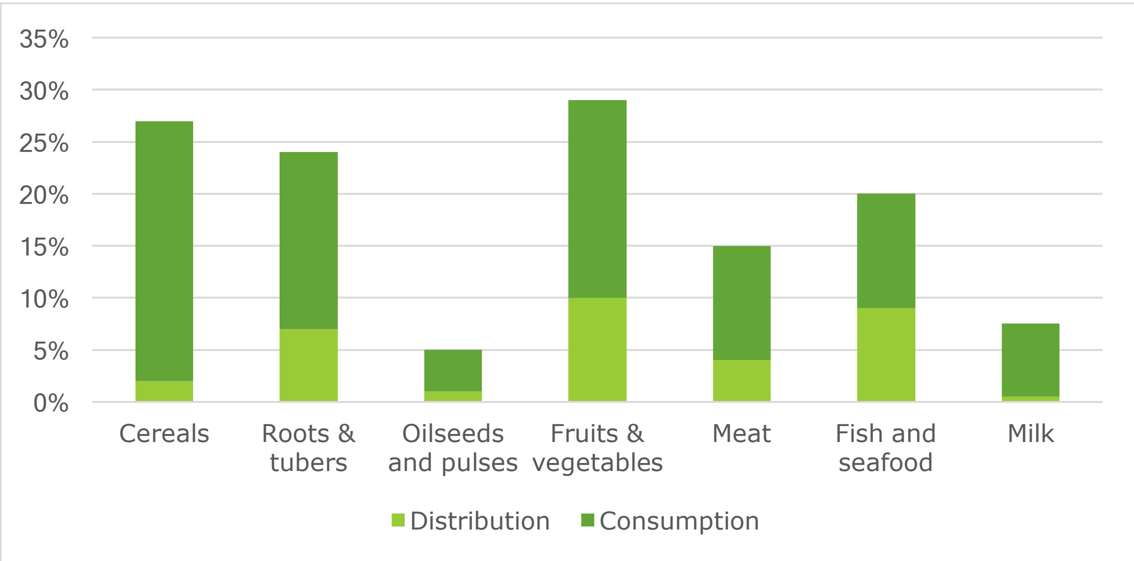

Figure 15 – Food wastes by food group in Europe in 2012 (Gustafsson et al., 2013)

It is worth mentioning that the food-waste from the production side is considered as an agriculture feature, included in the Climate-Smart Cropping and livestock production systems levers, following a similar approach (Baudry et al., 2019, p. 4).

5.1.1.2 Building's inputs

The building module provides agriculture with the bioenergy demand by type expressed in TWh, coming from the heating demand, excluding the district heating share. The heating demand in the building sector relies on the living space demand per person, the insulation quality, the average indoor temperature, the district heating share, the heating systems efficiency and finally the switch from fossils towards renewable energy, such as solar hot water systems and bioenergy.

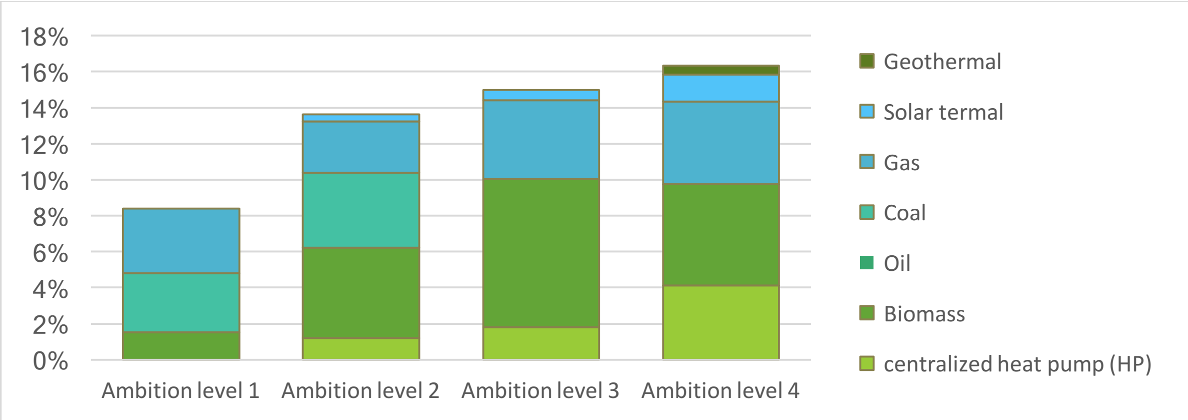

Figure 16 – Ambition levels for district heating penetration (%) by 2050 in the EU28+1

The district heating share as well as the fuel switch levers will directly affect the demand for bioenergy. The district heating share of the building module is based on the "Heat Roadmap Europe" project (Nijs et al., 2017). The later provides the district heating contribution as a whole, and by technology. As shown by Figure 16, depending on the lever setting, the biomass can contribute from 18 (level 1) to 55% (level 3) by 2050 in the EU28+1 as district heating fuel.

The switch from fossils towards renewable energy sets the energy mix for heating purposes, excluding district heating. The lever assumes a decrease of fossils fuels contribution, gas, oil and coal, from 5 to 95%, which would be substituted by bioenergy and heat pumps. Depending on the ambition level, biomass is assumed to substitute from 30 to 70% of the fossil fuels phase out.

The lever setting for living space demand per person, heating systems efficiency, the average indoor temperature, the renovation rate as well as the average insulation quality for new and existing constructions will drive the total energy demand and thus affect the bioenergy demand. As a result, the building sector will drive the bioenergy demand associated with the heat demand, expressed in TWh:

Table 5 – Bioenergy demand in the building sector in EU28+1

Bioenergy	Bioenergy type	EUCalc	Aggregation rationales in brief
	Solid bioenergy	Pellets & aggregates	Pellets regroup pellets, chips and other woody aggregates as the FAOSTAT database as well

		as EUROSTAT do not provide a detailed data base for EU28+1 since 1990
	Wood fuel	Wood fuel production and trade balance is provided by FAOSTAT, no aggregation required
Gaseous bioenergy	Biogas	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990, no aggregation required

How woody biomass demand from building or industry is estimated is detailed in WP2 and WP3 associated deliverables (See Deliverable D3.1).

5.1.1.3 Transport's inputs

The transport module provides agriculture with the bioenergy demand for transportation by type expressed in TWh/year/country. Such as the building sector, the transport module involves both direct and indirect drivers for bioenergy consumption through lifestyle and technology patterns.

<u>Direct drivers</u>: through the fuel mix lever, the transport sector sets the demand for the different fuels, including bioenergy. In the transportation scenarios, the demand for liquid biofuels range between 7% to 50% (Ecorys et al., 2017), which represents the current situation and the most ambitious biofuel scenario for Europe with 147 Mtoe by 2050 in volume against 14 in 2015.

<u>Indirect drivers</u>: The passenger travel distance is driven by the lifestyle patterns, through the transportation demand, expressed in passenger-kilometre. The vehicle technology mix, and thus fuel mix also affect the demand for bioenergy through the share of ICE vehicles (Internal Combustion Engine) for which biofuel blending are computed.

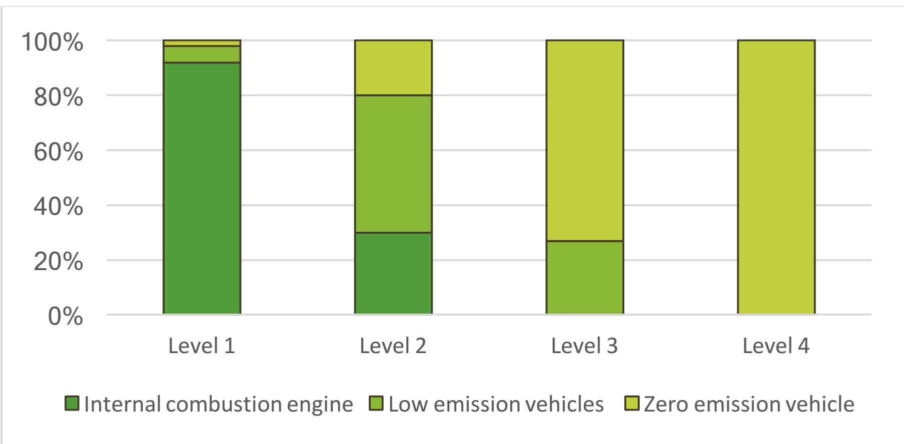

Figure 17 – Ambition levels for ICE phase out in the transport sector

Figure 17 illustrates the ambition levels of the transport sector regarding the phase out of ICE vehicles. Ambition levels presents the evolution of the sale of new cars from 2015 to 2050. The most ambitious levels imply a fast phase out of ICE vehicles, and thus a relative decrease of biofuel contribution to the transportation sector. Other drivers of bioenergy consumption in the transport sector includes the modal share (e.g. split between bus, metro, cars, etc.), the occupancy rate, and the passenger-vehicle efficiency.

Table 6 – Bioenergy demand in the building sector in EU28+1

	Bioenergy type	EUCalc	Aggregation rationales in brief
Bioenergy	Liquid bioenergy	Biodiesel	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990, no aggregation required
		Biogasoline	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990, no aggregation required
		Biojetfuel	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990, no aggregation required
	Gaseous bioenergy	Biogas	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990, no aggregation required

Table 6 presents the variables that are sent from transport to the agriculture module. The agriculture module then sets the technology mix and the feedstock mix to supply the bioenergy demand given the lever setting.

5.1.1.4 Industry's inputs

Industry in brief: The industry module is gathering together the demand for consumption goods from the lifestyle (e.g. appliances), building sector (e.g. construction) and transport sector (e.g. cars), and computes a demand for raw material and energy, including bioenergy and biosourced materials. The extent of the energy and material demand depends on the consumption levels, the self-sufficiency ratio, and the technology-mix & efficiency across multiple industries (e.g. steel, cement, chemicals, paper, aluminium, etc.). Such as the transport and building sectors, some levers have a direct impact on the demand for bioenergy and biosourced materials, while others have indirect impacts.

Direct drivers: the material switch lever allows the industry to switch from fossil and mineral based raw material to biosourced materials across multiple industrial sectors that are modelled. For instance, the construction industry can switch from steel to wood structures in some extent, based on the EU CTI 2050 Roadmap Tool[6] (2018) estimates. The energy carrier lever switch operates through a common pattern which is illustrated in Figure 18.

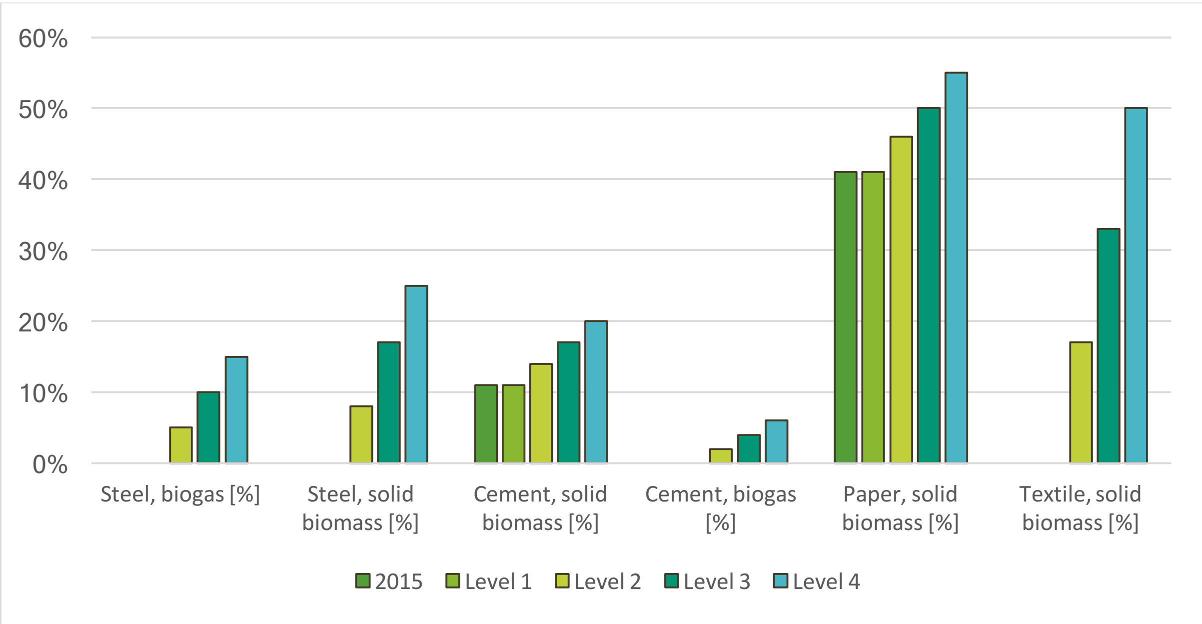

Figure 18 – Ambition levels for bioenergy penetration in several industries

Figure 18 illustrates how the biomass may contribute to supply the energy demand of different industries depending on the lever setting. The higher the ambition, the higher the bioenergy contribution. It is worth mentioning that the extent of this contribution not only depend on the industry type but also on the technology that is used.

Indirect drivers: Material efficiency, technology share & recycling are the main indirect drivers for biomass demand, for both bioenergy and biosourced materials. In other words, the higher the material efficiency, the more advanced the technology and recycling, the lower the overall demand for raw materials and energy, for both fossil and biosourced ones.

Table 7 presents the interface between the industry and agriculture modules. Liquid biomass as feedstock (e.g. ethanol) remains to be implemented.

[6] EU CTI 2050 Roadmap Tool (2018), Direct link: *https://europeanclimate.org/wp-content/uploads/2018/09/EU-2050-CTI-Industry-sector.pdf*

Table 7 – Bioenergy and biosourced biomass demand from the industry sector in the EU28+1

	Bioenergy type	EUCalc	Aggregation rationales in brief
Bioenergy & biosourced materials	Solid biomass	Wood pulp	Wood pulp consumption and production is provided by FAOSTAT for each EU members since 1990, no aggregation required
		Timber	Timber is converted in industrial wood, that is provided by FAOSTAT for each EU members since 1990
	Gaseous bioenergy	Biogas (energy)	Biogas consumption and production is provided by EUROSTAT for each EU members since 1990. No data base provides the distinguished biogas flows for bioenergy and biomaterial at the country level, they are assimilated in the model. Biogas is upgraded depending on its use in the energy supply module.
	Gaseous biomaterial	Biogas (feedstock)	

How woody biomass demand from building or industry is estimated is detailed in WP2 and WP3 associated deliverables (See Deliverable D3.1).

5.1.1.5 Climate inputs

The evolution of the climate and temperature will affect the crop yields, either positively or negatively depending on the European regions. Using the FAO factors developed for the 2050 alternative pathways for food and agriculture (FAO, 2018), the climate module provides the factors affecting each of the crop yields in a different extent depending on the European region and the crop type.

Table 8 – Crop yield factors implied by climate change in High income countries

		Crop type	Level 1	Level 2	Level 3	Level 4
		Scenario	**RCP 8.5**	**RCP 4.5**	**RCP4.5 2048**	**RCP4.5 2030**
Crop yields	High incomes	Cereal	103	102	102	102
		Rice	103	103	103	103
		Oil crop	94	101	101	101
		Pulses	94	101	101	101
		Starchy roots	94	101	101	101
		Sugar crops	94	101	101	101
		Fruits	98	102	102	102
		Vegetables	88	97	97	97
		Energy crops	94	101	101	101
		Microalgae	94	105	105	105
	Europe, others	Cereal	91	98	98	98
		Rice	96	100	100	100
		Oil crop	100	100	105	105
		Pulses	96	96	100	100
		Starchy roots	90	90	97	97
		Sugar crops	96	96	100	100
		Fruits	102	102	100	100
		Vegetables	94	94	99	99
		Energy crops	96	96	100	100

Table 8 presents how the climate change scenario will affect the yields in the agriculture module. A 100 ratio refers to a status-quo situation; values under 100 refers to a decrease of the yields whereas values over 100 refers to an increase. For instance, 90 refers to a 10% decrease of the yield by 2050 compared to 2012. The later mostly depends on the rest of the World emission patterns. Based on FAO, these climate impact factors are divided for Europe between high incomes country and the rest of Europe. The climate module setting considers RCP8.5 and three variants of RCP 4.5, for which sub-scenarios start to diverge by 2030 and 2048. For example, Level 4 means that the factors by 2050 are on the same trajectory until 2030, and then constant until 2050 .

5.1.2 Description of the agriculture module outputs

5.1.2.1 Synthetic fertilizer demand

Given the demand for crops to supply bioenergy, biosourced materials, food and animal feed products, the agriculture module is computing the demand for fertilizer. Fertilizers can be supplied through 4 main sources: (1) synthetic nitrogen; (2) manure application; (3) symbiotic fixation through crop rotation;(4) digestate application (Poux and Aubert, 2018). The extent of each fertilizer contribution relies on the actual deployment of climate-smart practices, either intensive or extensive. The synthetic fertilizer demand is supplying the mineral fertilizer industry (i.e. included in the industry module), expressed in metric tons.

Table 9 – Nitrogen balance in the EU28

Nitrogen source	EUCalc module	Main drivers in EUCalc
Synthetic fertilizers	Output Industry	- Intensive agriculture practices
Manure	Internal variable	Livestock population, agriculture practices
Symbiotic fixation	Internal variable	Extensive agriculture practices
Atmospheric position	Internal variable	Grassland management
Others	Not modelled	/

Such as the other industrial products, the industry module is computing the resources requirement to supply synthetic fertilizers, while considering a set of production pathways – lever dependant – that will drive a demand for gas, biogas and hydrogen.

5.1.2.2 Land-use, land-use change and forestry module

Given the demand for bioenergy, biosourced materials, food and animal feed products, the agriculture module is computing the demand for agriculture lands, including cropland and grassland. The cropland demand is driven by the demand for food, feed, bioenergy and biosourced material. The demand for grassland depends on the ruminant livestock population. The extent of the cropland and grassland demand, expressed in ha (hectare) thus rely on the other modules demand for biomass and food, and on the choice for agriculture practices (lever dependent).

Table 10 – Land demand from the agriculture module

Land	EUCalc module	Main drivers in EUCalc
Grassland	Output for LULUCF	Diets, climate smart livestock, livestock population
Cropland…	Output for LULUCF	Diets, biomass demand
…dedicated to human food	Output for the TPE	Diets
…dedicated to livestock feed	Output for the TPE	Diets, Livestock production practices
…dedicated to bioenergy	Output for the TPE	Biomass demand (transport, building, industry, lifestyle)
…dedicated to non-food	Output for the TPE	Alcohol beverages demand, biomass demand (industry)

Beyond the land demand, the agriculture module also computes the demand for wood expressed in roundwood equivalent in million cubic meter (Mm3). The wood demand is coming from the solid biomass demand. The scope of the LULUCF module is further detailed in the Section 5.2.

5.1.2.3 Energy supply module

Given the demand for agricultural commodities, the module is computing the demand for energy by carrier, expressed in TWh.

Table 11 – Energy demand from agriculture

Energy carrier	Main drivers in EUCalc
Diesel	Agriculture practice, net-import, food/biomass demand
Gasoline	Agriculture practice, net-import, food/biomass demand
Natural gas (including LNG, LPG)	Agriculture practice, net-import, food/biomass demand
Fuel oil	Agriculture practice, net-import, food/biomass demand
Coal	Agriculture practice, net-import, food/biomass demand
Electricity	Agriculture practice, net-import, food/biomass demand
Total	Agriculture practice, net-import, food/biomass demand

The sectoral energy demand is added up in the energy supply modules (i.e. electricity, storage and oil refinery), which enables the modelling framework to compute the energy and power unit capacity as well as the GHG emissions from energy production.

Such as the other sectoral energy demand, the energy supply module is adding up the energy demands and computes the resources requirement. The electricity mix is lever dependent, which set the power unit capacity. Given the balancing and typical electricity consumption patterns, the electricity carbon footprint can be computed and allocated to each of the sector respectively.

Through the climate smart agriculture practice, the supply of biogas may exceed the demand that is triggered through the other modules, namely building, industry, and transport. It is thus assumed that this extra biogas is used by the energy supply module for an upgrade and injection in the gas network. Similarly, the climate smart forestry lever set the harvest rate. When the wood supply exceeds the demand, the extra harvested wood is used as biomass-based electricity feedstock or exports.

5.1.2.4 Water management

The water management module requires activity data to assess the water demand associated with the crop and livestock-based production. Using water intensity factors, and given the global temperature, the water module is computing the irrigation needs for the production of crops, livestock and biomass.

Table 12 – Activity data sent to the water module

Activity data	Production	Unit	Main drivers in EUCalc
Livestock population	Bovine	lsu	Agriculture practice, net-import, food/biomass demand
	Pig	lsu	Agriculture practice, net-import, food/biomass demand
	Poultry	lsu	Agriculture practice, net-import, food/biomass demand
	Sheep	lsu	Agriculture practice, net-import, food/biomass demand
	Hens	lsu	Agriculture practice, net-import, food/biomass demand
	Milk	lsu	Agriculture practice, net-import, food/biomass demand
	Other animals	lsu	Agriculture practice, net-import, food/biomass demand
Crops	Cereal	kcal	Agriculture practice, net-import, food/biomass demand
	Oil crop	kcal	Agriculture practice, net-import, food/biomass demand
	Pulses	kcal	Agriculture practice, net-import, food/biomass demand
	Starchy roots	kcal	Agriculture practice, net-import, food/biomass demand
	Sugar crops	kcal	Agriculture practice, net-import, food/biomass demand
	Fruits	kcal	Agriculture practice, net-import, food/biomass demand
	Vegetables	kcal	Agriculture practice, net-import, food/biomass demand
	Cellulosic energy crops	kcal	Biomass-use hierarchy, bioenergy demand, resource availability, alternative protein sources

Other	Insect biomass	kcal	Alternative protein sources, livestock population
	Algae biomass	kcal	Alternative protein sources, livestock population

5.1.2.5 Employment module

Such as the water module, the employment module requires the activity data stemming from the agriculture module.

Table 13 – Activity data sent to the employment module

Energy carrier	TWh	Unit	Main drivers in EUCalc (not exhaustive)
Energy demand	Diesel	TWh	Agricultural practices, food, biomass demand
	Gasoline	TWh	Agricultural practices, food, biomass demand
	Natural gas	TWh	Agricultural practices, food, biomass demand
	Fuel oil	TWh	Agricultural practices, food, biomass demand
	Coal	TWh	Agricultural practices, food, biomass demand
	Electricity	TWh	Agricultural practices, food, biomass demand
Bioenergy supply	Liquid bioenergy	TWh	Bioenergy demand (transport, industry, building)
	Solid bioenergy	TWh	Bioenergy demand (transport, industry, building)
	Biogas	TWh	Bioenergy demand (transport, industry, building)
Fertilizer	Crop based	t	Agricultural practices, food, biomass demand
	Animal based	t	Agricultural practices, food, biomass demand

	Mineral based	t	Agricultural practices, food, biomass demand
Feed production	Processed crop based	kcal	Practices, alternative protein, food demand
	Unprocessed crop based	kcal	Practices, alternative protein, food demand
	Processed animal based	kcal	Practices, alternative protein, food demand
	Unprocessed animal based	kcal	Practices, alternative protein, food demand
Net-import balance	Processed crop based	%	Self-sufficiency, alternative protein, food demand
	Unprocessed crop based	%	Self-sufficiency, alternative protein, food demand
	Processed animal based	%	Self-sufficiency, alternative protein, food demand
	Unprocessed animal based	%	Self-sufficiency, alternative protein, food demand

The employment module uses inputs from the sectoral modules (e.g. Lifestyles, Buildings, Transport, Industry, Agriculture, Electricity) to reproduce the scenario defined by the user but through a macroeconomic model, in order to compute the employment impacts per economic sector and per educational attainment of workers of this scenario. Using these sectoral inputs, indicators of transition are computed to compare against a reference scenario simulated using the Computable General Equilibrium model GEMINI-E3. The indicators of transition are used to shock the reference scenario and reproduce the scenario defined by the user to deliver the employment impacts.

5.1.2.6 Climate

The agriculture module is providing the climate module with the GHG emissions by source, such as livestock manure treatment, enteric fermentation and so on (i.e. CO_2, CH_4 and N_2O). The climate module is computing the CO_2 emission equivalent from CH_4 and N_2O.

5.1.2.7 Air pollution

In order to assess the air pollutant emissions, the agriculture module is providing the activity data to the air pollution module.

Table 14 – Activity data sent to the air pollutant module

Activity data	Production	Unit	Main drivers in EUCalc
Livestock population	Bovine	lsu	Agriculture practice, net-import, food/biomass demand
	Pig	lsu	Agriculture practice, net-import, food/biomass demand
	Poultry	lsu	Agriculture practice, net-import, food/biomass demand
	Sheep	lsu	Agriculture practice, net-import, food/biomass demand
	Hens	lsu	Agriculture practice, net-import, food/biomass demand
	Milk	lsu	Agriculture practice, net-import, food/biomass demand
	Other animals	lsu	Agriculture practice, net-import, food/biomass demand
Energy demand	Diesel	TWh	Agricultural practices, food, biomass demand
	Gasoline	TWh	Agricultural practices, food, biomass demand
	Natural gas	TWh	Agricultural practices, food, biomass demand
	Fuel oil	TWh	Agricultural practices, food, biomass demand
	Coal	TWh	Agricultural practices, food, biomass demand
	Electricity	TWh	Agricultural practices, food, biomass demand
	Bioenergy (by type)	TWh	Agricultural practices, food, biomass demand
Input-use	Fertilizers	t	Agricultural practices, food, biomass demand
	Pesticides	t	Agricultural practices, food, biomass demand

5.1.2.8 GTAP

The agriculture sends activity and energy data to the GTAP module.

Table 15 – Activity data sent to the GTAP module

Activity data	Production	Unit	Main drivers in EUCalc
Livestock population	Bovine	lsu	Agriculture practice, net-import, food/biomass demand
	Pig	lsu	Agriculture practice, net-import, food/biomass demand
	Poultry	lsu	Agriculture practice, net-import, food/biomass demand
	Sheep	lsu	Agriculture practice, net-import, food/biomass demand
	Hens	lsu	Agriculture practice, net-import, food/biomass demand
	Milk	lsu	Agriculture practice, net-import, food/biomass demand
	Other animals	lsu	Agriculture practice, net-import, food/biomass demand
Crops	Cereal	kcal	Agriculture practice, net-import, food/biomass demand
	Oil crop	kcal	Agriculture practice, net-import, food/biomass demand
	Pulses	kcal	Agriculture practice, net-import, food/biomass demand
	Starchy roots	kcal	Agriculture practice, net-import, food/biomass demand
	Sugar crops	kcal	Agriculture practice, net-import, food/biomass demand
	Fruits	kcal	Agriculture practice, net-import, food/biomass demand
	Vegetables	kcal	Agriculture practice, net-import, food/biomass demand

	Cellulosic energy crops	kcal	Biomass-use hierarchy, bioenergy demand, resource availability, alternative protein sources
Other	Insect biomass	kcal	Alternative protein sources, livestock population
	Algae biomass	kcal	Alternative protein sources, livestock population
Meat	Bovine	kcal	Agriculture practice, net-import, food/biomass demand
	Sheep	kcal	Agriculture practice, net-import, food/biomass demand
	Pigs	kcal	Agriculture practice, net-import, food/biomass demand
	Poultry	kcal	Agriculture practice, net-import, food/biomass demand
	Other animals	kcal	Agriculture practice, net-import, food/biomass demand
	Offal	kcal	Agriculture practice, net-import, food/biomass demand biomass-use hierarchy, resource availability
	Fats	kcal	Agriculture practice, net-import, food/biomass demand biomass-use hierarchy, resource availability
	Milk	kcal	Agriculture practice, net-import, food/biomass demand
	Eggs	kcal	Agriculture practice, net-import, food/biomass demand
Energy demand	Diesel	TWh	Agricultural practices, food, biomass demand
	Gasoline	TWh	Agricultural practices, food, biomass demand
	Natural gas	TWh	Agricultural practices, food, biomass demand
	Fuel oil	TWh	Agricultural practices, food, biomass demand
	Coal	TWh	Agricultural practices, food, biomass demand
	Electricity	TWh	Agricultural practices, food, biomass demand
	Bioenergy (by type)	TWh	Agricultural practices, food, biomass demand

Input-use	Fertilizers	t	Agricultural practices, food, biomass demand
	Pesticides	t	Agricultural practices, food, biomass demand

5.1.2.9 Transition Pathway Explorer (TPE)

The Pathway Explorer enables the user to display the modelling framework output, which consists in the following regarding the agriculture module:

Direct GHG emission: As shown by Table 16, the agriculture module provides the direct GHG emissions per activity and by gas type, including CH_4, N_2O and CO_2.

Table 16 – TPE, direct GHG emissions

Direct emissions		Unit
CH_4 emission	Enteric fermentation	Mt
	Rice cultivation	Mt
	Manure treatment	Mt
	Crop residues	Mt
N_2O emission	Manure treatment	Mt
	Manure applied to soil	Mt
	Manure left on pasture	Mt
	Crop residues	Mt
CO_2 emission	Energy use, diesel	Mt
	Energy use, gas	Mt
	Energy use, fuel-oil	Mt
	Energy use, gasoline	Mt
	Energy use, coal	Mt

The GHG emissions from electricity consumption is computed by the energy supply module. These additional GHG emissions are computed by the TPE interface.

Activity data: the agriculture model is providing the activity data to the TPE, namely, the livestock population and the crop production.

Table 17 – TPE, activity data

Activity data	Production	Unit
Livestock population	Bovine	lsu
	Pig	lsu
	Poultry	lsu
	Sheep	lsu
	Hens	lsu
	Milk	lsu
	Other animals	lsu
Crops	Cereal	kcal
	Oil crop	kcal
	Pulses	kcal
	Starchy roots	kcal
	Sugar crops	kcal
	Fruits	kcal
	Vegetables	kcal
Other	Insect biomass	kcal
	Algae biomass	kcal

Crop consumption per use: the agriculture module keeps track of the crop-uses and provides the TPE with the use-split including food, feed, non-food and bioenergy uses.

Livestock feed consumption given the agriculture practices and the use of alternative protein sources; the agriculture provides the feed consumption by type.

Bioenergy feedstock mix & feedstock mix: the agriculture modules provides the TPE with the bioenergy mix and the feedstock mix of the designed pathways.

Table 18 – Bioenergy conversion pathways in the agriculture module

Type	Conversion pathway	Feedstock
Biodiesel	Esterification	vegetable oil, UCO, animal fats, algae oil, insect oil, energy crop
Biodiesel	Hydrotreated Vegetable Oil	vegetable oil, UCO, animal fats, algae oil, insect oil, energy crop
Biodiesel	Biomass To Liquid	agricultural residues, forestry-residues, energy crops
Jetfuel	Hydrotreated Vegetable Oil	vegetable oil, UCO, animal fats, algae oil, insect oil, energy crop
Jetfuel	Biomass To Liquid	agricultural residues, forestry-residues, cellulosic energy crop
Ethanol	Fermentation	sugar crop, cereal, energy crops
Ethanol	Enzymatic	agricultural residues, forestry-residues, cellulosic energy crop
Biogas	Anaerobic digestion	Manure, biowastes, energy crop
Solid bioenergy	-	agricultural residues, forestry-residues, wood fuel

5.2 Land-use, land-use change and forestry (lulucf)

5.2.1 Description of the LULUCF module inputs

The land-use module only received direct inputs from the agriculture and biodiversity modules.

5.2.1.1 Agriculture

See Section 5.1.2.2.

5.2.1.2 Biodiversity

The biodiversity module partly set the ambition levels for conservation and preservation based on the Aichi targets framework. The twenty Aichi Biodiversity Targets are organized under five strategic goals.[7]

[7] Aichi Biodiversity Targets - Convention on Biological Diversity;

'*Strategic Goal A*: *Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society;*

Strategic Goal B: *Reduce the direct pressures on biodiversity and promote sustainable use;*

Strategic Goal C: *To improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity;*

Strategic Goal D: *Enhance the benefits to all from biodiversity and ecosystem services;*

Strategic Goal E: *Enhance implementation through participatory planning, knowledge management and capacity building;'*

The module is tackling biodiversity from a habitat preservation perspective, as the only quantifiable way. Concretely, the biodiversity module provides the lulucf module with the land that needs to be frozen for biodiversity preservation (either agriculture or forest lands as a lever input, (Baudry et al., 2019, p. 4)), given a set ambition level, which cannot be used for another economic activity.

5.2.2 Description of the lulucf module outputs

5.2.2.1 Pathway Explorer

The land-use module provides the GHG emissions associated with LULUCF, expressed in tCO_2e (tons of CO_2 equivalent). The model aims at delivering the level of detail that is included in UNFCCC inventories regarding GHG emissions from LULUCF. In terms of forestry, the model aims at delivering the level of detail that is included in the European long-term strategy.

Land-use: the model enables to track the land-use covered by the UNFCCC inventories, namely: cropland, grasslands, forests, wetlands, settlements, and other lands:

Table 19 – Land demand

Land	Unit	Description
Grassland	ha	Total grassland cover
	ha	… under low pressure
	ha	… under medium pressure

Direct link: https://www.cbd.int/sp/targets/

	ha	… under high pressure
Cropland	ha	Total cropland
	ha	…dedicated to human food
	ha	…dedicated to livestock feed
	ha	…dedicated to bioenergy
	ha	…dedicated to non-food
Forest	ha	Total forest
	ha	… frozen for biodiversity conservation
	ha	… forest available for wood supply
	ha	… other forests
Settlements	ha	Total settlement areas
Wetlands	ha	Total wetland areas
Other lands	ha	Total other lands (glaciers, barren lands, etc.)

LULUCF emissions

The land module computes the GHG emissions associated with land-use and land-use change, possibly with the following level of detail, based on the UNFCCC inventories:

Table 20 – Emission associated to land

Land	Unit	Description
Grassland	$MtCO_2$	Emission associated with grassland remaining grassland
	$MtCO_2$	Emission associated with land becoming grassland
Cropland	$MtCO_2$	Emission associated with cropland remaining cropland
	$MtCO_2$	Emission associated with land becoming cropland
Forest	$MtCO_2$	Emission associated with forest remaining forest

	$MtCO_2$	Emission associated with land becoming forest
Settlements	$MtCO_2$	Emission associated with settlement remaining settlement
	$MtCO_2$	Emission associated with land becoming settlement
Wetlands	$MtCO_2$	Emission associated with wetland remaining wetlands
	$MtCO_2$	Emission associated with land becoming wetland
Other lands	$MtCO_2$	Emission associated with other lands remaining other lands
	$MtCO_2$	Emission associated with land becoming other lands
Net LULUCF	$MtCO_2$	Balance of LULUCF emissions

Forestry production: the activity data of the forestry module consists of the forestry products trade:

Table 21 – Forestry based biomass flows

Item	Unit	Description
Wood fuel	Mm^3	Production of wood fuel in roundwood equivalent, stemming from bioenergy demand
Pulp wood	Mm^3	Production of pulp wood in roundwood equivalent, stemming from industry demand
Forestry residues	Mm^3	Production of forestry residues and other aggregates in roundwood equivalent, stemming from bioenergy demand
Sawlogs	Mm^3	Production of sawlogs in roundwood equivalent, stemming from industrial wood demand
Wood import	Mm^3	Trade balance of wood products, use as a buffer variable in the model
Wood export	Mm^3	Trade balance of wood products, use as a buffer variable in the model

Forest carbon dynamics: given the demand for wood products, the forest management practices, and the land-use and land-use change dynamics, the modelling framework is providing the forest carbon dynamics:

Table 22 – Emission associated to forestry

Item	Unit	Description
Harvested wood products	$MtCO_2$	CO_2 emissions stored through the use of wood products
Afforestation	$MtCO_2$	CO_2 emissions captured by the development of new forest areas
Deforestation	$MtCO_2$	CO_2 emissions stemming from the deforestation
Forest management	$MtCO_2$	CO_2 emissions captured thanks to climate smart forestry management
Dead wood	$MtCO_2$	CO_2 emissions stored in deadwood
Forest litter	$MtCO_2$	CO_2 emissions stored in the forest litter
Biomass increment	$MtCO_2$	CO_2 emissions captured though the forest growth
Biomass removal	$MtCO_2$	CO_2 emissions stemming from biomass removal

Forests natural disturbances involves direct GHG emissions (e.g. fire) through the growing stock dynamics because of wildlife and grazing, insects and diseases, storm wind and snow, and wildfires. EUCalc considers the historical trends for the natural disturbances and considers that the forest resilience to these damages can be improved through the deployment of CSF (Nabuurs and al. 2017). The impact is computed by considering damaged areas, and for wildfires, an additional CH4, N2O and CO2 emissions are computed using UNFCCC inventory emission factors. Deforestation dynamics also considers these emission factors, considering that a share of wood is burnt on-site while the rest is used as roundwood equivalent supply (again based on UNFCCC inventories).

5.3 Biodiversity

5.3.1 Inputs

As mentioned above, the biodiversity module does not receive input from any other module.

5.3.2 Outputs

5.3.2.1 Land-use

The biodiversity module generates a demand for the restoration of agricultural lands and forest lands to 'natural' states, expressed in hectares.

Table 23 – Land demand

Land	Unit	Description
Agriculture	ha	Restoration of lands associated with crop production for human or livestock consumption, grassland areas and feedstock production for energy.
Forest	ha	Restoration of lands associated with supply of wood products for bioenergy and biomaterial.

5.3.2.2 Climate Emissions

To reflect the net sink capacity of protected areas, the biodiversity module provides GHG emissions associated with the protected natural habitat. Values are provided for CO_2, CH_4 and N_2O (to avoid double counting, the protected areas are excluded from the emissions calculation in the LULUFC module).

Table 24 – Emissions associated with protected areas

Item	Unit	Description
Protected and restored areas	$MtCO_2$	CO_2 emissions from lands protected for biodiversity
	MtN_2O	N_2O emissions from lands protected for biodiversity
	$MtCH_4$	CH_4 emissions from lands protected for biodiversity

5.3.2.3 Transition Pathway Explorer (TPE)

The biodiversity module provides GHG emissions associated with the protection of natural habitat. Values are provided for CO_2, CH_4 and N_2O.

5.4 Water

5.4.1 Inputs

5.4.1.1 Lifestyle

The lifestyle module provides the water module with population counts in inhabitants. through population counts in inhabitants. This information is used to compute the demands for water in households & services.

5.4.1.2 Industry

The production & manufacturing module provides the water module with domestic material production and manufacturing of products in megatons.

5.4.1.3 Agriculture/Land-use

The agriculture/land-use module provides the water module with domestic production of crops for food, animal feed and bioenergy in kilo calories. It also provides the livestock counts in livestock units.

5.4.1.4 Energy supply

The energy supply module provides the water module with electricity production through various energy vectors in terawatt hours. This electricity production will be transformed into water demand for cooling of power plants. Water for oil & gas extraction and refining is not considered.

5.4.1.5 Climate

The climate module provides the water module with the water availability dataset corresponding to the level chosen by the climate lever. The water demand for agricultural commodities are based on Mekonnen (2011) and Hoekstra (2012) (Table 25):

Table 25 - Water-use factors for agriculture commodities

Crop	***Agriculture Water Factor [m3/kcal]***
Fruit	3.2E-04
Sugar crops	1.8E-04
Vegetables	1.8E-04
Cereals	7.1E-05
Oil crops	7.6E-05
Pulses	4.2E-05
Fibre crops	5.6E-05
Starchy roots	7.1E-05

Considering how water stress and scarcity would affect the crop yields could not have been done without inducing a feedback loop between the agriculture and water modules. As a trade-off, we used a warning signal for the user to inform any issues in terms of water stress and scarcity for each country and sub-region given the lever setting. As shown by Figure X, the user is informed in which country water issues occur and how to remedy the problem through a lever set suggestion.

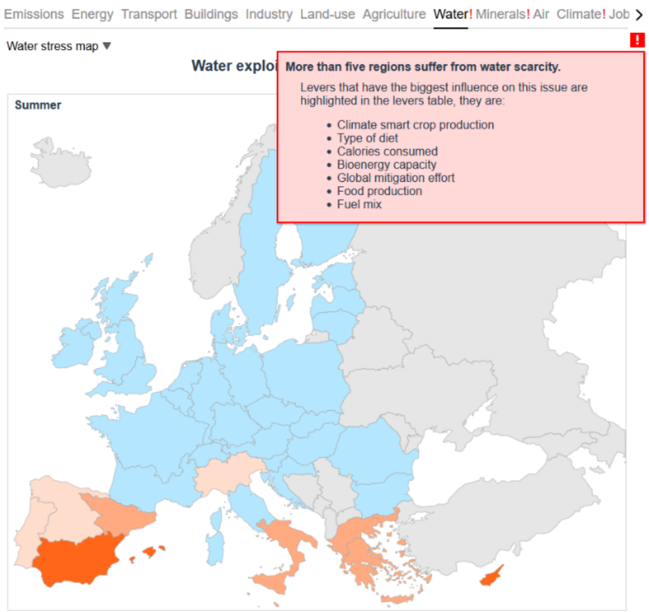

Figure 19 - Water associated warnings

The list of inputs used by the water module are presented in Table 26.

Table 26 – List of inputs from other modules to the water module

Module	Variable
Lifestyle	lfs_pop_population[inhabitants]
Industry	ind_material-production_steel[Mt] ind_material-production_cement[Mt] ind_material-production_paper[Mt] ind_material-production_chem[Mt] ind_material-production_ammonia[Mt] ind_material-production_aluminium_prim[Mt] ind_material-production_aluminium_sec[Mt] ind_material-production_lime[Mt] ind_material-production_glass[Mt]

Agriculture/Land use	agr_liv-population_meat_poultry[lsu] agr_liv-population_meat_bovine[lsu] agr_liv-population_meat_pig[lsu] agr_liv-population_meat_oth-animals[lsu] agr_liv-population_abp_dairy-milk[lsu] agr_liv-population_abp_hens-egg[lsu] agr_liv-population_meat_sheep[lsu] agr_domestic-production_afw_cereal[kcal] agr_domestic-production_afw_oilcrop[kcal] agr_domestic-production_afw_pulse[kcal] agr_domestic-production_afw_fruit[kcal] agr_domestic-production_afw_veg[kcal] agr_domestic-production_afw_starch[kcal] agr_domestic-production_afw_sugarcrop[kcal] agr_domestic-production_afw_algae[kcal] agr_domestic-production_afw_insect[kcal] agr_domestic-production_afw_gas_energycrop[kcal] agr_domestic-production_afw_lgn_energycrop[kcal]
Energy supply	elc_energy-production_electricity_pv_solar-power[TWh] elc_energy-production_electricity_biomass[TWh] elc_energy-production_electricity_concentrated_solar-power[TWh] elc_energy-production_electricity_hydro[TWh] elc_energy-production_electricity_marine[TWh] elc_energy-production_electricity_geothermal[TWh] elc_energy-production_electricity_coal[TWh] elc_energy-production_electricity_oil[TWh] elc_energy-production_electricity_gas[TWh] elc_energy-production_electricity_uranium[TWh] elc_energy-production_electricity_onshore_wind[TWh] elc_energy-production_electricity_offshore_wind[TWh]
Climate	wat_water-availability[m3]

5.4.2 Outputs

The water module provides the TPE with water consumption and water withdrawal for all relevant sectors (households, industrial manufacturing, electricity generation, agriculture), as well as the water stress levels displayed on a map of Europe. Figure 18 shows an example of graphs displayed by the pathway explorer, and Figure 19 gives an idea of what the water stress map will look like.

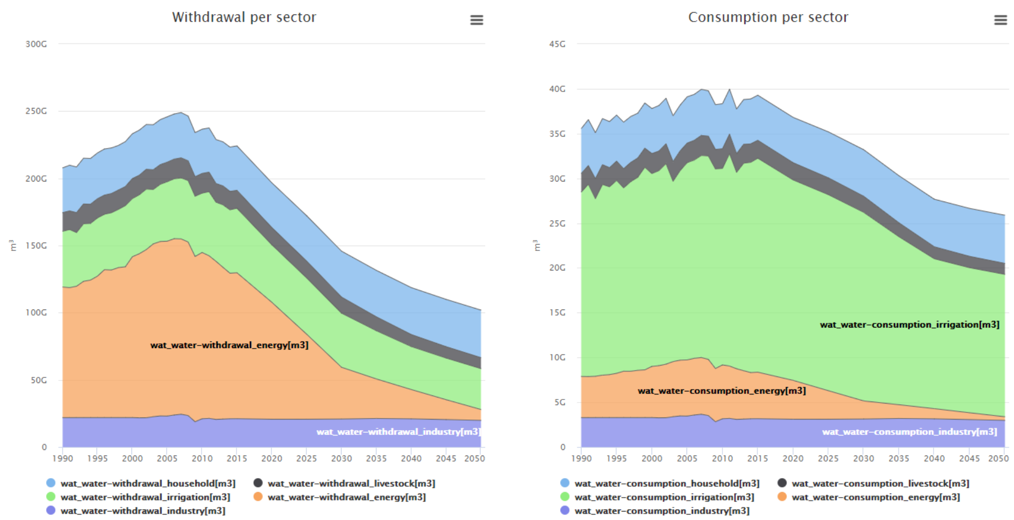

Figure 20 – Visual representation on the Pathway Explorer of water withdrawals and water consumptions in Europe

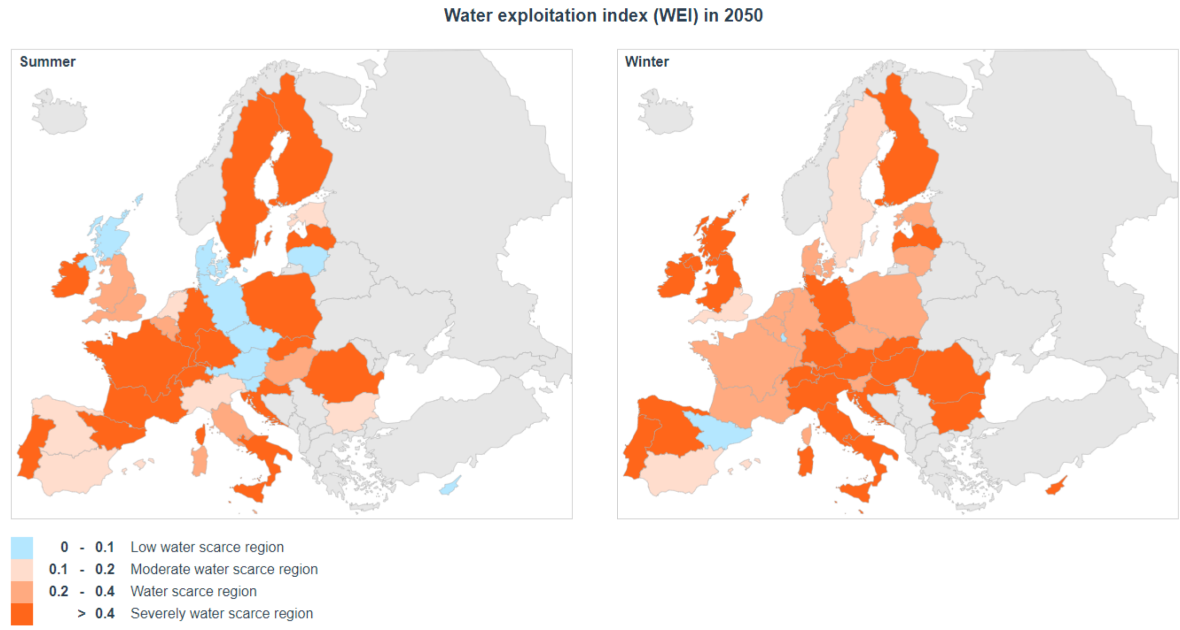

Figure 21 – Visual representation on the Pathway Explorer of water stress in Europe in 2050

5.5 Minerals

5.5.1 Inputs

The inputs are explained below and Table 27 shows the variable names passed as inputs to the mineral module from the sectors listed below.

5.5.1.1 Lifestyle

The industry module provides material demand to the mineral module. It provides historical data for material demand in EU as well as the forecast for 2050.

5.5.1.2 Transport

The input from transport is with regards to the demand for vehicles each year with certain specificities requirements. For cars, trucks (light, medium, and heavy), motorcycles, and buses there is a segregation between the demand in vehicles with Internal Combustion Engines (ICE), Electric Vehicles (EV), Fuel-Cell Vehicles (FCV), and Plug-Hybrid Electric Vehicles (PHEV). For trains, ships, planes, and tramways, there are no differences between whether trains are diesel or electric, or improvement in engine technologies for planes and ships. Finally, not included in the transport model, but still included in the inputs is the demand for roads, rails, and trolley cables. Demand for trains and tramways are provided as number of carriages.

5.5.1.3 Building

There are two types of inputs from the building module: one related to construction and another related to apparatuses. Inputs are the demand for renovation and construction of residential and non-residential buildings. There is also the demand for district heating. The building module also sends its demand for the main electric apparatus, in particular, domestic appliances – (dryers, washing machines, dishwashers, fridges, freezers) – and hand consumer electronics such as, phones (smartphones), computers (laptops and fixed computers irrespectively) and TVs.

5.5.1.4 Storage

The storage module sends both electricity generating technologies and storage technologies to the mineral module. Among electricity generating technologies, there are newly created fossil fuel plants (gas, oil, and coal), renewable energy plants (geothermal and hydro) and renewable energy technologies (solar photovoltaic, onshore and offshore wind turbines, and solar concentrated power)

5.5.1.5 Industry

Apart from glass and aluminum pack production, the main inputs from industry are the *levers* which are used in the mineral module in the similar fashion as in the industry module, with small differences. The product net import lever is used to compute the amount that are produced outside of the EU28 and Switzerland. The material efficiency lever computes the process efficiency in production and in the product itself (needing less for similar results). The *lever* material switch concerns the material that might be replaces by another. In the model, switch to aluminum is accounted and discounted. The others (chemicals, timbers, etc.) are solely discounted. For instance, steel to plastic is discounted from steel but not added to plastic (not modelled in the mineral module), unlike steel to aluminum that is discounted from steel and added to aluminum. Finally, the technology development concerns development in production technology going from more energy intensive – and emitting – to less energy intensive. In the realm of metal production, they concern the use of scrap (recycled metals).

5.5.1.6 Oil Refinery

The module sends to the mineral module the demand for oil, gas, and coal to be compared with reserves.

5.5.1.7 Agriculture

The mineral module's input from agriculture concerns the demand for fertilizers only as the use of organic fertilizers is already accounted for within the agriculture model itself.

5.5.1.8 CCUS

The generation of natural gas from CCUS technology is used by the mineral module to decrease the amount of gas generated from extraction.

Table 27 - List of inputs from other modules to the mineral module (levers are in italics)

Module	Variable
1.1 Lifestyle	lfs_pop_population[inhabitants]
	lfs_pop_world [inhabitants]
2.1 Building	bld_new_dhg_pipe[km]
	bld_floor-area_new_non-residential[m2]
	bld_floor-area_reno_non-residential[m2]
	bld_floor-area_new_residential[m2]
	bld_floor-area_reno_residential[m2]
	bld_new_fridge[num]
	bld_new_freezer[num]
	bld_new_wmachine[num]
	bld_new_dishwasher[num]
	bld_new_dryer[num]
	bld_new_tv[num]
	bld_new_computer[num]
	bld_new_phone[num]
2.2 Transport	tra_road[km]
	tra_rail[km]
	tra_trolley-cables[km]
	tra_subways[number]
	tra_2W_ICE[number]
	tra_HDVH_ICE[number]
	tra_HDVL_ICE[number]
	tra_HDVM_ICE[number]
	tra_LDV_ICE[number]
	tra_bus_ICE[number]
	tra_2W_PHEV[number]

	tra_HDVH_PHEV[number]
	tra_HDVL_PHEV[number]
	tra_HDVM_PHEV[number]
	tra_LDV_PHEV[number]
	tra_bus_PHEV[number]
	tra_2W_EV[number]
	tra_HDVH_EV[number]
	tra_HDVL_EV[number]
	tra_HDVM_EV[number]
	tra_LDV_EV[number]
	tra_bus_EV[number]
	tra_2W_FCEV[number]
	tra_HDVH_FCEV[number]
	tra_HDVL_FCEV[number]
	tra_HDVM_FCEV[number]
	tra_LDV_FCEV[number]
	tra_bus_FCEV[number]
	tra_ships[number]
	tra_planes[number]
	tra_trains[number]
3.1 Industry	ind_material-production_glass[Mt]
	ind_production_aluminiumpack[Mt]
	ind_product-net-import_new_dhg_pipe[%]
	ind_product-net-import_fridge[%]
	ind_product-net-import_dishwasher[%]
	ind_product-net-import_wmachine[%]
	ind_product-net-import_cars-ICE[%]
	ind_product-net-import_trucks-ICE[%]
	ind_product-net-import_cars-FCV[%]
	ind_product-net-import_trucks-FCV[%]
	ind_product-net-import_cars-EV[%]
	ind_product-net-import_trucks-EV[%]
	ind_product-net-import_ships[%]
	ind_product-net-import_trains[%]
	ind_product-net-import_planes[%]
	ind_product-net-import_road[%]
	ind_product-net-import_rail[%]
	ind_product-net-import_trolley-cables[%]
	ind_product-net-import_freezer[%]
	ind_product-net-import_dryer[%]
	ind_product-net-import_tv[%]

	ind_product-net-import_phone[%]
	ind_product-net-import_computer[%]
	ind_technology-development_steel_BF-BOF[%]
	ind_technology-development_steel_scrap-EAF[%]
	ind_technology-development_steel_hydrog-DRI[%]
	ind_technology-development_steel_hisarna[%]
	ind_technology-development_aluminium_prim[%]
	ind_technology-development_aluminium_sec[%]
	ind_technology-development_copper_tech[%]
	ind_material-switch_cars-steel-to-chem[%]
	ind_material-switch_trucks-steel-to-chem[%]
	ind_material-switch_trucks-steel-to-aluminium[%]
	ind_material-switch_build-steel-to-timber[%]
	ind_material-efficiency_steel[%]
	ind_material-efficiency_aluminium[%]
	ind_material-efficiency_copper[%]
3.2 CCUS	ccu_ccus_gas-ff-natural[Mt]
4.3 Agriculture	agr_demand_phosphate[Mt]
	agr_demand_potash[Mt]
5.2 Oil Refinery	fos_primary-demand_gas[TWh]
	fos_primary-demand_oil[TWh]
	fos_primary-demand_coal[TWh]
5.3 Storage	elc_exist-capacity_RES_other_geothermal[GW]
	elc_exist-capacity_RES_other_hydroelectric[GW]
	elc_exist-capacity_RES_other_marine[GW]
	elc_exist-capacity_RES_solar_csp[GW]
	elc_exist-capacity_RES_solar_pv[GW]
	elc_exist-capacity_RES_wind_offshore[GW]
	elc_exist-capacity_RES_wind_onshore[GW]
	elc_exist-capacity_fossil_coal[GW]
	elc_exist-capacity_fossil_gas[GW]
	elc_exist-capacity_fossil_oil[GW]
	elc_exist-capacity_nuclear[GW]
	elc_exist-capacity_RES_solar_Pvroof[GW]
	elc_exist-capacity_RES_solar_Pvutility[GW]

5.5.2 Outputs

The outputs of the mineral module are solely sent to The Pathway Explorer (TPE) demonstrating both mineral demand per sector and mineral availability.

5.5.2.1 Pathway Explorer

The mineral module is a non-core module at the end of the input-output model. Therefore, it does not send data to other modules apart from the Pathway Explorer. Similar to the above segregation, there are two main outputs, mineral demand which shows the demand for each mineral segregated by sectors, and mineral availability, which takes into consideration recycling rates with respect to the status of European allocated reserve (reserve per capita x European population) in 2050 for each mineral.

5.5.2.1.1 Mineral Demand

Each mineral demand is segregated by sector, which shows the main sectors requiring mineral extraction. Figure 22 shows example of outputs for Iron, Bauxite (Aluminum), and copper.

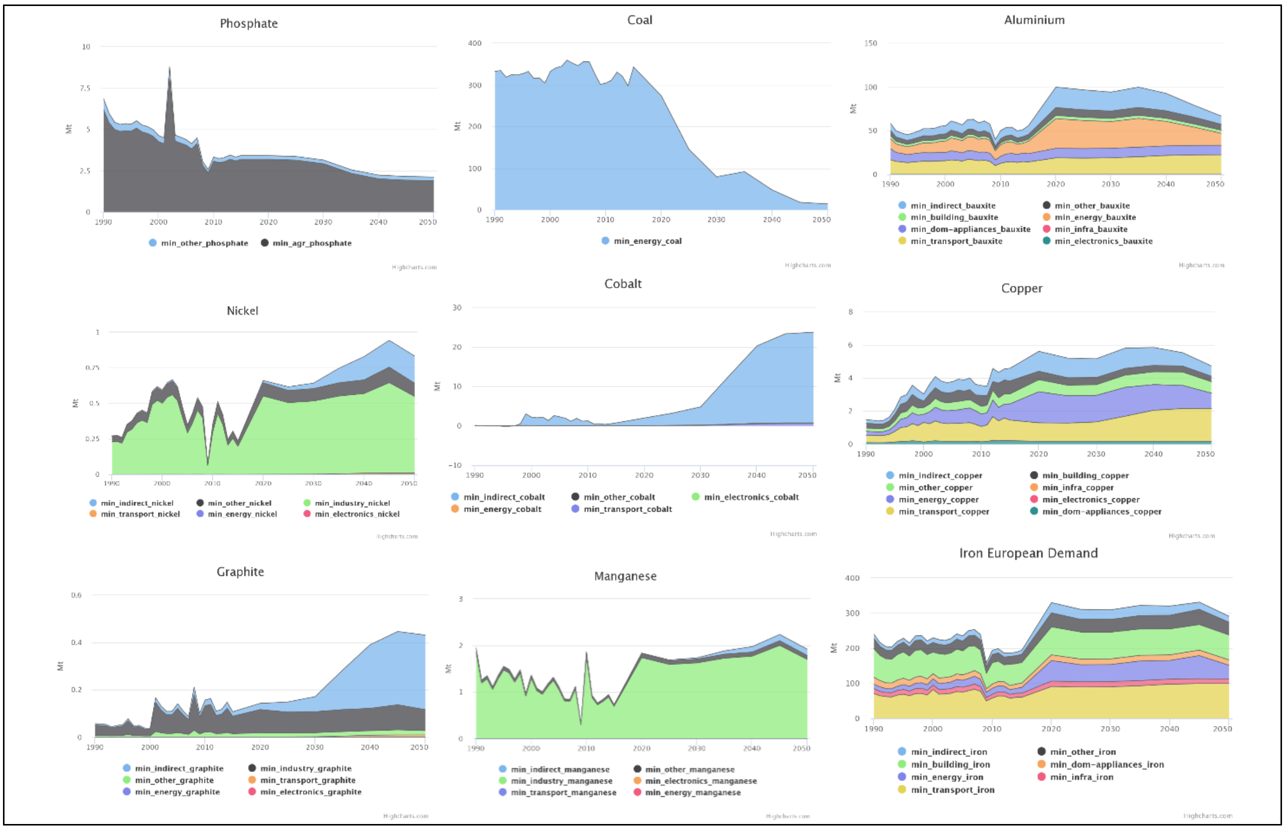

Figure 22 - Graph examples for mineral and fossil fuel demand

5.5.2.1.2 Mineral Availability

Mineral availability shows the effect of extraction on the resource allocated to the EU28 and Switzerland. A recycling factor – through the use of scrap metal in the production – has been applied. Table 28 demonstrates examples of outputs in the TPE that could show the effect the lever settings onto the resources.

Table 28 - Examples of outputs demonstrated by the model shown as a table. The outputs here are hypothetical. Warning levels calculations are further developed in section 6.5.2.3

Mineral	***Allocated Reserve Used in 2050***	***Warning Level***
Bauxite (Aluminium)	*84%*	
Copper	*243%*	
Cobalt	*200%*	
Graphite	*114%*	
Iron (Steel)	*110%*	
Lead	*194%*	*2*
Lithium	*226%*	
Manganese	*166%*	
Nickel	*268%*	
Phosphate	*21.6%*	
Potash	*44.3%*	
Oil BP	*7.1%*	
Gas BP	*116%*	*1*
Coal BP	*4.3%*	

6 Detailed Calculation Trees

6.1 Agriculture

6.1.1 From food demand to domestic production (livestock-based products)

Objective

Livestock based products requires animal feed inputs but also yields valuable by-products that are feedstock for food, feed, bioenergy and biosourced material markets. The modelling framework first enables to compute the domestic production for livestock-based products, including:

Table 29 – Variables computed in the module

# food group	**sub-group**	**variables**
		Bovine meat
Livestock based products	Meat	Sheep meat
		Pig meat

Other animal based products	Poultry meat
	Other meat
	Eggs
	Milk
	Animal fats
	Offal

Food demand accounting for waste

The total food demand is computed by summing up the food demand by group (e.g. cereal, bovine meat) with the wastes and losses from the consumer and distribution stages, expressed in kcal:

$$food\ demand\ accounting\ for\ wastes\ [kcal] = food\ demand\ [kcal] + food\ wastes\ [kcal]$$

Equation 1 - Food demand accounting for waste

Both input variables are driven by the lifestyle patterns, but the amount of wastes has to be considered individually to keep track of wastes & losses as feedstock for other uses such as used cooking oil (UCO) as biofuel feedstock.

Given the food demand – accounting for wastes & losses – and the self-sufficiency pattern, the modelling framework computes the domestic production for livestock-based food (lbf) groups, expressed in kcal:

$$lbf\ domestic\ production\ [kcal] = lbf\ demand\ [kcal].self\ sufficiency\ ratio\ [\%]$$

Equation 2 - Self-sufficiency & trade balance

The output enables to set domestic production level and the trade balance. Self-sufficiency input depend on the food self-sufficiency lever. A self-sufficiency ratio ranging between 0 and 1 – excluding one - implies a net-import trade balance for a country. On the opposite, a self-sufficiency ratio greater than 1 involves a net-export trade balance.

Livestock based food domestic production, accounting for wastes & losses

The total food domestic production is computed by multiplying the domestic production with the wastes and losses ratio from the agriculture, postharvest handling and storage, processing and packaging stages, expressed in percentage (%):

$$\begin{aligned} &lbf\ domestic\ production\ accounting\ for\ wastes\ [kcal] \\ &\quad = lbf\ domestic\ production\ .\ lbf\ losses\ and\ wastes\ ratio\ [\%] \end{aligned}$$

Equation 3 - Livestock based food domestic production, accounting for wastes & losses

The level of food wastes and losses of livestock-based food products is set by the climate smart livestock production system lever.

6.1.2 From meat domestic production to livestock population and by-products

Objective

Given the livestock-based products demand and the set of livestock production system patterns, the modelling framework is computing the livestock population (Baudry et al., 2019), expressed in livestock unit (lsu), for each animal type including bovines (non-dairy), sheep, pigs, poultry, other animals, dairies, laying hens. Given the livestock population being slaughtered, by-products (i.e. animal fats, offal and wastes that can be used as feedstock for biomaterials and bioenergy) are being computed and expressed in kcal.

Livestock being slaughtered

The livestock yields are set through the production system patterns. The yields enable to compute the livestock population that is slaughtered:

$$livestock\ being\ slaughtered\ [lsu] = lbf\ domestic\ production\ [kcal]/livestock\ yield\ [kcal/lsu]$$

Equation 4 - Livestock being slaughtered

Livestock population

The slaughtering age of each livestock type is set through the production system patterns, and enable to compute the livestock population from the livestock being slaughtered:

$$livestock\ population\ [lsu] = livestock\ being\ slaughtered\ [lsu]/slaughter\ rate\ \ [\%]$$

Equation 5 - Livestock population

Livestock-based by-products

Given the livestock being slaughtered, the modelling framework is computing the by-production of animal fats and offal for each livestock type, expressed in kcal.

$$livestock\ byproducts\ [kcal] = livestock\ being\ slaughtered\ [lsu] * byproducts\ yields\ \ [kcal/lsu]$$

Equation 6 - Livestock-based by-products

The animal fat and offal are used as feedstock for food, feed, fertilizer, bioenergy and other uses later on in the calculation tree.

$$livestock\ byproducts\ for\ non-food\ uses\ [kcal] \\ = livestock\ byproducts\ production\ [kcal] - byproducts\ food\ demand\ [kcal]$$

Equation 7 - Livestock-based by-products for non-food use

The livestock by-products implicitly supply the food demand, and only the remaining share can be used for non-direct human consumption (e.g. animal based meals, biodiesel).

6.1.3 From livestock population to feed demand

Objective: the modelling framework is computing the feed requirement given the livestock population.

Feed requirement

The feed requirement is computed given the livestock population by type and the energy efficiency of meat and livestock-based products production (Alexander et al., 2016):

> *'The energy efficiency of meat and livestock-based products production is defined as the percentage of energy (caloric) inputs as feed effectively converted to animal product. An efficiency of 25% would mean 25% of calories in animal feed inputs were effectively converted to animal product; the remaining 75% would be lost during conversion'*

The following Figure presents the energy efficiency that are being used in the agriculture module (Alexander et al., 2016):

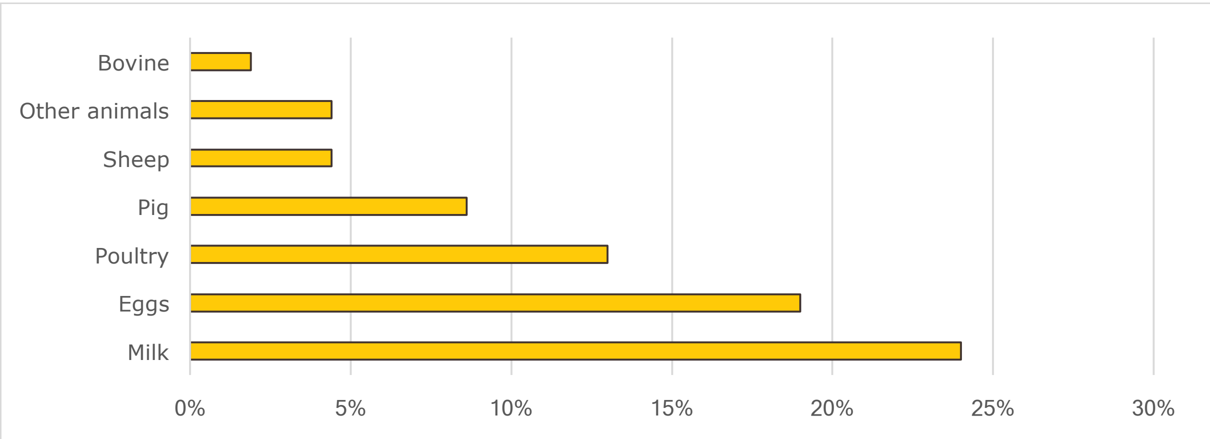

Figure 23 – Energy efficiency of meat and livestock-based products production

$$feed\ requirement\ [kcal] = livestock\ poulation\ [lsu].\ energy\ efficiency\ ratio\ [kcal/kcal]$$

Equation 8 - Feed requirement

The total feed requirement is then computed from the requirement for each livestock type (bovine, sheep, poultry, and so on):

$$total\ feed\ requirement\ [kcal] = Sum\ (feed\ requirement\ by\ livestock\ type)$$

Equation 9 – Total feed requirement

The feed typical ration depends on both the livestock production system patterns (e.g. extent of the pastureland contribution), the alternative protein source deployment (e.g. share of insect-based meal) and the use of industrial based products, which are computed later on in the calculation tree.

6.1.4 From alcoholic beverages production to by-products supply

Objective

The modelling framework enable to compute the demand for crops as well as the by-product supplies from the alcoholic beverage production, and to drive the by-products feedstock towards different uses (See table below).

Table 30 – Variables computed in the beverage's module

# food group	variables
Alcoholic beverages	Wine
	Beer
	Alcoholic beverages
	Fermented beverages
Alcoholic beverage by-products	DDGS
	Yeast
	Lees
	Grape marc

Alcoholic beverages biorefinery

Given the domestic production of beverages, the demand for cereals (beer, fermented alcohol) and fruits (wine, distilled alcohol) is computed. The by-products of wine and beer are also computed. Given the production small volume, the by-products stemming from distilled and fermented alcohol are not considered.

$$beverages\ byproducts\ [kcal] = beverage\ domestic\ production\ [kcal].\ byproducts\ yields\ [kcal/kcal]$$

Equation 10 - Alcoholic beverages biorefinery (1)

$$crop\ demand\ [kcal] = beverage\ domestic\ production\ [kcal].\ yields\ [kcal/kcal]$$

Equation 11 – crop demand for alcoholic beverages biorefinery

Table 31 – Alcoholic beverages yields in kcal/kcal

Beverage	Wine	Beer	Distilled alcohol	Fermented alcohol
Cereal demand	-	94.5	-	290
Marc supply	137	-	-	-
Lees supply	20.6	-	-	-
Cereal meals	-	96.6	-	-
Yeast supply	-	21.7	-	-
Fruit demand	113.6	-	288	-

Given the lack of data at the country scale, the beverages yield data is based on the French report for the by-product resource and availability in the agri-food industry (Réséda et al., 2017), presented in Table 27. For example, for each kilocalorie of beer produced, 0.945 kcal of cereals is required, and 0.966 kcal and 0.217 kcal of cereal meals and yeast are generated as by-products.

Alcoholic beverages by-product uses

Given the beverages by-products supply, and the biomass-use hierarchy setting, the by-products are driven towards animal feed, bioenergy, fertilizer and other-uses. Other uses mainly include pet food and oleochemical industry which are currently not taken into account, but are still considered to avoid multiple counting issues regarding the biomass availability.

$$beverages\ byproducts\ per\ use[kcal] = beverages\ byproducts\ [kcal].hierarchy\ uses\ [\%]$$

Equation 12 - Alcoholic beverages by-product per use

The modelling framework also keeps track of biomass-use to allocate the land-use to food, non-food and bioenergy purposes. For instance, summing the wine and beer by-products used as fertilizer, bioenergy and so on:

$$beverages\ byproducts\ use\ as\ fertilizer[kcal] = Sum(byproducts\ used\ as\ fertilizer)$$

Equation 13- Alcoholic beverages by-product used as fertilizers

6.1.5 Alternative Protein Sources for livestock (APS)

Objective

The APS computation enables to consider the deployment of insect farming and microalgae biorefinery. Moreover, the demand for APS for feed also drives the biomass availability for bioenergy and fertilizer through their by-products (e.g. microalgae oil, insect manure). It is also worth mentioning that the framework has been developed to enable adding extra APS easily.

$$APS\ meals\ demand\ [kcal] = feed\ requirement\ by\ livestock\ type\ [kcal].APS\ share\ by\ type\ and\ livestock\ type[\%]$$

Equation 14 - Alternative Protein Sources meals demand

The microalgae and insect-based meals demands are computed by multiplying the share of APS in the total feed intake for each livestock type. It is worth mentioning that the maximum share of APS corresponds to the highest share that is considered healthy for each animal type (derived from Madeira et al., 2017 and Makkar et al., 2014). The overall microalgae and insect-based meals demand are then summed up to enable computing the by-products supplies:

$$microalgae\ meals\ demand\ [kcal] = Sum(microalgae\ meals\ demands)$$

Equation 15 - Alternative Protein Sources for livestock microalgae meal demand

$$Byproduct\ supplies\ [TWh, t] = microalgae\ meals\ demand\ [kcal].byproduct\ yields[TWh, t/kcal]$$

Equation 16 - Alternative Protein Sources by-product supplies

$$Resource\ demand\ [TWh, t] = microalgae\ meals\ demand\ [kcal].resource\ yields[TWh, t/kcal]$$

Equation 17 - Alternative Protein Sources resource demand

The resource demand includes the microalgae biomass and insect requirements, but the specific energy and water demands remain to be implemented in the next releases (Equation 17).

The yields for insect farming and microalgae biorefinery are based on Baudry et al., (2018), and Wang et al., (2017).

Table 32 – APS yields in kcal/kcal

Product	Insect farming	Microalgae biorefinery
Animal feed meal	100	100
Biomass input	130	150
Oil	27	50
Biowastes & residues	3500	/
Bio-organic fertilizer	1700	/

6.1.6 From liquid bioenergy production, to crop demand

Objective

The bioenergy production capacity is set through the bioenergy capacity lever. The feedstock requirement is computed from these capacities given the load and efficiency factors and the lever setting.

Technology mix

First the technology mix is set based on the observed data for the period 1990-2015 (Eurostat). For the future time series, the biomass-use hierarchy lever affects the technology mix. The implicit assumption is that biomass availability is driving the technology bioenergy mix. For example, if the lever setting does not allow food crop-based feedstock to supply the bioenergy sector, it is considered that advanced biofuels that use cellulosic feedstock will be deployed.

$$Bioenergy\ production\ per\ technology\ [TWh] = Bioenergy\ production\ [TWh].\ technology\ mix[\%]$$

Equation 18 - Bioenergy feedstock technology mix

Feedstock type requirement

Given the technology mix and associated yields, the demand for biomass feedstock type is computed (e.g. oil, cellulosic material and residues):

$$Biomass\ demand[TWh] = Bioenergy\ production\ per\ technology\ [TWh] * Technology\ yields[t, kcal/TWh]$$

Equation 19 - Bioenergy feedstock type requirement

Feedstock balance

Given the feedstock demand and byproducts/wastes supplies, the demand/supply balance is computed:

$$feedstock\ remaining\ demand\ per\ type\ [kcal] = feedstock\ demand\ per\ type\ [kcal] - byproducts\ supply\ per\ type\ [kcal]$$

Equation 20 - Bioenergy feedstock balance

From this point several scenarios can occur. First, whether the user able or disable food and energy crop-based bioenergy or not. If yes, the balance is done by yielding a food-crop demand and/or energy crop demand. If not, either there is enough residues and wastes, or a warning will inform the user than that biomass availability does not allow such a bioenergy production.

6.1.7 Typical livestock ration

Objective

The modelling framework is computing the livestock typical ration given the biomass hierarchy and climate-smart livestock production systems. First, the grass, APS, and industrial by-products allocated to animal feed uses are summed up. Then, the remaining feed share is computed, expressed in kcal. Finally, the remaining feed requirement is split.

Table 33 – Variables computed in the beverage's module

# food group	variables
Crop-based	Cereal
	Oil crop
	Sugar crop
	Pulses
	Vegetables
	Fruits
	Starch
	Cakes
	Molasse
	Oil
Livestock-based	Animal meals
	Fish-meals
APS	Insect meals
	Algae meals

Total low-carbon feed

According to the FAO, low carbon feed includes feed crop produced through low-carbon agriculture practices, from lands that are not recently been forests or grasslands, and it includes agri-food industry by-products.

$$Total\ low\ carbon\ feed\ [kcal] = Sum(alternative\ feed\ supply)[kcal]$$

Equation 21 - Total low-carbon feed

Remaining feed demand

Given the alternative feed sources, the remaining feed demand is computed.

$$remaining\ feed\ demand\ [kcal] = total\ feed\ requirement[kcal] - total\ low\ carbon\ feed\ [kcal]$$

Equation 22 - Remaining feed demand

Typical feed ratio

The remaining feed per type is computed assuming the feed mix in each country remains relatively constant for the other feed groups.

$$remaining\ feed\ demand\ by\ group\ [kcal] = remaining\ feed\ demand. feed\ split\ [kcal]$$

Equation 23 - Typical feed ratio

6.1.8 From livestock population to manure and enteric fermentation emissions

Objective

The modelling framework is computing the livestock associated GHG emissions expressed in N_2O and CH_4, coming from enteric fermentation and manure management.

Enteric fermentation emission

Enteric fermentation emissions are computed by multiplying the livestock population expressed in lsu with the enteric fermentation emission factors expressed in $MtCH_4$/lsu, specific to each livestock type.

$$enteric\ emission\ [MtCH4] = livestock\ popultaion[lsu] * enteric\ fermentation\ emission\ factor\ [MtCH4/lsu]$$

Equation 24 - Enteric fermentation emission

Manure volume

The manure volumes expressed in nitrogen content are computed by multiplying the livestock population expressed in lsu with the manure generated by each livestock type expressed in MtN/lsu.

$$Manure\ [MtN] = livestock\ popultaion[lsu] * manure\ yiels\ [MtN/lsu]$$

Equation 25 - Manure volume

Manure management practices

The manure management per practices are computed by multiplying the manure volumes for each livestock type, with the split of manure management practices expressed in %. The manure management practices include manure treatment, manure applied to soil, and manure left on pasture.

$$manure\ management\ per\ practices[MtN] = manure\ [MtN] * manure\ management\ practices\ split\ [\%]$$

Equation 26 - Manure management practices

Manure CH_4 emission

The CH4 emission that stem from manure are computed by multiplying the manure volumes to the emission factors expressed in MtCH4/MtN, specific to each management practice.

$$manure\ CH4\ emission\ [MtCH4] = manure\ management\ per\ practices[MtN] * emission\ factors\ per\ practices\ [MtCH4/MtN]$$

Equation 27 - Manure CH4 emission

Manure N_2O emission

The N_2O emission that stem from manure are computed by multiplying the manure volumes to the emission factors expressed in MtN_2O/MtN, specific to each management practice.

$$manure\ N2O\ emission\ [MtN2O] = manure\ management\ per\ practices[MtN] * emission\ factors\ per\ practices\ [MtN2O/MtN]$$

Equation 28 - Manure N2O emission

6.1.9 From processed crop-based products to crop demand

Objective

The demand for processed food and feed commodity, including vegetable oil, oil crop cakes, sugar, and sweeteners are converted in crop equivalent, expressed in kcal.

$$crop\ demand\ [kcal] = processed\ crop\ food\ demand[kcal] * conversion\ factors\ [kcal/kcal]$$

Equation 29 - From processed crop-based products to crop demand (1)

$$crop\ demand\ [kcal] = processed\ crop\ feed\ demand[kcal] * conversion\ factors\ [kcal/kcal]$$

Equation 30 - From processed crop-based products to crop demand (2)

6.1.10 From food demand to crop domestic production

Objective

The model is summing up the crop demand for the different use and computes the crop domestic production expressed in kcal, with the exception of energy crops expressed in tons (t).

Total food crop demand

The food crop demand driven by the food, feed, bioenergy and biosourced materials is summed up for each crop-based food groups (CBF), expressed in kcal.

$$food\ crop\ demand\ [kcal] = Sum(foodcrop\ demand\ per\ use)[kcal]$$

Equation 31 - Total food crop demand

Self-sufficiency & trade balance

Given the food demand – accounting for wastes & losses – and the self-sufficiency pattern, the modelling framework computes the domestic production for CBF, expressed in kcal:

$$cbf\ domestic\ production\ [kcal] = cbf\ demand\ [kcal].self\ sufficiency\ ratio\ [\%]$$

Equation 32 - Self-sufficiency & trade balance

The output enables to set domestic production level and the trade balance. Self-sufficiency input depend on the food self-sufficiency lever. A self-sufficiency ratio ranging between 0 and 1 – excluding one - implies a net-import trade balance for a country. At the opposite, a self-sufficiency ratio greater than 1 involves a net-export trade balance.

Food crop-based food domestic production, accounting for waste & losses

The total food domestic production is computed by multiplying the domestic production with the wastes and losses ratio from the agriculture, postharvest handling and storage, processing and packaging stages, expressed in percentage (%):

$$\begin{aligned} &cbf\ domestic\ production\ accounting\ for\ wastes\ [kcal] \\ &\qquad = cbf\ domestic\ production\ .cbf\ losses\ and\ wastes\ ratio\ [\%] \end{aligned}$$

Equation 33 - Food crop-based food domestic production, accounting for waste & losses

The level of food wastes and losses of livestock-based food products is set by the climate smart cropping production system lever.

6.1.11 From crop production to residues

Objective

Given the crop domestic production, the volume of residues is computed for each crop type.

Crop residues

Based on Malins and Searle (2016) estimation, the volume of crop residues generated given the demand for crops is computed. The production ratio has been aggregated for each country based on the following assumption:

Table 34 – Crop residues production ratio in t/t (Searle and Malins, 2016)

Crop	production ratio
Barley	1.18
Maize	1.27
Oats	1.31
Rapeseed	1.08
Rice	1.59
Rye	1.37
Soybeans	3.5
Sunflower	1.77
Triticale	1.28
Wheat	1.18
Sugar beet	0.27

The production ratio refers to the ratio of residues to harvested crop. A ratio that is greater than 1 means that more residues is produced compared to the part of the crop that is used. Given the present ratio, Searle and Malins (2016) estimated the total residues available in the EU up to 367 Mt, regardless to soil quality preservation.

$$Residues\ production\ [Mt] = crop\ production\ [kcal].residues\ production\ ratio\ [Mt/kcal]$$

Equation 34 - Crop residue production

As a second step, the overall residue production is summed up:

$$Total\ residues\ production\ [Mt] = Sum\ (residues\ production\ per\ crop[Mt])$$

Equation 35 – total crop residues production

Crop residues per use

Depending on the lever setting, crop residues can be used for soil quality preservation, as nitrogen input, for bioenergy and for other uses.

$$Residues\ per\ use\ [Mt] = Residues\ production\ [Mt] * use\ hierarchy\ [\%]$$

Equation 36 - Crop residues per use

6.1.12 From woody biomass demand to roundwood equivalent wood demand

Objective

The wood demand is triggered by various modules through different products. The following equation enables us to express these wood-based products (e.g. pellets, wood fuel, timber) as roundwood equivalent [m^3].

Roundwood demand

Woody biomass demand is expressed as roundwood equivalent (Mm^3). For example, a demand for 1 t of fuelwood is equivalent to 1.20 t of wood under bark, and 1.66 m^3.

$$Wood\ demand\ [m3] = woody\ product\ by\ type[t].conversion\ factor\ [\frac{m3}{t}]$$

Equation 37 – Wood demand as roundwood equivalent

and summed up to express the demand for wood:

$$Wood\ demand\ [Mm3] = Sum(woody\ biomass\ [Mm3])$$

Equation 38 – Total roundwood demand

6.1.13 Land allocated to cropland

Objective

Given the demand for crops and the climate smart agriculture production systems patterns, the land demand is computed.

Defining crop yields

[not fully implemented in the KNIME framework yet]

Given the climate change and temperature levels, production factor is affecting the crop yields.

$$Net\ copland\ demand[ha] = \ Cropland\ demand\ [ha] * cropping\ intensity\ factor\ [\%]$$

Equation 39 - Defining crop yields

Cropland demand

Given the cropland demand and yields the cropland demand is computed:

$$Cropland\ demand\ [ha] = Crop\ demand\ [kcal]\ /\ crop\ yield\ [kcal/ha]$$

Equation 40 - Cropland demand

Emission from rice cultivation

Given the emission factors for rice cultivation, expressed in MtCH4/ha, the CH4 emissions associated with rice cultivation are computed:

$$CH4\ emission\ (rice)[MtCH4] = Rice\ land\ [ha] * CH4\ emission\ factor\ [MtCH4/ha]$$

Equation 41 - Emission from rice cultivation

Overall cropland demand

The overall demand for cropland is summed up:

$$total\ cropland[ha] = Sum(cropland\ per\ crop\ type[ha])$$

Equation 42 - Overall cropland demand

6.1.14 Synthetic fertilizer-use & emissions

Objective

Synthetic fertilizer use is computed given the climate smart cropping systems patterns. The modelling framework is computing the demand for synthetic fertilizer expressed in t, and the associated emissions expressed in MtN_2O.

Synthetic fertilizer-use

Given the deployment of the climate smart cropping production system patterns, the fertilizer demand is computed by multiplying the agriculture land with the fertilizer-use expressed in t/ha.

$$Synthetic\ fertilizers[t] = agriculture\ land[ha].synthetic\ fertilizer\ use[t/ha]$$

Equation 43 - Synthetic fertilizer-use

Fertilizer associated emissions

The N_2O emissions are computed from the fertilizer-use and the synthetic fertilizer emission factors.

$$N2O\ emission[MtN2O] = fertilizer\ use[t].emission\ factor[tN2O/t]$$

Equation 44 - Fertilizer associated emissions

6.1.15 Energy consumption

Objective

The modelling framework is computing the energy demand given the climate-smart agriculture production systems. The first version of the agriculture model used to dissociate the irrigation energy demand from the other consumption using FAOSTAT[8] database. Nevertheless, given the significant gap between the JRC IDEES and FAOSTAT database concerning energy-use in agriculture, added to the need for the use of a common database across the modules concerning energy demand and supply for consistency and calibration sake, IDEES[9] have been used to track energy consumption for each sector and modules. As a drawback, IDEES does not dissociate energy-use for irrigation, which induce a limitation of the module regarding this specific issue

8 Food and Agriculture Organization (FAO), FAOSTAT, Energy-use – Energy for power irrigation. Direct link: http://www.fao.org/faostat/en/#data/GN

9 The JRC "Integrated Database of the European Energy System" (JRC-IDEES). Direct-link: https://ec.europa.eu/jrc/en/potencia/jrc-idees

Energy-use by vector

The energy demand is computed by multiplying the energy use by hectare with the agriculture land [ha]. The energy demand is then split between the different energy types:

$$energy - use[TWh] = agriculture\ land[ha].energy\ use[TWh/ha]$$

Equation 45 - Energy-use by hectare (1)

$$energy - use\ by\ type\ [TWh] = energy\ use[TWh] * energy\ mix\ [\%]$$

Equation 46 - Energy-use by type (2)

Direct energy GHG emission

Direct CO_2 emissions are computing by multiplying the energy consumption [TWh] by energy emission factors [$MtCO_2e/TWh$]. Electricity associated emissions are computed in the energy module (WP5), given the levers setting for electricity mix.

$$CO2\ emissions\ [MtCO2] = energy\ consumption\ by\ type\ [TWh] * emission\ factors\ [MtCO2/TWh]$$

Equation 47 - Direct energy GHG emission

6.1.16 GHG emissions

Objective

The total emissions of the agriculture sector are summed up by gas type, including CO_2, CH_4, N_2O.

$$CO2\ emissions\ [Mt] = Sum(CO2\ emission[Mt])$$

Equation 48 – CO2 emissions

$$CH4\ emissions\ [Mt] = Sum(CH4\ emission[Mt])$$

Equation 49 – CH4 emission

$$N2O\ emissions\ [Mt] = Sum(N2O\ emission[Mt])$$

Equation 50 – N2O emissions

6.1.17 Bioenergy costs

Objective

EUCalc considers the energy-costs and thus the cost of moving towards renewables and more advanced technology, considering the cost dynamics (e.g. learning by doing).

Costs

The cost of biofuels is computed based on IEA biofuel roadmap cost dynamics estimation by 2050 (IEA and IRENA, 2013), for the following:

- biogas
- advanced biodiesel
- conventional biodiesel
- advanced biogasoline
- conventional biogasoline
- solid bioenergy

$$Costs[EUR] = bioenergy\ by\ type\ [ktoe].cost\ by\ type[\frac{€}{ktoe}]$$

Equation 51 - Land demand

6.2 Land-use, land-use change and forestry (lulucf)

6.2.1 Land dynamics over the years

A part of the lands is converted into different uses each year. First, the new land allocation is computed given the demand for each land type, namely the cropland, grassland, wetland, settlements, and other lands. If this land demand is exceeding the last year demand, net deforestation occurs otherwise, spared lands are allocated thanks to the land-management lever as forest, grassland, or unmanaged lands.

$$land\ demand(year\ i)[ha] = Sum[land\ demand\ per\ use\ and\ cover\ (year\ i)]$$

Equation 52 - Land demand per year

$$land\ balancing(year\ i)[ha] = land\ demand(year\ i)[ha] - land\ demand(year\ i - 1)[ha]$$

Equation 53 - Land Balance per year

If land demand for land balancing negative:

$$deforestation\ (year\ i)[ha] = -: land\ balancing(year\ i)[ha]$$

Equation 54 - Deforestation balancing

Else:

$$\begin{aligned} new - land\ allocation\ (year\ i)[ha] \\ = land\ balancing(year\ i)[ha] * land\ allocation\ breakdown\ [\%] \end{aligned}$$

Equation 55 - New land allocation per year

Providing the land-use for the current year in the model.

6.2.2 Land dynamics in the year

The land dynamics intra year is computed for all land types but forest, grassland and cropland:

$$\begin{aligned} &converted\ land\ per\ type\ (year\ i)[ha] \\ &\qquad =: converted\ land\ [ha] * land - use\ matrix\ breakdown\ [\%] \end{aligned}$$

Equation 56 - Converted land per type per year

Providing the land-dynamics expressed in ha for the lands converted to settlements, wetlands and other lands as well as the settlements, wetlands and other lands converted in other land-use types.

Given the agriculture patterns, the land-dynamics for cropland and grassland is computed the same way but through different levers/dynamics.

6.2.3 Carbon dynamics

Given the land-use change matrix, i.e. the area converted into each land-type expressed in ha, is multiply by the land emission factors.

$$\begin{aligned} &carbon\ dynamics\ per\ land - use\ change\ and\ per\ carbon - pool\ (year\ i)[ha] \\ &\qquad = X\ converted\ to\ Y\ [ha] * emission - factoe\ X\ converted\ to\ Y\ [tC/ha] \end{aligned}$$

Equation 57 - Carbon dynamics per use change and per carbon

Emission factors are country/years/pool/dynamics specific, which means 29 countries x 5 carbon pools x 36 possible dynamics -5220 factors- are used to compute the carbon stock per hectare each year. The following factors are based on the UNFCCC inventories. Additional factors are also used for biomass burning, and other land-management issues (agroforestry, no tillage and so on).

6.2.4 Gross and net biomass increment

Given the climate-smart forestry setting, the gross biomass increment expressed as m^3/ha is computed for both FAWS and non-FAWS.

$$faws\ (year\ i)[ha] = forest\ land(year\ i)[ha] - frozen\ forest\ land\ (year\ i)[ha]$$

Equation 58 – Forest Available for Wood Supply (FAWS) per year

Depending on the deployment of CSF practices, the dynamics of biomass increment is computed given the gross increment rate (Equation 60), the extent of natural losses (Equation 61), the felling rates (Equation 62).

$$\begin{aligned} &gross\ increment\ (year\ i)[m^3/ha] \\ &\qquad = standard\ gross\ increment\ (year\ i)[m^3/ha] \\ &\qquad + additional\ CSF\ gross\ increment\ (year\ i)[m^3/ha] \end{aligned}$$

Equation 59 - Gross increment per year

The biomass increment is then lowered by considering natural-disturbances including pest and diseases, wildlife, weather and fires given the forest resilience(climate-smart-forestry).

$$net\ increment\ (year\ i)[m^3/ha] = gross\ increment\ [m^3/ha] * natural\ losses\ [m^3/ha]$$

Equation 60 - Net increment per year

Biomass removal is computed given the harvest rate which also depends on the climate-smart-forestry lever

$$fellings\ (year\ i)[m^3/ha] = net\ increment\ (year\ i)[m^3/ha] * harvest\ rate\ [\%]$$

Equation 61 - Fellings per year

$$net\ change\ (year\ i)[m^3/ha] = net\ increment\ (year\ i)[m^3/ha] - \ fellings\ (year\ i)[m^3/ha]$$

Equation 62 - Net change per year

The net biomass increment is then computed.

$$\text{growing stock change (year i)}[m^3] = \text{net change (year i)}[m^3/ha] * forest\ lands\text{(year i)}[m^3]$$

Equation 63 - Growing stoch change

6.2.5 Wood trade balance

Woody biomass demand from the different sectors are expressed in TWh, tonnes, and cubic meters (m^3). First, the woody biomass is expressed as m^3.

$$wood\ trade\ balance\ [Mm^3] = wood\ demand[Mm^3] - wood\ supply\ [Mm^3]$$

Equation 64 - Wood trade balance

$$if: wood\ trade\ balance > 0\ then\ wood\ import\ [Mm^3] = -wood\ trade\ balance\ [Mm^3]$$

$$Else: wood\ import[Mm^3] = 0$$

$$if: wood\ trade\ balance < 0\ then\ woodfuel\ supply\ [Mm^3] = wood\ trade\ balance\ [Mm^3] * wood\ fuel\ share$$

$$elif: wood\ trade\ balance < 0\ then\ wood\ export\ [Mm^3] = wood\ trade\ balance\ [Mm^3] * industrial\ wood\ share$$

Equation 65 - Wood trade balance conditional equation

6.3 Biodiversity

6.3.1 Land dynamics over the years

Objective

The total land demand for biodiversity protection depends on the protection target set by the lever. In cases where an extension of the existing network is necessary, agricultural land or natural habitat has to be reallocated to protected areas.

Depending on the setting of the lever for land prioritization, the module calculates the annual changes in land allocation.

If the land required to meet the protection expansion target exceeds the amount of natural land within the boundaries of existing protected areas the previous year, then the module first targets restoration of agriculture lands within the existing protected area boundaries. If the appropriate amount of land is not available, the lands from outside these boundaries have to be reallocated and restored. Depending on lever `land prioritization`, the restoration occurs firstly either within agricultural land or within previously unprotected natural land. In cases where the first level of restoration is inadequate to reach the protection target, restoration will occur within any unprotected area until the demand is met or no additional land is available.

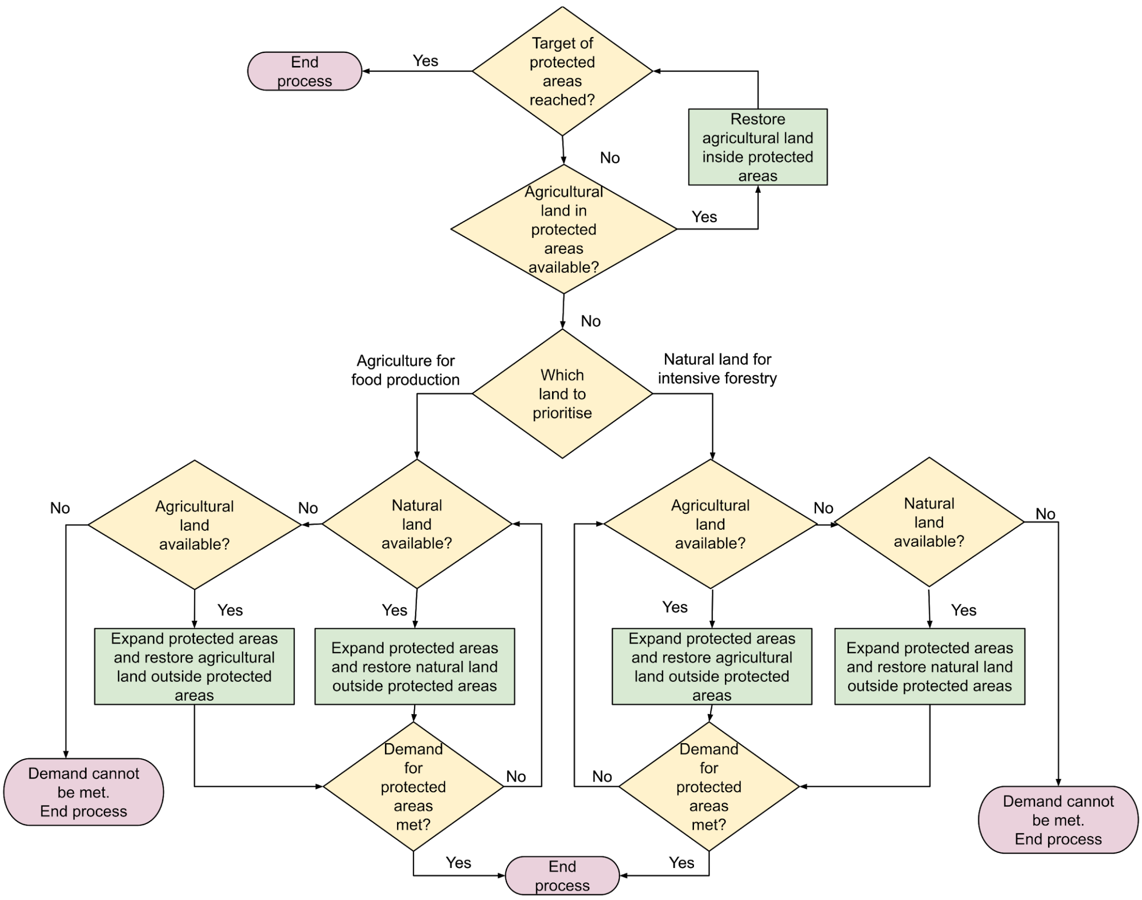

Figure 24 - Flow of restoration and protected areas expansion within the biodiversity module

Although theoretically possible, the modelling framework does not consider the case in which protected areas are released (i.e., degazetted) or downgraded. The reason for this choice is that this practice is at odds with existing policies and previous behaviours, which favour the creation of a static network of protected areas. Instead, the focus is kept on the improvement of habitat and reduction of human pressure within protected areas, aided by further expansion of the existing network.

6.3.2 Emissions

Objective

Depending on the lever settings, land use changes will occur that affect land composition and protected area size, thus resulting in changes of emissions originating from these areas.

$$Emissions[CO2] = Protected\ Area[\%] * Emissions\ Factor[CO2/\%]$$

Equation 66 - Biodiversity CO2 emissions

$$Emissions[N2O] = Protected\ Area[\%] * Emissions\ Factor[N2O/\%]$$

Equation 67 - Biodiversity N2O emissions

$$Emissions[CH4] = Protected\ Area[\%] * Emissions\ Factor[CH4/\%]$$

Equation 68 – Biodiversity CH4 emissions

6.4 Water

6.4.1 Water Demand

6.4.1.1 Households & services

The goal of this step is to compute consumption and withdrawal water flows from the water demand for households & services. This sector covers water uses from households and other services (hotels, restaurants, hospitals, schools, etc.). Figure 25 illustrates the calculation tree for households & services water flows. For readability purposes, the term "households & services" is shortened to "household".

Figure 25 – Calculation tree for household water demand and flows

First, the household water demand is computed by multiplying the population counts with an average water use per capita (Equation 69). This basic approach is similar to the methodology applied in the WaterGAP model (Flörke et al., 2012).

*household water demand [m3] = Population [#inhabitants] * water use per capita [m3/capita]*

Equation 69 - Water households & services

Historical values for household water use per capita are taken from Reynaud (2015). In this study, household water use is defined as "the quantity of water used to cover the household and related utility needs of the population through the water supply industry and self-supply". The author strived to remove water use from other types of consumers (small industrial and commercial entities) that are already computed in our industrial manufacturing calculation tree, thus avoiding double counting issues.

From household water demand we then compute the household water withdrawal:

Household water withdrawal [m3] = Household water demand[m3] / (1 – water losses[%])

Equation 70 - Household water withdrawal

Equation 71 outputs water withdrawn from freshwater resources by considering the water losses due to the various efficiencies of public water supply network. The historical efficiency values for EU28 were provided by JRC. The value for Switzerland was extracted from the report from the SKAT foundation (Saladin, 2002).

Similarly, household water consumption is derived from household water demand as follows:

*Household water consumption[m3] = Household water demand[m3] * consumptive use [%]*

Equation 71 - Household water consumption

We assume that consumptive use for households is 20% of the water demand, implying that 80% flows back to the environment as waste water (Bisselink et al., 2018).

Further improvement could integrate the percentage of population connected to public water supply prior to calculating households water demand. Due to a high range of missing data on the EUROSTAT database[10] we made the rather coarse assumption that every EU28+1 inhabitant have access to public water. The calibration process adjusts our calculated values in order to mitigate our approximation. As in the WaterGAP model, future iterations of the calculator could include changes in household water use intensity (m3/capita/year) due to structural and technological changes (Alcamo et al., 2003).

6.4.1.2 Electricity generation

The objective is to compute consumption and withdrawal water flows from the electricity generation cooling water demand. Figure 26 illustrates the calculation tree for electricity generation water flows.

[10] EUROSTAT, Population connected to public water supply (%), direct link: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00012&plugin=1

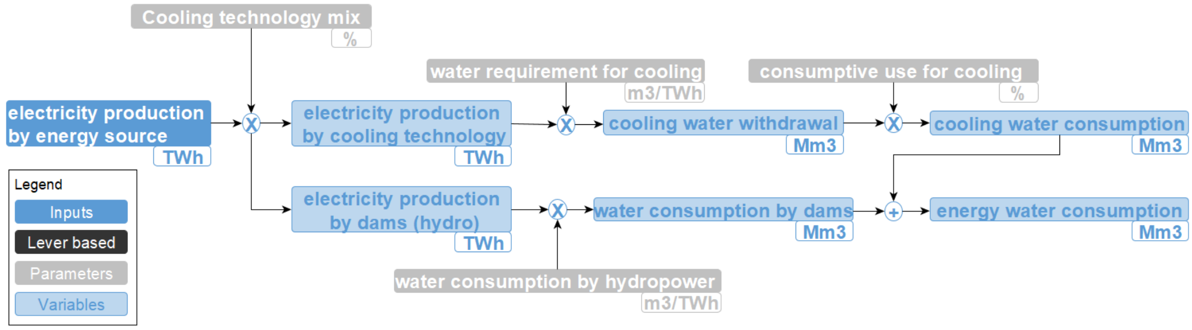

Figure 26 – Calculation tree for electricity generation water demand and flows

The first calculation step is to split the electricity production input (in TWh) by cooling technologies. We use the cooling system shares for thermoelectric generation technologies reported in Davies et al. (2013) to split coal, oil, gas, nuclear and biomass-based electricity productions. Cooling system technologies considered in our model include once-through cooling (open-loop cooling), wet recirculating cooling (evaporative towers) and dry cooling (air-cooled condensing) (Macknick et al., 2012).

Then we multiply these values with water requirements for cooling (in m3/TWh) found in literature for thermal and non-thermal electricity generation technologies (Davies et al., 2013; Fricko et al., 2016). Literature provides distinct values per cooling technology for water consumption and for water withdrawal, as presented in Equation 72 and Equation 73:

*Electricity generation water withdrawal[m3] = Electricity production by energy source[TWh] * water withdrawal for cooling[m3/TWh]*

Equation 72 - Electricity generation water withdrawal (1)

*Electricity generation water consumption[m3] = Electricity production by energy source[TWh] * water consumption for cooling[m3/TWh]*

Equation 73 - Electricity generation water withdrawal (2)

Once water flows are calculated by cooling technology, these are summed to obtain total cooling water consumption and withdrawal. Cooling water consumption is then summed with hydropower water consumption due to evaporation in dams. For more details, please refer to Deliverable 5.3.

Further improvements could include a future shift from once-through to recirculating cooling systems over time. This feature was not relevant in this model since future power-plants constructions plans for which different cooling technologies could be applied are low, thus not really impacting our modelling results.

6.4.1.3 Industrial manufacturing

The goal is to compute consumption and withdrawal water flows from the industrial manufacturing water demand. Figure 27 illustrates the calculation tree for industrial manufacturing water flows.

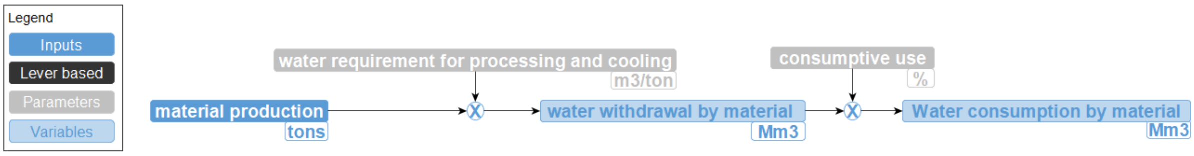

Figure 27 – Calculation tree for industrial manufacturing water demand and flows

The water demand from this sector excludes water demands for oil and gas production and coal mining, as well as the indirect water demand for producing the energy used in industrial processes. Our definition differs from the "industrial water withdrawals" used in FAO Aquastat[11] since the latter includes electric power generation, while EUCalc granularity allows to distinguish the industrial processes from the electric power generation. As in Bisselink et al. (2018), we thus separate water demand for energy and cooling from manufacturing water demand.

Our procedure consists in using water requirements for industrial processing and cooling (m3/ton) and multiplying them with specific material production (tons) to derive water withdrawal by material type. The corresponding equation is the following:

*Material water withdrawal[m3] = Material production[tons] * water requirement for processing and cooling[m3/ton]*

Equation 74 - Material water withdrawal

As water requirement values are not available for all industrial productions covered in EUCalc, we introduce a specific sub-sector labelled "other-industries" which is calibrated to match historical water demands for the whole industrial sector. For the other EUCalc industrial sub-sectors, water requirements for industrial processing and cooling (m3/ton) are defined as follows:

- For **steel**, we use a combination of the blue water footprints of "Chromium-nickel unalloyed steel" and "Unalloyed steel" from (Gerbens-Leenes et al., 2018) weighted by the steel quality shares in Europe in 2017 (EUROFER, 2018).
- For **cement**, we use a combination of the blue water footprints of "Portland Cement" (CEMI) and "Portland composite cement" (CEMII) from (Gerbens-Leenes et al., 2018) weighted by the cement shares by process in Europe in 2015 (European Commission, 2018).
- For **glass**, we use the blue water footprint of "Soda-lime float glass" from (Gerbens-Leenes et al., 2018).
- For **lime**, we assume that the water requirement for lime corresponds to the transformation step in the cement process that transforms limestone into lime and which requires washing (Gerbens-Leenes et al., 2018).
- For **paper** (woodpulp and recycled), we use the estimation of the water footprint of paper products in industrial stage for the USA industry from (Van Oel, P. R., & Hoekstra, A. Y., 2010).

[11] FAO Aquastat database, direct link: http://www.fao.org/nr/water/aquastat/data/query/index.html

- For **aluminium** (primary and secondary), we use the values provided in the Environmental Profile Report from European Aluminium (European Aluminium, 2018) We apply the water supply value for an aluminium sheet production for primary aluminium, and the total water supply value after scrap remelting for secondary aluminium.
- For **ammonia**, we use an average value between blue water footprints of "Nitrogen-phosphorus-potassium (NPK) fertilizer (12:32)" and "Nitrogen-phosphorus-potassium (NPK) fertilizer (10:26)" given in the Tata Industrial Water Footprint Assessment report (Unger et al., 2013).
- For **other chemicals**, we assume that the production is mainly related to the demand of plastic packs from the Lifestyle module. Consequently, we decide to use the average water footprint of plastics found by Li et al. in their report on the water footprint of Tetra Pak carton (Li et al., 2010).

These water requirements are presented in Table 35.

Table 35 - List of material water requirements for industrial processing and cooling used in the water module

Material production	Water requirement (m3/ton)	Source / *Adapted from
Steel	65,2	*Gerbens-Leenes et al., 2018
Cement	3,2	*Gerbens-Leenes et al., 2018
Glass	5,9	Gerbens-Leenes et al., 2018
Lime	0,19	Gerbens-Leenes et al., 2018
Paper (pulp & recycled)	5,5	Van Oel, P. R., & Hoekstra, A. Y., 2010
Aluminium (primary)	3,9	European Aluminium, 2018
Aluminium (secondary)	6,8	European Aluminium, 2018
Ammonia	4,96	*Unger et al., 2013
Other chemicals	13,7	Li et al., 2010

Water consumption is then derived by multiplying water withdrawal with an average consumptive use of 15% (Bisselink et al., 2018) (Equation 75).

$$Material\ water\ consumption[m3] = Material\ water\ withdrawal[m3] * consumptive\ use[\%]$$

Equation 75 - Material water consumption

Usually, industrial water uses are approximated by using the ratio of water abstracted over the manufacturing gross value added (GVA) (Flörke et al., 2013). However, given that these GVA values are only available at aggregated level, this large-scale approach did not suit our sub-sectoral approach. Furthermore, using GVA values as inputs would create loops with other modules that could compromise the objective of real-time computation.

6.4.1.4 Livestock

The objective is to compute consumption and withdrawal water flows from the livestock drinking water demand. Figure 28 illustrates the calculation tree for livestock drinking water flows.

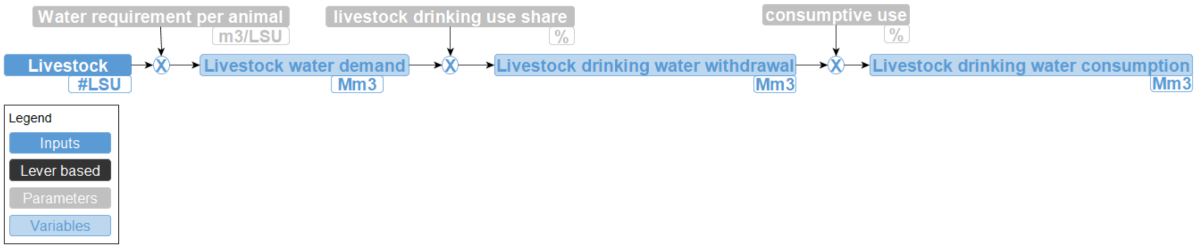

Figure 28 – Calculation tree for livestock drinking water demand and flows

The water footprint of animals includes the indirect water footprint of ingested feed which is considered in the irrigation section, and the direct water footprint associated with drinking and servicing which is tackled in this section. Drinking water mainly comes from blue water sources whereas water in feed may come from blue or green water sources[12] depending on irrigation practices to produce feed. The outflows correspond to respiration, perspiration, excreta as manure and urine, and water incorporated into livestock products (milk, meat, wool, etc.) (FAO, 2018). The consumptive use of livestock is rounded for all animals to 15% of livestock water demand (Bisselink et al., 2018).

In this section, we use the Livestock Unit (LSU) which is defined by Eurostat as *a reference unit which facilitates the aggregation of livestock from various species and age as per convention, via the use of specific coefficients established initially on the basis of the nutritional or feed requirement of each type of animal.*[13]

As shown in Equation 76, the first step of calculation consists in multiplying livestock counts per year (LSU) by the water requirement (m3/LSU) to obtain livestock water demand in m3.

$$\text{Livestock water demand}[m3] = \text{Livestock}[LSU] * \text{water requirement per LSU}[m3/LSU]$$

Equation 76 - Livestock water demand

The water requirements per LSU are pre-calculated using the average annual water footprint per animal presented in Mekonnen & Hoekstra (2012) and the unit

[12] **Water footprint (blue):** Used and defined by the Water Footprint Network (WFN). It can be defined as water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time (Hoekstra, 2011). Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

Water footprint (green): Used and defined by the Water Footprint Network (WFN). This is the water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants (Hoekstra, 2011). The green water is particularly relevant for agricultural, horticultural and forestry products.

[13] Eurostat glossary link: https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Livestock_unit_(LSU)

conversion factors to transform animals counts into LSU.[14] Complementary water footprint values were found in Tschudin et al. (2011). Since water requirements are at first assumed constant across Europe, these are readjusted with correction factors to account for country level variations (see Deliverable 4.1).

The second step is to select the share of livestock water demand related to drinking and other services. According to Mekonnen & Hoekstra (2012), the largest water footprint for animals come from their feed which is tantamount to 98% of the total water footprint, while drinking and other services only represent 2% of the total water footprint. Consequently, we multiply the livestock water demand by the drinking use share (approximately 2%):

*Livestock drinking water demand[m3] = Livestock water demand[m3] * livestock drinking use share[%]*

Equation 77 - Livestock drinking water demand

We assume in our model that *livestock drinking water demand* corresponds to the water withdrawal for livestock drinking so that no water loss is accounted.

Finally, the water consumption for livestock drinking is calculated in Equation 78 by multiplying the "livestock drinking water withdrawal" with the livestock consumptive use from JRC (equal to 15%) (Bisselink et al., 2018).

*Livestock drinking water consumption[m3] = Livestock drinking water withdrawal[m3] * livestock consumptive use[%]*

Equation 78 - Livestock drinking water consumption

6.4.1.5 Irrigation

The goal is to compute consumption and withdrawal water flows from the irrigation water demand. Figure 29 illustrates the calculation tree for irrigation water flows.

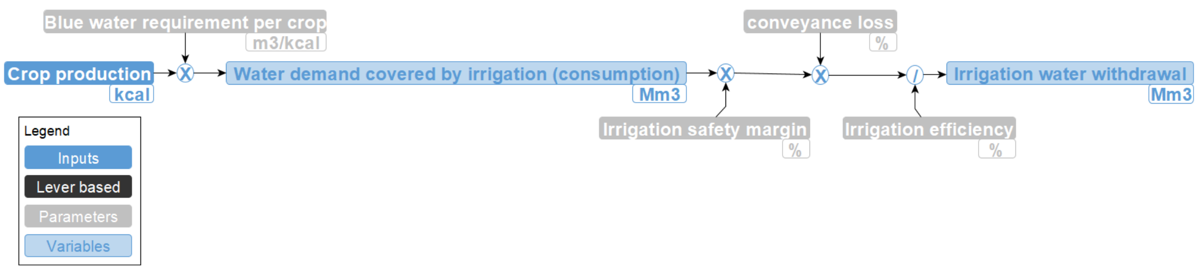

Figure 29 – Calculation tree for irrigation water demand and flows

First, we compute in Equation 79 the irrigation water demand by using blue water footprints[15] from Mekonnen & Hoekstra (2011):

[14] https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Livestock_unit_(LSU)

[15] **Water footprint (blue):** Used and defined by the Water Footprint Network (WFN). It can be defined as water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a

*Irrigation water demand[m3] = crop production[kcal] * blue water requirement per crop[m3/kcal]*

Equation 79 - Irrigation water demand

Since water requirements are at first assumed constant across Europe, these are readjusted with correction factors to account for country level variations (see Deliverable 4.1).

In this case, irrigation water demand corresponds to the net irrigation water consumption since we assume that water demand corresponds to the amount of water entirely consumed by plants for growth.

Water withdrawals for irrigation are derived from net irrigation consumption by counting efficiency losses, 20% of conveyance losses, and another 20% of safety margin (irrigation is generally greater than needed to prevent soil salination) (Bisselink et al., 2018):

*Irrigation water withdrawal[m3] = Irrigation water demand[m3] * irrigation safety margin[%] * conveyance losses[%] / irrigation efficiency[%]*

Equation 80 - Irrigation water withdrawal

Irrigation efficiencies have been provided by JRC, as well as irrigation safety margin and conveyance losses. Conveyances losses are not regarded as consumption since it assumed that water lost during conveyance is returned to the environment.

6.4.2 Water Stress

This section describes the procedure to calculate the water stress, considered as the most common warning sign regarding water scarcity (Rijsberman, 2006).

We use the Water Exploitation Index "normal" (WEI-normal), defined as the ratio between water consumption versus local water availability (see Equation 81). This indicator is derived from the WEI+, which was defined by EU member states in the Water Scarcity and Droughts Working Group in 2011 as the total consumption of water divided by the renewable freshwater resources (Faergemann, 2012).

In order to model waterstress. we decided to increase spatial and temporal granularity to better reflect the regions prone to water shortage and the periods when water scarcity is more acute.

This increment in granularity posed a modelling challenge since the water module is the only piece of the calculator that integrates this feature. Indeed, where other sectors use country level and yearly data, we decided to use finer spatial and temporal scales so as to obtain more reliable results. Consequently, the first step prior to the calculation introduced in Equation 81 is to adapt our aggregated output from the water demand section to the granularity given by the local water availability

product or taken from one body of water and returned to another, or returned at a different time (Hoekstra, 2011). Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

data by splitting yearly water demand values into semester water demand values thanks to semester shares derived from the monthly calibration data provided by JRC for historical water demands in EU28+1. The local water availability dataset used in the calculation is defined by the climate lever input.

WEI-normal[-] = total water consumption[m3] / local water availability[m3]

Equation 81 - Water stress

Note that WEI-normal uses local water availability which does not take into account upstream inflow.

6.5 Minerals

The following sections presents the calculation breakdown of the module. The section describes the calculation processes for mineral demand. The legend for the following section is indicated in Figure 30.

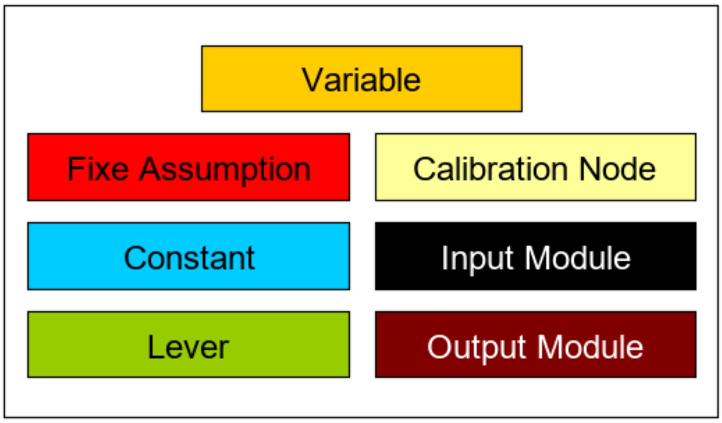

Figure 30 - Legend for the details of each node in the module to add comprehension

6.5.1 Mineral Demand

6.5.1.1 Direct and indirect demand

The goal of the node (Figure 31) is to compute the direct and indirect product demand. Inherently, the node leads to three kinds of outputs: European Production (Equation 82), European Exports (Equation 83) and European Imports (Equation 84). This inherently leads to direct demand (Equation 85) and indirect demand (Equation 86). After the node, the model provides product direct and indirect consumption per country not their potential for production (computed in the industry module).

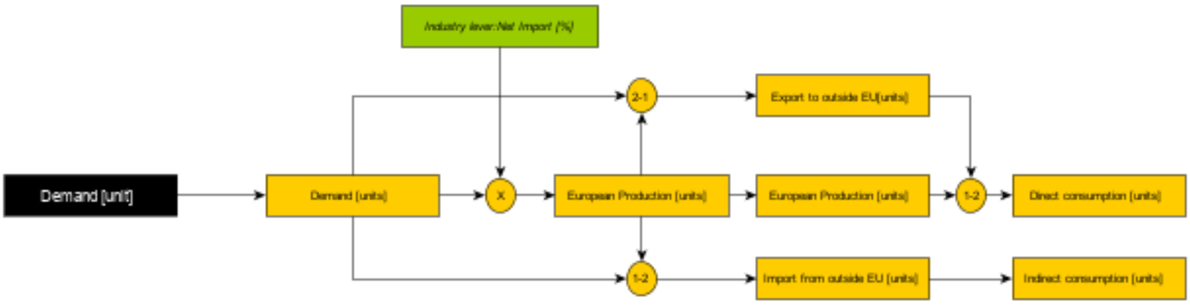

Figure 31 - Calculation nodes to compute the direct and indirect demand

$$Product\ Production\ [unit] = Product\ demand[unit] * Product\ Net\ Import[\%]$$

Equation 82 – Product trade equation

$$Product\ Export\ [unit] = Product\ Production[unit] - Product\ Demand[unit] > 0$$

Equation 83 – Net export equation for production in Europe and consumption outside of the EU

$$Product\ Import\ [unit] = Product\ Demand[unit] - \ Product\ Production[unit] > 0$$

Equation 84 – Net import equation for production outside Europe and consumption in the EU

$$Direct\ Demand\ [unit] = Product\ Production[unit] - \ Product\ Export\ [unit]$$

Equation 85 – Direct demand equation for European consumption with production in Europe

$$Indirect\ Demand[unit] = Product\ Import\ [unit]$$

Equation 86 - Indirect demand equation

6.5.1.2 Mineral Decomposition

The mineral decomposition node (Equation 87) computes the mineral amount for each product and sums them up per sector. Not showing in Figure 32 is the pathway which decompose minerals per sector inherently providing the mineral amount necessary per sector. The module keeps European Production instead of direct and indirect demand to facilitate the calibration operated at the EU28+1 granularity.

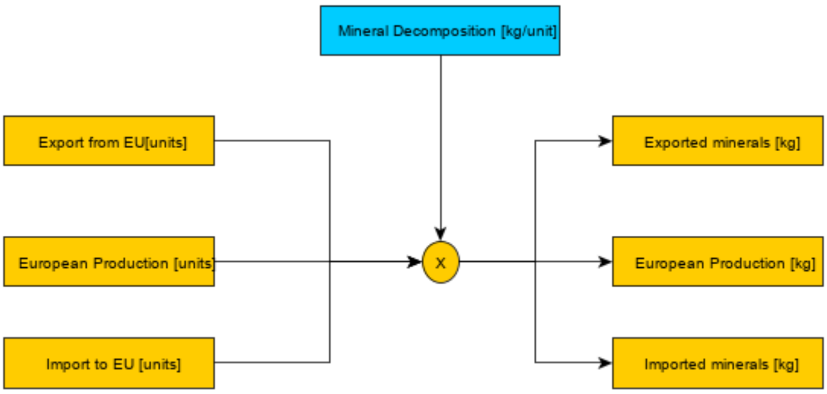

Figure 32 - Calculation nodes to compute the direct and indirect demand for minerals

$$mineral\ demand[kg] = Product\ demand[unit] * mineral\ amount[kg/unit]$$

Equation 87 - Mineral decomposition equation

6.5.1.3 Lever application

The lever application node serves to apply the levers sent by the industry module (see input section). Material switch (Equation 88) refers to switching a material by another such as steel by aluminium. The efficiency lever (Equation 89) indicates how production processes might lead to less loss in minerals as well as the efficiency of the mineral in the apparatus.

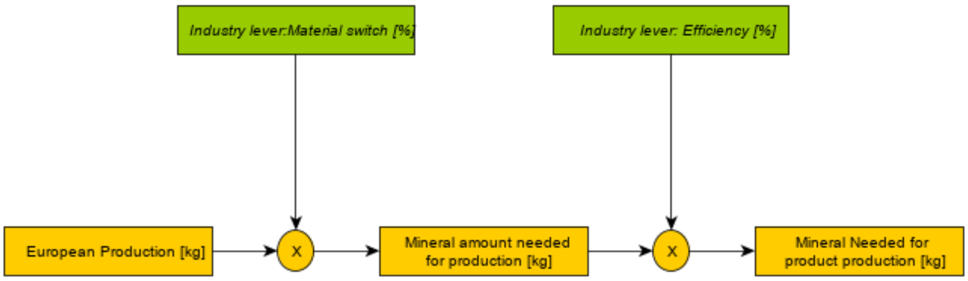

Figure 33 - Calculation nodes to compute the mineral amounts required after the efficiency and the material switch levers have been applied. The levers concern only the future time series between 2015 and 2050.

$$mineral\ demand[unit] = mineral\ demand[kg] - (mineral\ demand[kg] * material\ switch[\%])$$

Equation 88 - Material switch lever application

$$mineral\ demand[unit] = mineral\ demand[kg] * (100 - efficiency[\%])$$

Equation 89 - Efficiency lever application

6.5.1.4 Processing factors

Some minerals have been modelled in their processed form, namely steel and aluminium. The factors convert (Equation 90) the processed form into raw materials before sending the results to the TPE. This will give the output of mineral demand/consumption in the EU28 and Switzerland per sector in addition to indirect consumption.

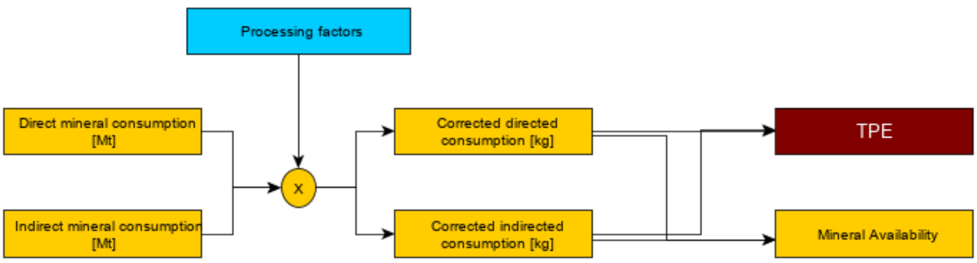

Figure 34 - Calculation nodes to compute raw mineral consumption. The outputs are sent to the Pathway Explorer (TPE) as well as continue processing in the mineral availability element of the module.

$$Raw\ Mineral\ Demand\ [Mt] = Mineral\ Demand\ [Mt] * Factor$$

Equation 90 - Converting equation from processed material to raw minerals

6.5.2 Mineral Availability

Mineral availability refers to the mineral demand for extraction. Extraction demand is intertwined with the use of scrap to make new products.

6.5.2.1 Technology Development

Technology development is connected to the use of scrap in the refining process. It is linked to the recycling capacity that has not been modelled in EUCalc. Nonetheless, as recycling capacity improves, more 'urban mines' will be available, decreasing the EU dependence onto international extraction. Apart from steel, aluminium, and copper, little information is available, so the inputs represent averages.

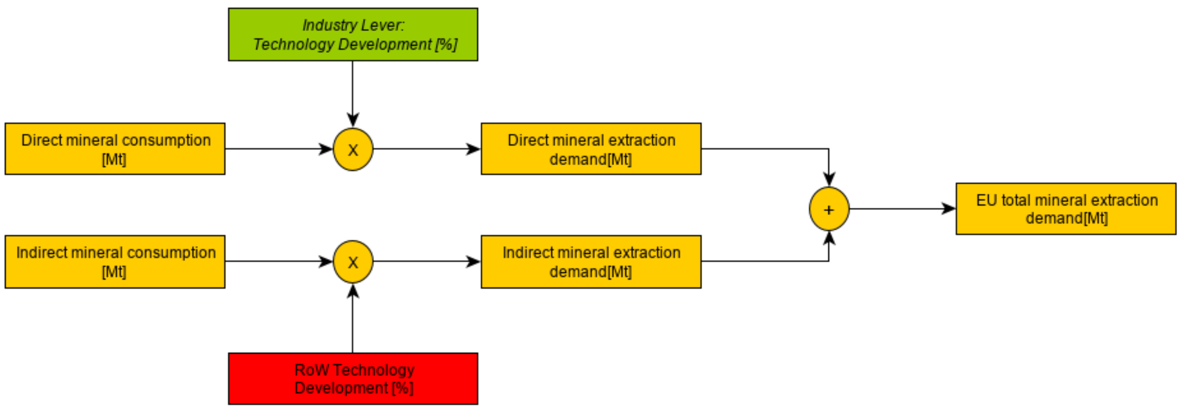

Figure 35 - Use of scrap in product manufacturing introduced by the technology development lever either in the European Union level or at the Rest of the World (RoW) level. For both the EU and RoW, an average is taken

$$Mineral\ extraction\ [kg] = Mineral\ Demand\ [kg] * technology\ development\ [\%]$$

Equation 91 - Application of secondary production

$$Total\ EU\ mineral\ extraction\ [kg] = Indirect\ mineral\ extraction\ [kg] + Direct\ mineral\ extraction[kg]$$

Equation 92 - Concatenation of direct and indirect consumptions

6.5.2.2 Reserves allocated to the EU28 and Switzerland

In order to find a fair distribution of mineral reserves, the model takes the assumption that from 2015 to 2050 each member of the population have the same amount of mineral. Figure 36 shows how the mineral reserves allocated to the EU28 and Switzerland is computed from 2015 onward (Equation 93).

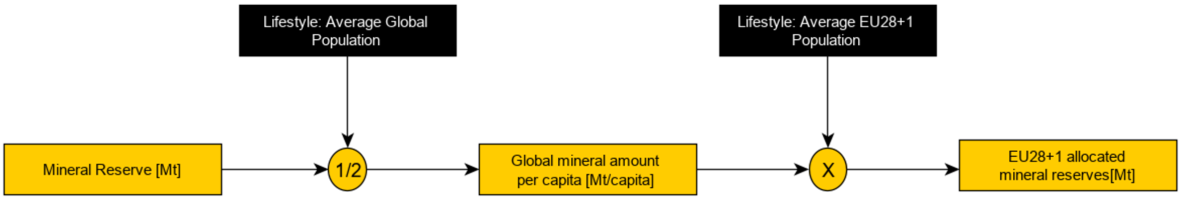

Figure 36 - Resource allocated to Europe using the fairness approach that in 2015, everybody in the world has the same amount of mineral resource necessary for their development

$$EU\ Mineral\ Reserves\ [kg] = \frac{mineral\ reserves[Mt]}{Global\ population} * EU\ population$$

Equation 93 - European allocated reserves calculation

6.5.2.3 Relative reserves left for EU28 and Switzerland and warnings

The node (Figure 37) computes the relative amount (Equation 94) of mineral reserves left in 2050 for EU28+1, based on the chosen trajectory, starting from 2015 The node computes in addition the warning level. If one mineral reserve (one for fossil fuel) is depleted (Equation 95), the warning level is 1 (orange). If two or more mineral reserves (one for fossil fuels) are depleted (Equation 96), the warning level is 2 (red).

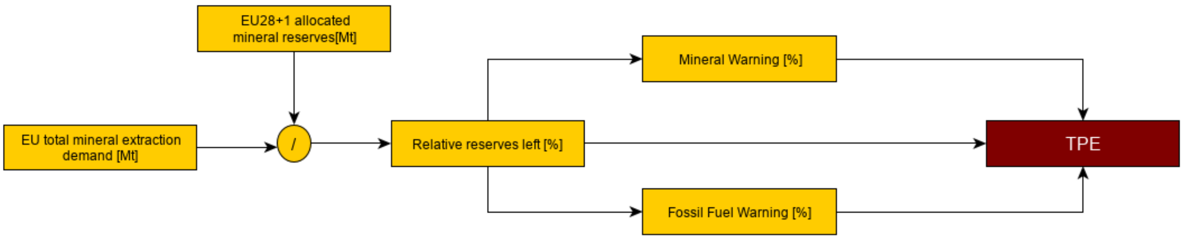

Figure 37 - Node demonstrating the association to compute the mineral reserve left in 2050. If the relative amount is >1 then the reserve allocated to Europe in 2015 are depleted. If <1 then the mineral reserves are not depleted in 2050. The warning levels are 1.

$$Relative\ Reserves\ [\%] = \frac{\sum_{2015}^{2050} EU\ Extraction\ Demand[Mt]}{EU\ Allocated\ Reserves[Mt]}$$

Equation 94 - Relative reserve calculation

$$If\ num(Relative\ Reserves\ [\%] > 1) = 1, then\ Warning = 1\ (orange)$$

Equation 95 - Orange warning logic

$$If\ num(Relative\ Reserves\ [\%] > 1) => 2, then\ Warning = 2\ (red)$$

Equation 96 - Red warning logic

7 References

7.1 Agriculture references

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Rounsevell, M.D.A., 2016. Human appropriation of land for food: The role of diet. Glob. Environ. Change 41, 88–98. https://doi.org/10.1016/j.gloenvcha.2016.09.005

Baudry, G., Bouchet, A., Forstenhaeusler, N., Price, J., Raffray, M., Mwabonje, O., Woods, J., 2019. D4.1_Land, land use, minerals, water and biodiversity input spreadsheets for calculator model. Imperial College London, University of East Anglia, EPFL.

Baudry, G., Mwabonje, O., Woods, J., Rankovic, A., Patrick, G., 2018. D4.2 Expert consultation workshop on land, land use and carbon stock dynamics (LULUCF), biomass provision (food, energy, materials) & minerals. Imperial COllege London, SeeChange.

Costa, L., n.d. European Calculator: Lifestyle documentation.

EFI & FAO, 2015. State of Europe's forests. European Forest Institute.

Baudry, G., Macharis, C., Vallée, T., 2018. Can microalgae biodiesel contribute to achieve the sustainability objectives in the transport sector in France by 2030? A comparison between first, second and third generation biofuels though a range-based Multi-Actor Multi-Criteria Analysis. Energy 155, 1032–1046. https://doi.org/10.1016/j.energy.2018.05.038

Ecorys, E3M lab, WIP, EFI, EuroCare, INUG, 2017. Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe (European Commission, DG for Research and Innovation).

IEA, IRENA, 2013. Production of Liquid Biofuels, technology brief. IEA-ESTAP, IRENA.

FAO, 2018. The future of food and agriculture, Alternative pathways to 2050. FAO, Rome.

Gustafsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. The methodology of the FAO study: Global Food Losses and Food Waste - extent, causes and prevention"- FAO, 2011. SIK Institutet för livsmedel och bioteknik.

Madeira, M.S., Cardoso, C., Lopes, P.A., Coelho, D., Afonso, C., Bandarra, N.M., Prates, J.A.M., 2017. Microalgae as feed ingredients for livestock production and meat quality: A review. Livest. Sci. 205, 111–121. https://doi.org/10.1016/j.livsci.2017.09.020

Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Nabuurs, G.-J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., Lindner, M., 2017. By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. Forests 8, 484. https://doi.org/10.3390/f8120484

Nijs, Ruiz Castello, Hildago Gonzaless, 2017. Baseline scenario of the total energy system up to 2050 (EU deliverable).

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

Rafiaani, P., Kuppens, T., Dael, M.V., Azadi, H., Lebailly, P., Passel, S.V., 2018. Social sustainability assessments in the biobased economy: Towards a systemic approach. Renew. Sustain. Energy Rev. 82, 1839–1853. https://doi.org/10.1016/j.rser.2017.06.118

Réséda, FranceAgriMer, Valoria, Idele, CNC, 2017. Gisements et valorisations des coproduits des industries agroalimentaires. Réséda.

Searle, S.Y., Malins, C.J., 2016. Waste and residue availability for advanced biofuel production in EU Member States. Biomass Bioenergy, Biomass & Bioenergy special issue of the 23rd European Biomass Conference and Exhibition held in Vienna, June 2015 89, 2–10. https://doi.org/10.1016/j.biombioe.2016.01.008

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., Vries, W. de, Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562, 519. https://doi.org/10.1038/s41586-018-0594-0

Strapasson, A., Woods, J., Mbuk, K., 2016. Land use futures in Europe How changes in diet, agricultural practices and forestlands could help reduce greenhouse gas emissions.

Wang, H., Rehman, K. ur, Liu, X., Yang, Q., Zheng, L., Li, W., Cai, M., Li, Q., Zhang, J., Yu, Z., 2017. Insect biorefinery: a green approach for conversion of crop residues into biodiesel and protein. Biotechnol. Biofuels 10, 304. https://doi.org/10.1186/s13068-017-0986-7

7.2 Biodiversity references

CBD. 2010. Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at its Tenth Meeting. X/2. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets. Secretariat of the Convention on Biological Diversity.

UNEP-WCMC and IUCN. 2018. Protected Planet: The World Database on Protected Areas (WDPA) (version August 2018). Cambridge, UK: UNEP-WCMC and IUCN. www.protectedplanet.net

Warren, R., J. Price, J. VanDerWal, S. Cornelius, and H. Sohl. 2018. The Implications of the United Nations Paris Agreement on Climate Change for Globally Significant Biodiversity Areas. Climatic Change 147 (3): 395–409.

7.3 Water references

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., & Siebert, S. (2003). Development and testing of the WaterGAP 2 global model of water use and availability. Hydrological Sciences Journal, 48(3), 317-337.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L. and De Roo, A., Impact of a changing climate, land use, and water usage on Europe's water resources, EUR 29130 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-80287-4, doi:10.2760/847068, JRC110927.

Davies, E. G., Kyle, P., & Edmonds, J. A. (2013). An integrated assessment of global and regional water demands for electricity generation to 2095. Advances in Water Resources, 52, 296-313.

EUROFER (2018) European Steel in Figures 2018. Link: http://www.eurofer.org/News%26Events/News/European%20Steel%20in%20Figures%202018.fhtml

European Aluminium (2018). Life-Cycle inventory data for aluminium production and transformation processes in Europe.

European Commission (2018). Competitiveness of the European cement and lime sectors. Link: https://publications.europa.eu/en/publication-detail/-/publication/07d18924-07ce-11e8-b8f5-01aa75ed71a1/language-en/format-PDF/source-65040600

FAO. 2018. Water use of livestock production systems and supply chains – Guidelines for assessment (Draft for public review). Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO, Rome, Italy.

Faergemann H. (2012). Update on Water Scarcity and Droughts indicator development, European Commission.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., & Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environmental Change, 23(1), 144-156.

Fricko, O., Parkinson, S. C., Johnson, N., Strubegger, M., van Vliet, M. T., & Riahi, K. (2016). Energy sector water use implications of a 2 C climate policy. Environmental Research Letters, 11(3), 034011.

Gerbens-Leenes, P. W., Hoekstra, A. Y., & Bosman, R. (2018). The blue and grey water footprint of construction materials: Steel, cement and glass. Water resources and industry, 19, 1-12.

Hoekstra, A.Y. (2011). The Water Footprint Assessment Manual, Water Footprint Network – WFN.

Khelil-Arfa, H., Boudon, A., Maxin, G., & Faverdin, P. (2012). Prediction of water intake and excretion flows in Holstein dairy cows under thermoneutral conditions. Animal, 6(10), 1662-1676.

Li, C., & Nwokoli, S. (2010). Investigating the water footprint of Tetra Pak Carton Economy's beverage portfolio.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters, 7(4), 045802.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences, 15(5), 1577-1600.

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. Ecosystems, 15(3), 401-415.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785.

Reynaud A. (2015). "Modelling Household Water Demand in Europe". JRC Technical Reports.

Rijsberman, F. R. (2006). Water scarcity: fact or fiction?. Agricultural water management, 80(1-3), 5-22.

Saladin M. (2002). Community water supply in Switzerland – What can we learn from a century of successful operation?. Skat Foundation.

Tschudin, A., Clauss, M., Codron, D., Liesegang, A., & Hatt, J. M. (2011). Water intake in domestic rabbits (Oryctolagus cuniculus) from open dishes and nipple drinkers under different water and feeding regimes. Journal of animal physiology and animal nutrition, 95(4), 499-511.

Unger, K., Zhang, G. and Mathews, R. (2013). Water Footprint Assessment Results and Learning: Tata Chemicals, Tata Motors, Tata Power, Tata Steel, Tata Quality Management Services, International Finance Corporation, and Water Footprint Network. Link: https://waterfootprint.org/media/downloads/WFN_2013.Tata_Industrial_Water_Footprint_Assessment.pdf

Van Oel, P. R., & Hoekstra, A. Y. (2010). The green and blue water footprint of paper products. Value of Water Research Report Series, 46.

7.4 Mineral references

Çiftçi, Dr Baris Bekir. 2019. *World Steel Association: Raw Materials.* February. Accessed May 2019. https://www.worldsteel.org/steel-by-topic/raw-materials.html.

Accenture Strategy. 2017. "Steel Demand Beyond 2030: Forecast Scenario." Paris: OECD, 28 September.

Backman, Carl-Magnus. 2008. "Global Supply and Demand of Metals in the Future ." *Journal of Toxicology and Environmental Health* 71 (18): 1244 - 1253.

Blagoeva, Darina T., Patrícia Aves Dias, Alain Marmier, and Claudiu C. Pavel. 2016. *Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU.* JRC Science for Policy Report, Petten: Joint Research Centre (JRC).

BRGM. 2015. *Critical minerals for the EU economy: foresight to 2030.* Report, Brussels: European Commission.

Canuto, Otaviano. 2014. *The Commodity Super Cycle: Is This Time Different? .* Economic Premise Note, The World Bank, Washington D.C.: The World Bank.

Coulomb, Renaud, Simon Dietz, Maria Godunova, and Thomas Bligaard Nielsen. 2015. *Critical minerals today and in 2030: an analysis of OECD countries .* Policy Paper, Centre for Climate Change Economics and Policy, London: Centre for Climate Change Economics and Policy.

Department of Mining and Tunnelling, University of Leoben, Austria. 2004. *Minerals Planning Policies and Supply Practices in Europe.* Commissioned by the European Commission Enterprise Directorate General under Contract n° ETD/FIF 2003 0781, Brussels: European Commission .

Dobbs, Richard, Jeremy Oppenheim, Fraser Thompson, Marcel Brinkman, and Marc Zornes. 2011. *Resource Revolution: Meeting the world's energy, materials, food, and water needs.* Report, McKinsey Sustainability & Resource Productivity Practice, McKinsey Global Institute, London: McKinsey & Company.

Elshkaki, Ayman, T.E. Graedel, Luca Ciacci, and Barbara K. Reck. 2016. "Copper demand, supply, and associated energy use to 2050." *Global Environmental Change* 39: 305 - 315.

Eurostats. 2019. *Physical Imports and exports.* April. Accessed May 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Physical_imports_and_exports#Physical_trade_by_stage_of_manufacturing.

Global CCS Institute. 2010. *Foresight projections .* Accessed May 2019. https://hub.globalccsinstitute.com/publications/global-technology-roadmap-ccs-industry-steel-sectoral-report/foresight-projections.

HistAlu. n.d. *La production d'aluminium : de la bauxite à l'alumine.* Accessed May 2019. http://www.histalu.org/laluminium/les-grandes-etapes-de-production/la-production-daluminium-de-la-bauxite-a-lalumine/.

International Aluminium Institute. 2019. *Primary Aluminium Production.* 23 April. Accessed May 2019. http://www.world-aluminium.org/statistics/.

International Resource Panel. 2019. *Global Resources Outlook 2019: Natural Resources for the Future We Want.* Report, New York: United Nations Environment Programme.

Reichl, C., M. Schatz, and G Zsak. 2019. *World Mining Data 2019.* Report, Vienna: Austrian Ministry of Tourism and Sustainability.

Rogich, Donald G., and Grecia R. Matos. 2008. *The Global Flows of Metals and Minerals.* Open-File Report, US Geological Survey, Reston, VA: US Geological Survey.

Schüler, Doris, Stefanie Degreif, Peter Dolega, Diana Hay, Andreas Manhart, and Matthias Buchert. 2017. *EU raw material import flows – acknowledging non-EU environmental and social footprints.* Policy Brief, Brussels: Strategic Dialogue on Sustainable Raw Materials for Europe (STRADE).

Torres, Aurora, Jodi Brandt, Kristen Lear, and Jianguo Liu. 2017. "A looming tragedy of the sand commons." *Science* 970-971.

U.S. Department of Energy. 2007. *U.S. Energy Requirements for Aluminum Production Historical Perspective, Theoretical Limits and Current Practices.* Report, U.S. Department of Energy.

United Nations. 2004. *World Population to 2300.* New York: Department of Economic and Social Affairs.

United States Census Bureau. 2011. *World Population: 1950 - 2050.* United States Census Bureau. June. Accessed May 15, 2019. https://www.census.gov/library/visualizations/2011/demo/world-population--1950-2050.html.

US Department of the Interior. 2019. "Mineral Commodity Summaries 2001: Appendix C." *U.S. Geological Survey.* Accessed May 2019. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcsapp2019.pdf.

US Geological Survey. 2019. *National Minerals Information Center: Commodity Statistics and Information.* Accessed April 2019. https://www.usgs.gov/centers/nmic/commodity-statistics-and-information.

World Steel Association. 2019. *Statistics.* Accessed May 2019. https://www.worldsteel.org/steel-by-topic/statistics.html.