Horizon 2020 Societal challenge 5
Climate action, environment, resource
Efficiency and raw materials

D3.4: FINAL REPORT ON THE COMPLEXITY SCIENCE AND INTEGRATION METHODOLOGIES

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3.2	ELKE STEFHEST	13/01/2020	SUBMISSION OF THE UPDATED DOCUMENT, UPDATES IN SECTION 3.12

Table of Contents

LIST of FIGURES

Executive summary

This work package (WP3), concerns the development and implementation of the complexity science in all the SIM4NEXUS case studies. This deliverable is an important outcome from Task 3.4, delivering in detail the modelling for complexity science with regards to the Nexus, as well as the models developed using System Dynamics as the preferred method of integration (Deliverable 3.2).

SIM4NEXUS developed System Dynamics Models (SDM) as the integration methodology for Complexity Science, selected and suitable for all the Case Studies. The first stage for SDM was the development of the Conceptual Complexity Science models to be used as tools for the development of the SDMs. The Conceptual Complexity Science models have been developed and drawn by each Case Study team, with the help and assistance of WP3 and WP4 key persons, with continuous consultation and participation to weekly regular teleconferences, several face-to-face meetings with WP3 key persons from IHE-Delft, so as to be compatible and suitable as tools for the quantitative SDM models. All the conceptual models were completed in Year 2 and submitted as Milestone MS18.

In Year 3 (M25-M36) the SDM for each Case Study has been developed, based on the Conceptual models, in STELLA environment. A participatory process has been followed again, but with the following differences:

Four Case Studies (Sardinia, Andalusia, South West UK and Greece) developed the SDM on their own, while for the remaining eight Case Studies, the SDM was developed by IHE-Delft (Janez Susnik and Sara Masia) in consultation with the local teams at each Case Study.

Both the Conceptual models and the SDMs take into account the scope of each Case Study, as defined in WP5, the intended policies, as defined in WP2 and the requirements for further development of the SDM to a Serious Game in WP4 in Year 4.

This report shows the Conceptual Complexity Science graphs and the System Dynamic Models (structure and components), to be used as tools for the next stage of SDM development, i.e. the population of the models with quantitative data in Year 4 (Task 3.5). For each Case Study the components and the structure of the SDM is shown in detail and with explanations and clarifications for its structure.

The Conceptual Complexity Science and System Dynamic Models tools for each Case Study are presented in the following order:

A. Regional Case Studies (Sardinia, Andalusia, South West UK)
B. National Case Studies (Greece, Latvia, Sweden, Netherlands, Azerbaijan)
C. Transboundary Case Studies (France-Germany, Germany-Czech Republic-Slovakia)
D. Higher Level (European, Global)

WP3, and especially T3.4 is linked to all other SIM4NEXUS work packages, but is especially closely linked to WP2 (policy analysis), WP4 (serious game development) and WP5 (the case studies). As defined in the Grant Agreement, it plays a critical role in the development and implementation of the complexity science models, and critically relies on input regarding case-study level policy analysis, data from the

thematic models, expertise from the case study leaders and stakeholder groups and itself forms a critical input for the Knowledge Elicitation Engine (KEE) and Serious Game (SG) in SIM4ENXUS

Task duration: Task 3.4 started in Month 4 and has been completed by Month 36, with a duration of 32 months. This Deliverable (3.4) is the final outcome for this Task.

Changes with respect to the DoA

There are no changes with respect to the DoA.

Dissemination and uptake

Although this Deliverable is public, the content is technical and hard for the general public. The audiences to be targeted are primarily researchers and academics at a global scale. It is also useful for stakeholders in the Nexus domain, and obviously for the EC experts.
Within the project the Deliverable targets all the project partners, especially those involved in the 12 Case Studies.

Short Summary of results (<250 words)

SIM4NEXUS selected System Dynamics Modelling (SDM) for the Complexity Science models for 12 Case Studies. Deliverable 3.4 presents the Conceptual models and the SDMs for each Case Study in detail, with a description of each Case Study. These are the main outcomes from Task 3.4 and show the modelling of the Nexus interconnections and interactions in case studies that range from regional to national, continental (European) and global. Although the basis of analysis is similar, there are significant differentiations with regards of the priorities and significance of several Nexus components, due to the stakeholders' requirements for each Case Study.

Evidence of accomplishment

This report, screenshots of the models, the models in STELLA environment, which have all been developed and remain with the teams that are leading each Case Study or with IHE-Delft.

Glossary / Acronyms

As the document is being written, terms and glossary will be added here as needed. Before the last version is submitted this list will be re-arranged alphabetically by the lead author.

TERM	EXPLANATION / MEANING
CAP	COMMON AGRICULTURAL POLICY
GHG	GREENHOUSE GAS EMISSIONS
KEE	KNOWLEDGE ELICITATION ENGINE
SDM	SYSTEM DYNAMICS MODEL
SG	SERIOUS GAME
SIMR	REGIONAL MULTISECTORAL WATER SYSTEM -SARDINIA
STELLA	SDM GRAPHICS ENVIRONMENT

1 Introduction

This Deliverable (3.4) is the main and final outcome from Task 3.4., a major Task in WP3. The goals for the Task and the Deliverable are the following:

A. Review and selection of appropriate complexity science methodologies and integration approach(es) for each case study. Initially the following complexity/integration methodologies were considered: System Dynamics Modelling, Cellular Automata, Fuzzy Cognitive Mapping, Material Flow Analysis. The comparison took place during the first year of the project and is summarised in other deliverables (e.g. Deliverable 3.2)

System Dynamics Modelling was selected as the most appropriate methodology for Complexity Science integration for SIM4NEXUS for the following reasons:

- It can be understood by stakeholders with its graphics environment, so as to facilitate the validation process
- It is very flexible and can integrate different types of data and components in a single model
- It is suitable for the type of modelling required for the development of the Serious Game (WP4) and can be automatically translated to Python for the Knowledge Elicitation Engine (KEE) of the Serious Game.
- It can make good use of the lumped, downscaled outputs from the thematic models (Task 3.2 and Task 3.3)

B. Development of complexity science model(s) for each case study at conceptual stage, at a higher level of integration and a lower level of detail, as needed, for WP4 (M13-M24)

This goal was achieved in Year 2 and the outcome was submitted as Milestone MS18 (short report).

C. Development of detailed SDMs for each Case Study out of the conceptual models, updating and revising them during Year 3, based on specific implementation issues, as needed (M25-M36)

The SDMs for all the Case Studies have been developed and are presented in detail in this report.

1.1 Structure of the document

In WP3, SIM4NEXUS intends to develop System Dynamics Models (SDM) as the integration methodology for Complexity Science, for all the Case Studies. The first stage for SDM is the development of the Conceptual Complexity Science models to be used as tools for the development of the SDMs. The Conceptual Complexity Science models have been developed and drawn by each Case Study team, with the help and assistance of WP3 and WP4 key persons (Lydia Vamvakeridou-Lyroudia, Janez Susnik and Sara Masia), with continuous consultation and participation to weekly regular teleconferences, so as to be compatible and suitable as tools for the quantitative SDM models. All the conceptual models were completed in Year 2 and submitted as Milestone MS18.

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F. National Case Studies (Greece, Latvia, Sweden, Netherlands, Azerbaijan)
G. Transboundary Case Studies (France-Germany, Germany-Czech Republic-Slovakia)
H. Higher Level (European, Global)

This document is structures as follows: Chapter 2 presents the interactions with other Work Packages. Chapter 4 details the models for Each Case Study, while Chapter 4 presents the Conclusions and further planned work for WP3.

2 Interactions with other Work Packages

This work package, concerned with developing and implementing the complexity science in all the SIM4NEXUS case studies is linked to all other SIM4NEXUS work packages, but is especially closely linked to WP2 (policy analysis), WP4 (serious game development) and WP5 (the case studies). As defined in the Grant Agreement, it plays a critical role in the development and implementation of the complexity science models, and critically relies on input regarding case-study level policy analysis, data from the thematic models, expertise from the case study leaders and stakeholder groups and itself forms a critical input for the Knowledge Elicitation Engine (KEE) and Serious Game (SG) in SIM4ENXUS. These interactions are an iterative process within the project. Figure 1.1.1 summarizes the interconnections between WP3 tasks and efforts in other Work Packages of the project.

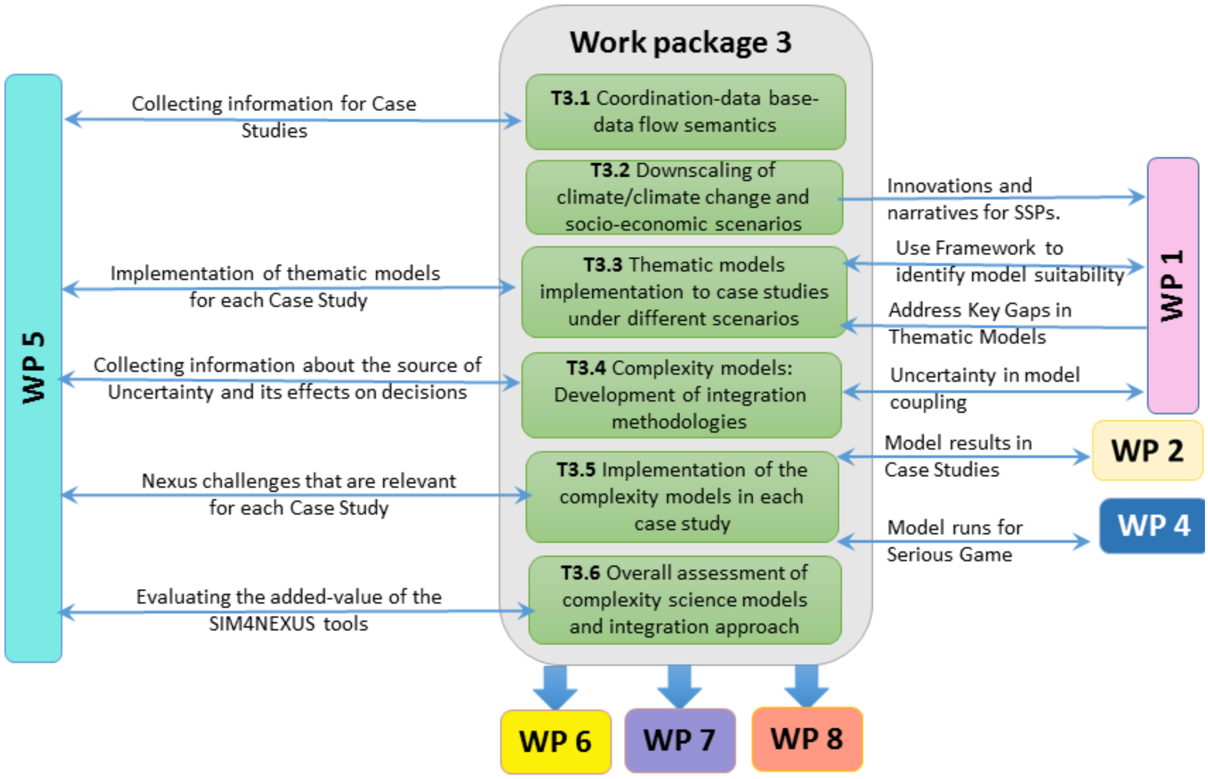


Figure 1.1.1: Task by Task diagram of Work Package 3 and interactions with other Work Packages in the project as established in the SIM4NEXUS Grant Agreement

2.1 Interactions with WP1

Within WP1 tasks, the complexity science models are guided to some degree by the extensive analysis carried out in T1.1 "scientific Inventory of the Nexus" (months 1 – 9). Identification of interactions between systems is a key step in the development of the complexity science models. Also inputs from Task 1.3 "Thematic models capacity for Nexus and Policy" (months 1 – 12) aided thematic model selection for each individual case study based on their own requirements and desires.

2.2 Interactions with WP2

Activities in Task 2.1 “Identification of policy areas” (months 3 – 12) directly link to efforts in WP3 by identifying key driving nexus policy areas worldwide and in Europe. In addition, a key link exists with Task 2.2 “review of nexus-related policies for each national and regional SIM4NEXUS case study” (months 9 – 26), an extensive and exhaustive review of nexus relevant policies for each SIM4NEXUS case study. This review is critical in helping to define coherent policy scenarios in the modelling exercises that are consistent and relevant to case-study level policy targets currently in operation.

2.3 Interactions with WP4

In the Grant Agreement, a two-way interaction between WP3 and WP4 exists. This link is absolutely critical, and maintaining a close collaboration with personnel in WP4 is essential to the successful development and implantation of the SGs. WP3 and 4 have worked very closely on a number of activities that mutually help both WPs:

- a consistent naming convention for complexity science model variables that are also used for SG development purposes. With this, the WPs can ‘talk’ to each other where model parameters are concerned.
- Establishing an online model parameter and data viewer/tool. In this tool, all complexity science data is stored in a single database, and made available via an online tool using PowerBi. All data from multiple sources and models, across multiple SSPs are harmonised and made easily available both to model developers in WP3, to SG developers in WP4, and to the case studies in WP5.
- WP3 feeds the system of equations for each case study to WP4 SG developers, by translating the model in Python. From this start point, the SG is developed, including the game logic, indicator elaboration and policy scenario layout/game logic.

2.4 Interactions with WP5

The interaction between WP3 and WP5 is also critically important to the successful development of the complexity science models, as indicated by the numerous links depicted in **Error! Reference source not found.**. The interaction, which has been very strong since the start of the project has included:

- Assessing local policy relevance in the nexus for each case study, and using this to guide to focus are of the model to be developed, and to decide on policy scenarios to be modelled;
- Developing, in collaboration with local stakeholder groups, conceptual models of the nexus system to study in the case study. This conceptualisation is a critical step in the process, and requires a lengthy process to be properly completed;
- Using the conceptual diagrams, thematic model requirements were decided upon, along with locally available data that were also relevant for the modelling;
- Also using the conceptual diagrams, and still in close cooperation with case study partners, development of the quantitative complexity science models, using the system dynamics modelling (SDM) paradigm. These models feed the SG for each case;
- Analysis and verification of results, including considering options for further add value to the work in SIM4NEXUS for each case study.

Figure 2.4.1 shows the 12 Case Studies in SIM4NEXUS, together with the main goals for them, as defined by stakeholders in WP5.

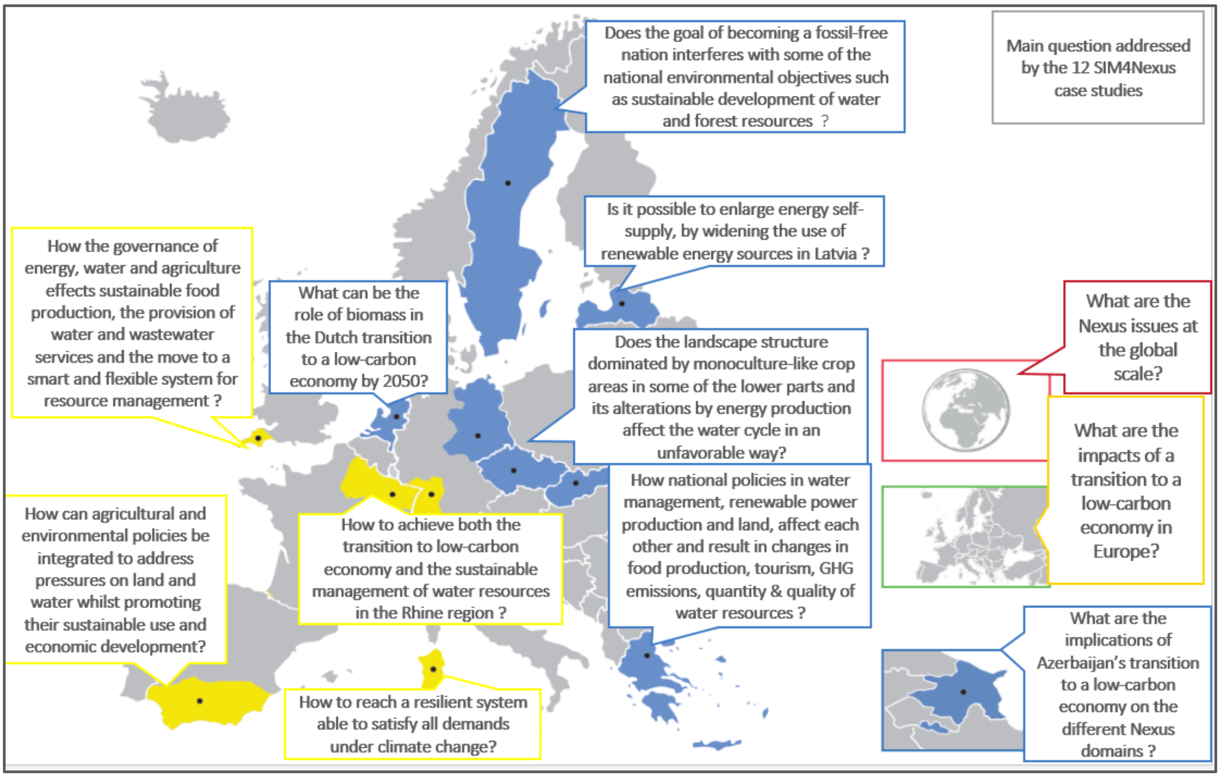


Figure 2.4.1: The 12 Case Studies in SIM4NEXUS and their main goals as defined by the stakeholders.

3 Description of the first implementation of the complexity science models for all the SIM4NEXUS Case Studies

This section presents a short description of each case study, including physiographic setting and main nexus challenges to be addresses. It also presents the final conceptual models that feed development of the complexity science SDMs and describes the SDMs developed in detail (components and structure). The SDMs have been developed in STELLA ® environment.

3.1 Sardinia case study

3.1.1 Short description of the case study

In Sardinia, as in many Mediterranean areas, balance between water demand and availability has reached critical and unsustainable levels of exploitation. The Mediterranean region has become particularly vulnerable to drought, with extremely variable rainfall patterns and decreasing effectiveness to regenerate water resources. Furthermore, water resources are subject to strong conflicts between sectors leading to overexploitation and unsustainable degradation. A sharp increase in agricultural productivity over the last 50 years has been associated with both intensification and mechanization of agricultural processes, with a strong adoption of irrigation practices. Currently, Mediterranean agriculture reaches a share between 50 and 80% of total water consumption (in Sardinia about 70%), due to a strong dependence on irrigation to support and increase yields of different crops (EEA, 2009). This intensification leads to several negative impacts on the ecological properties of agricultural systems, but also to eutrophication and water degradation (Langmead et al., 2007). Important sectoral interests (agriculture, domestic, tourism, ecosystems) must be both safeguarded and balanced, following social and economic priorities. Conflicts between sectors for water resources emerge even more critically because higher demand occurs during summer months when water resources are scarcer.

Many studies suggest that intensive agricultural areas will continue to increase in the future (Busch, 2006) in association with a growing irrigation demand. Furthermore, urban development is expected to increase throughout Europe (Reginster and Rounsevell, 2006) with rather strong concentrations of demands of water and energy resources for civil use and thus greater susceptibility to possible resources crises. Further pressure on water resources would be hardly sustainable in the Mediterranean, given climate changes expected for the region. Climate models predict warmer and drier summers for southern Europe with a progressive increase in the frequency and severity of droughts (Sousa et al., 2011). In southern Europe, soil water content will decrease, saturation and runoff limited to winter and spring periods (García-Ruiz et al., 2011). This translates into a reduction in the flow of rivers and surface and ground water resources (Senatore et al., 2011), with negative impacts on various ecosystems. A reduction in water resources is often associated with a deterioration in water quality, because less water is available to dilute pollutants. Furthermore, saline intrusion are affecting coastal aquifers, especially those more overexploited.

Following the Water Framework Directive issued by the European Community, the Sardinia region introduces with the Regional Law 19/2006 the concept of Regional Multisectoral Water System (SIMR) with the aim of achieving management and good status of water resources. The coordinated management of the regional multi-sector water system is entrusted to the Water Authority of Sardinia

(ENAS), with a subdivision of the regional territory into seven Hydrographic Districts. On the basis of specific monitoring programs and assessment of the impact of human activities on the status of water bodies, a Management Plan for the Hydrographic District of Sardinia (PdG-DIS) was drawn with a program of intervention measures. The PdG-DIS was adopted by the Sardinian Basin Authority in 2010 and subsequently by the President of the Council of Ministers in 2013, with an update of the PdG-DIS completed in 2016. The characterization and monitoring of all water bodies was first accomplished in 2009-2010, revealing a high quality of surface water (high quality in 77.7% of the monitored surface bodies, fair in 19.4% and poor in 2.9%), and somehow lower quality for groundwater (high quality in 54.9% of monitored sites, fair in 20.4% and poor in 24.7%). The main causes of water degradation are due to the release of organic substances related to livestock activities and in the use and dispersion of phytosanitary products, synthetic and organic fertilizers. Furthermore, saline intrusion phenomena can occur due to excessive exploitation of aquifer in coastal areas.

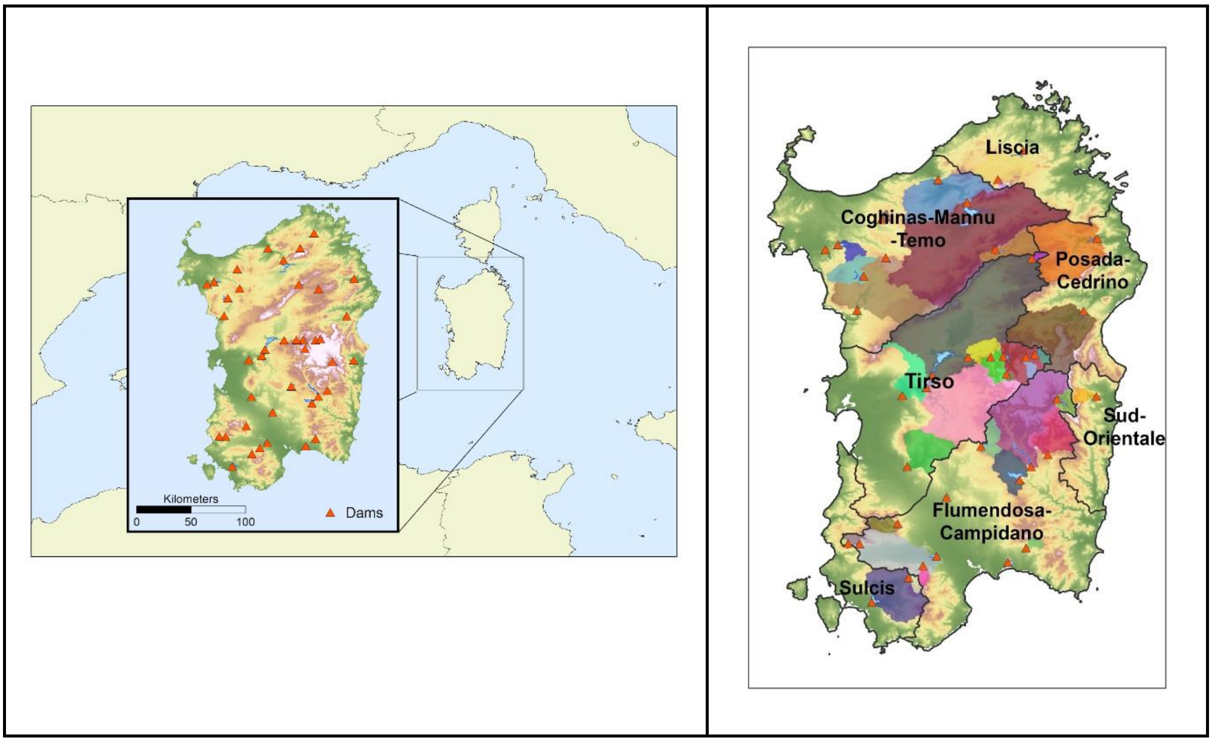


Figure 3.1.1 The figure on the left represents the position of Sardinia in the middle of Mediterranean. The figure on the right show both the seven Hydrographic districts, and the water basins upstream to the different red Dams/Reservoirs are represented as red triangles

The SIMR is divided into seven hydrographic districts or "water systems". Each system consists of an interconnected set of artificial reservoirs (resource nodes) and centers of demand (civil, agricultural, industrial, hydroelectric and environmental), with a set of connection lines between resource nodes and centers of demand. The SIMR include 32 artificial reservoirs (with a total current capacity of approximately 1,865 million cubic meters) and 25 small dams, to which are added 5 hydroelectric plants and 47 pumping plants that convey water over 850 linear kilometers of large aqueducts and just over 200 km of canals. Water distribution serves a population of 1.6 million inhabitants, about 160,000 ha of cropland equipped for irrigation and 11 industrial areas. The Regional Multisectoral Water System makes available 75% of the water resources used in Sardinia for the various uses, mainly using surface water resources, while the remaining 25% is extracted from underground resources and used mostly for localized uses. The authorized capacity of reservoirs in Sardinia has undergone a significant increase in recent years which has increased overall water availability. Nevertheless, the system is still subject to a high vulnerability due to strong climatic fluctuations that require careful management. Furthermore, the management plan highlights a low capacity for recovery, given that the water resources in the reservoirs are re-established very slowly over time.

Use of water for categories of users in Sardinia

The regional multi-sector water system is responsible for the Sardinian water supply system, including the collection and storage of surface water, mostly stored and regulated by artificial reservoirs, and the wholesale distribution of raw water to various water services operators or user categories. These managers are then responsible for handling and distributing to end users. The water users are divided according to the following macro-categories:

- civil uses: those relating to human consumption and hygiene services, both collective and private;
- agricultural uses: those related to agricultural purposes;
- industrial uses: those related to the use of water resources for industrial purposes;
- environmental uses: those that ensure a share of minimum environmental flows necessary to guarantee the natural protection of aquatic ecosystems

Considering the volumes distributed by the Multi-Sectoral Water Service over the period between 2008 and 2014, it is evident that the total water volume supplied rose from 594.04 Mm3 to 684.60 Mm3 over 6 years, with an increase of about 15 %. This has been facilitated by the increase in recent years of the authorized capacity of the reservoirs in Sardinia, rather than by favourable climatic conditions. In the period under consideration, water volumes for irrigation use in agriculture increased by 31%, going from 330.13 Mm3 to 433.13 Mm3, while the volumes of raw water for industrial use decreased by about 27%, passing by from 31.20 Mm3 in 2008 to 22.53 Mm3 in 2014. The civil sector remained substantially unchanged, around 220-230 Mm3 in the period 2008-2014. As of 2014, agriculture is the sector that uses the largest proportion of water with a share of 63.27% of the total, while the civil and industrial sectors use the remaining 33.44% and 3.29% of water resources respectively.

Following data analyses from the 6th Agricultural Census of 2010, it can be stated that 73% of the total volume for irrigation uses is derived from aqueducts and canals through irrigation reclamation consortia. The collective irrigation in Sardinia, served by the Multi-Sectoral Water Service, is managed by 9 Reclamation Consortia: Nurra; Northern Sardinia; Gallura; Central Sardinia; Ogliastra; Oristano; Southern Sardinia; Cixerri; Basso Sulcis. Sardinian agriculture is predominantly extensive, which favors an important balance between soil management, biodiversity and conservation of resources and natural landscapes (77.2% of agricultural areas classified as with low intensity, 17.4% with medium intensity and 5.5% with high intensity). These types are mainly associated with permanent meadows and pastures (a total of 692,990 ha, which corresponds to 20% of Italian pastures).

The area actually irrigated in Sardinia in 2010 constitutes only a small portion of the total agricultural area (5.5%). Prevalent irrigation systems are mainly managed with high-efficiency technologies (53% with sprinkler and 29% with micro-irrigation methods), while other more traditional and less efficient systems such as submersion and surface flow respectively cover only 5% and 6% of irrigated area. The prevalence of distribution irrigation networks of pipelines with pressurized systems in Sardinia is more than double the national one (70.3% against 32.1%), favouring the trend towards more efficient irrigation methods. According to the 6th Agricultural Census of 2010, irrigated areas are mainly represented by forage crops alternated (29%), vegetables (20%), maize and green maize (11.6%), grapevines (8.7%), olive trees (6.5%), rice (5.5%), citrus fruits (5.5%), permanent meadows and pastures (4.6%), cereals for the production of grain - excluding corn and rice (3.9%), fruit crops (3%) and potatoes (0.5%).

In Sardinia the water service for industrial purposes is managed by seven industrial consortia. The CACIP of Cagliari alone used 15.269 Mm3 of water in 2012, equal to 67% of the total water resource supplied in Sardinia for industrial uses. Other 4 Mm3 and 2.6 Mm3 of water were supplied to the industrial area of Sassari (CIP Sassari) and Sulcis Iglesiente (CIP Sulcis Iglesiente) with shares of 17.6% and 11.5% of water use respectively in Sardinia for industrial uses. Uses for the other 4 Industrial Consortia are not very significant. Given the severe economic crisis in most of the industrial area of Sardinia, which has put this sector in serious difficulty with uncertain future developments and drastic repercussions on employment, there is a drastic drop in water and energy consumption for industrial purposes.

Activities for civil uses account for collection of water resources, purification, adduction to urban centres, distribution to users, collection of wastewater and consequent purification. For the production and distribution of drinking water, a system of 45 water purifiers is used, out of a total of 50 distributed throughout the entire region. In addition to the exploitation of 220-230 Mm3 of surface water accumulated in the reservoirs, managed by ENAS, there is an additional water system of 50-70 Mm3 consisting of small springs and wells, whose production capacity is linked to climatic trends. In addition, approximately 4300 km of aqueducts guarantees drinking water supplies, with a network of 7700 km of urban distribution and 6400 km of sewage, serving 346 urban centres and a resident population of 1,528,000 persons.

Climate trends show high and significant variability of precipitations with more and more recurrent droughts that exacerbate water imbalances between available water resources and sectoral needs. The Sardinia Region has implemented a warning system monitoring water resources in the reservoirs and anticipating water crises. The General Directorate of the Regional Agency of the Hydrographic District of Sardinia publishes every month a "Bulletin of the artificial reservoirs of the multi-Sectoral water system of Sardinia" which reports the quantity of water present in the reservoir system, and percentage of the total authorized capacity. Available water resources are then related with estimated needs for different sectors, developing water balance scenarios in the short and medium term for all the reservoirs of the regional multi-sector water system. This information is transformed into drought indicators for the water systems relevant as planning tools, assessing the risks and proactively managing eventual water crises. Activation of specific procedures functional to crisis management plan, based on drought indicators and water resources availability, puts in act specialized infrastructures for management rules under emergency supply risks (restrictions for specific sectors; combined and optimal use of surface and underground resources; other mitigation measures).

Sardinia, as many other Mediterranean regions, must implement a sustainable approach to water management, focused on water conservation and more efficient use to reduce conflicts between sectors. This approach must take into account an equitable distribution of water resources between different sectors, economic needs and social priorities, but also the need to preserve the ecology of freshwater ecosystems. In many river basins, water resources are already widely exploited and their reliability is threatened by the decline induced by climate change in recharging inland waters and by the increase in irrigation demand (Majone et al., 2012). While driven by strong interests to secure food provisions, an increase in irrigation in the Mediterranean may not be totally sustainable (Olesen et al., 2011). Irrigation requirements in the Mediterranean is projected to increase between 4 and 18% by the end of the century due to climate change alone (Fader et al, 2016). In particular, irrigation requirements simulated for different crops for 3 agricultural areas (Sulcis, Gallura and Nurra) in Sardinia, show average increases of around 8-10% for 2050 compared to present conditions (Masia et al., 2018). The data from Masia et al. (2017) show that over the same period the inflow in the reservoirs can decrease between 5 and 20% and the evaporation losses from the water surface bodies in the reservoirs increase by about 10%. To meet these criticalities in agriculture, irrigation systems should increase to support food security (Daccache and Lamaddalena, 2010) with new infrastructures and investments that would require for more efficient systems (van der Velde et al., 2010). All this would require changes in institutional and market conditions with a more cautious water management that includes prices and recycling policies to ensure adequate future water supply and prevent tensions between different sectors (García-Ruiz et al., 2011).

To support effective and targeted adaptation measures, planning should make use of results based on solid scientific research that takes into consideration measures of the uncertainty of climate change forecasts and the impacts associated with it. To this end, considering the multiple interests related to the management of inland waters, it is appropriate to involve all the interested parties and coordinate an integrated management of water resources in the planning processes, which makes use of an optimal complementarity in the use of surface waters and groundwater and which recognizes links between quantity and water quality in restoring natural systems for sustainable adaptation planning (World Bank, 2007). It is important to develop and optimize the use of tools that can evaluate available water resources balances and conflicts between various sectors, as already considered in the "Bulletins of the artificial reservoirs of the multisectoral water system of Sardinia" of the General Directorate of the Regional Agency of the Hydrographic District Of Sardinia, but also more widely assess the effect of various policies, technologies and adaptation practices in the field of water resources management comprehensively on a water-energy-food-land-climate NEXUS. The obstacles to adaptation in the management of water resources are not only technical, but also include problems related to human and institutional capacities, financial resources, lack of awareness and communication

3.1.2 Evolution and description of the conceptual diagram

To articulate a conceptual framing for the Sardinia case, interactive workshops with local experts and stakeholders, including academics, public authorities, decision makers and unions, were carried out to define the key nexus sectors to consider, identify sector drivers, relevant key policies, and crucially, how sectors and policies interact. At the end of a preliminary process a conceptual diagram was expanded in terms of: i) nexus sectors, which now include energy, land and food; ii) spatial scope, from district level to integrating sectorial interactions for the whole Sardinia region; and iii) increasing the detailed representation of nexus sectors in the model, including the policies that affect them. Figure 3.1.2 shows a preliminary conceptual system diagram developed for the Sardinia fast-track, on which further quantitative model development was based.

It should be pointed out that the preliminary Conceptual Model for Sardinia was the basis for the fast track approach adopted by SIM4NEXUS, to create the proof of concept for a Case Study from start to finish (from the Conceptual to Serious Game) and has been published (Susnik et al, 2018).

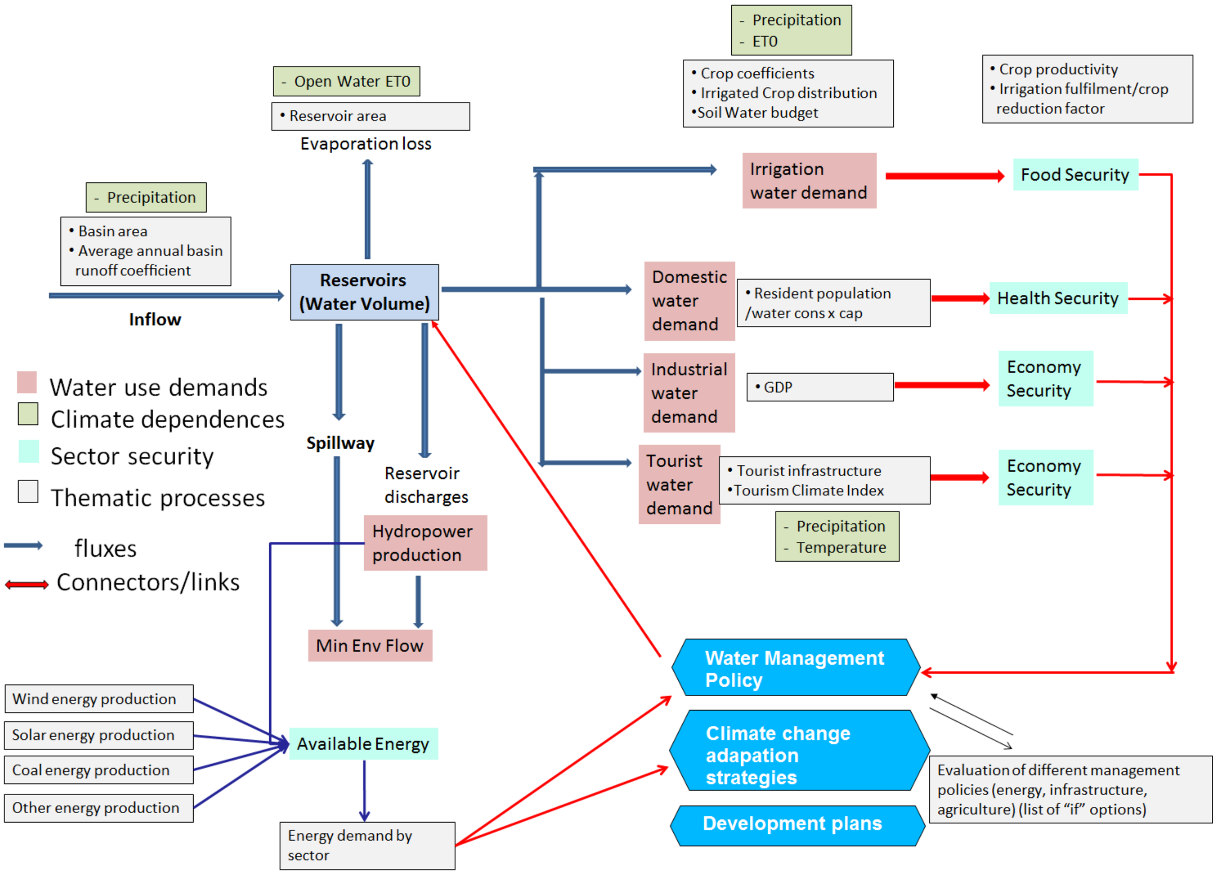


Figure 3.1.2 : Initial version of conceptual diagram describing the major nexus components relevant for the Sardinia case study.

Based on the above conceptualisation, it was possible to identify relevant 'thematic models' from which data would be required: CAPRI (a global agricultural and production model), GTAP project database (www.gtap.agecon.purdue.edu/), E3ME (a global economic and energy model), downscaled climate data from HadGEM2-ES from ISIMIP), as well as locally relevant data (e.g. for reservoir operating rules and environmental flow regulations), were acquired. Although the present framework already gives a reasonably accurate representation of the nexus in Sardinia, the conceptual framework was further elaborated and improved during the SIM4NEXUS project. Data under different RCP climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5) and socio-economic scenarios (SSP2) were gathered and used for quantitative model development. For full model development in SIM4NEXUS case studies, projections to 2050 will be simulated.

For the Sardinia case study, the main focus was the representation of the reservoir water balance for the island, accounting predominantly for water supply and for water demand related to agricultural, energy-related, and domestic/tourist consumption. On the water supply side, the model accounts for inflows to the reservoirs based on precipitation partitioning to runoff over the catchment area upstream of reservoirs. For the purposes of the fast track, water supply for the 40 main reservoirs and multiple demands were aggregated at island level. However, final case study results will aim at a more articulated disaggregation within seven hydrological districts in Sardinia (figure 1).For water demand, the model considers: 1) open-water evaporation from reservoir surfaces; 2) discharges for hydroelectric generation; 3) spillways in times of overflow; 4) irrigation requirements; 5) industrial demand; 6) domestic and tourist water requirements and; 7) environmental flows (i.e. the minimum amount of water needed to preserve ecological functions and values in watercourses). With irrigated agriculture being the largest water consumer, this sector was modelled in more detail. The crop water requirements per unit-area, and the area planted, were taken into consideration for 13 major crops on Sardinia as a function of current and changing climatic conditions. Touristic fluxes, and relative water demands, are modelled based on a Touristic Climate Index and socio-economic scenarios.

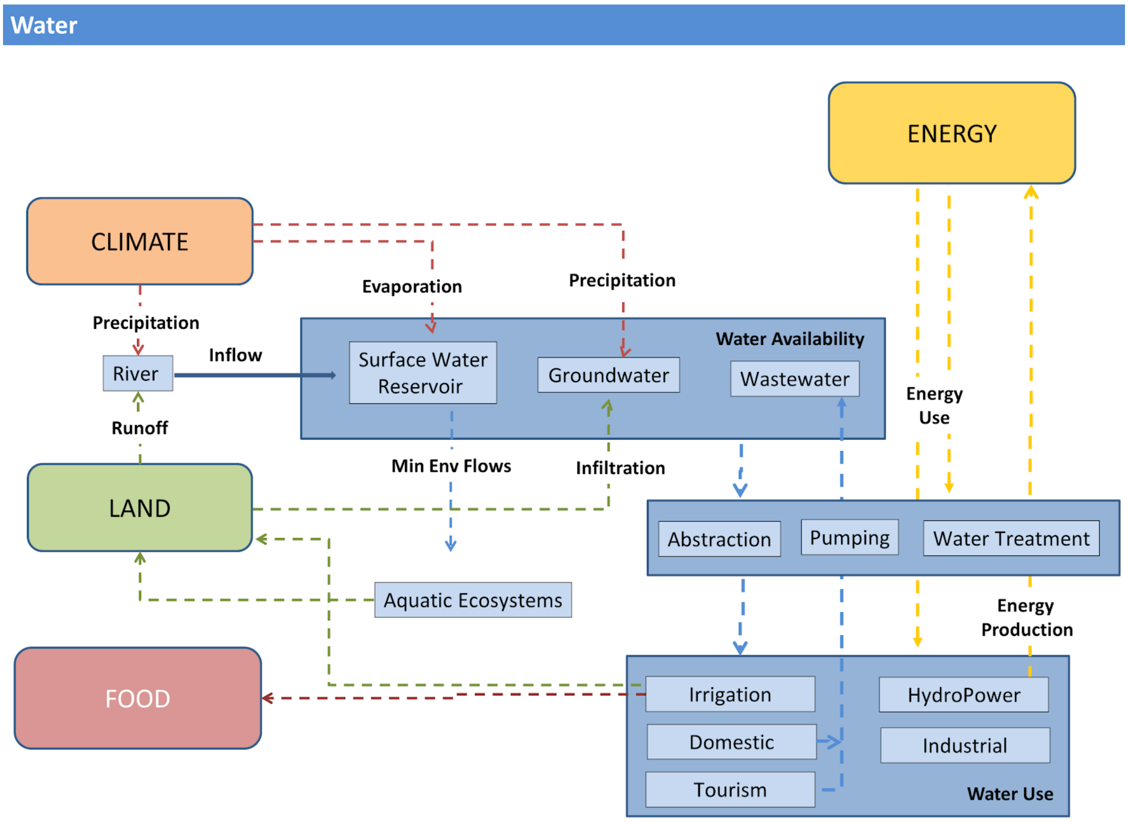


Figure 3.1.3: Conceptual model. The Water sector for Sardinia

While water is the central focus, this model is not only concerned with Sardinian hydrology and is not a hydrological model, but considers other nexus sectors including energy, climate, food and land use. Energy generation and consumption were also important along with the mode of generation and sector of consumption, as was modelling the change in crop types (i.e. land use and food production changes) and the crop water requirements associated with potential crop and cropped area changes, and in response to change in the local climate. Energy production is modelled from sources including oil and gas, solar, wind and hydropower, while energy demand comes from the agricultural, domestic, industrial and service sectors.

Energy

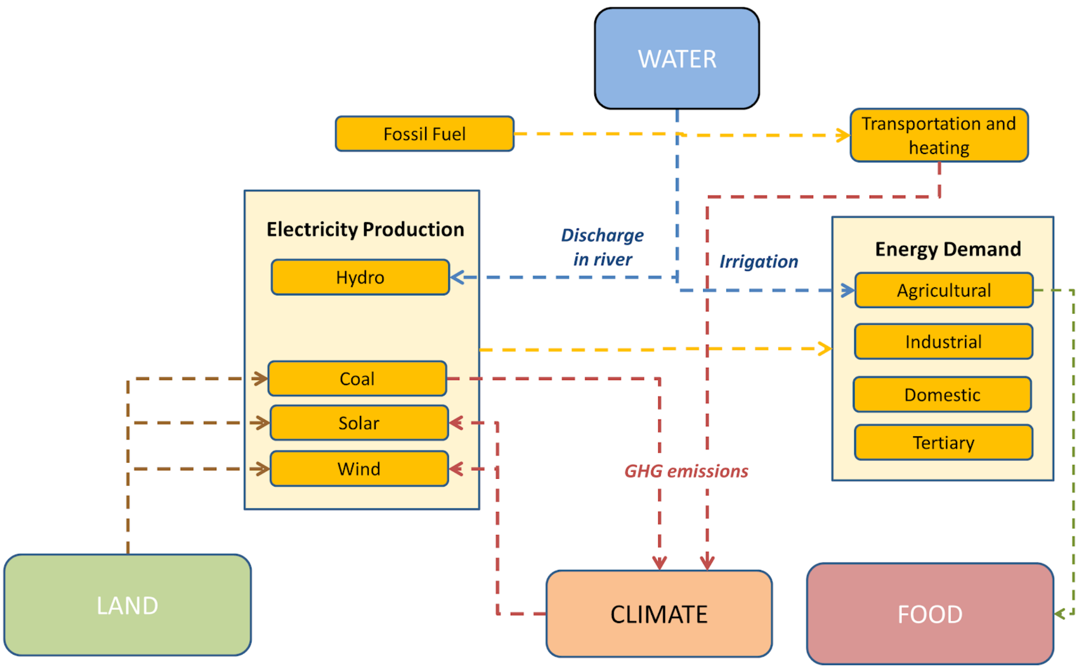


Figure 3.1.4: Conceptual model. The Energy Sector for Sardinia

Climate change will have an impact on evaporation rates, crop water requirements, precipitation recharge to reservoirs, but also touristic fluxes.

Climate

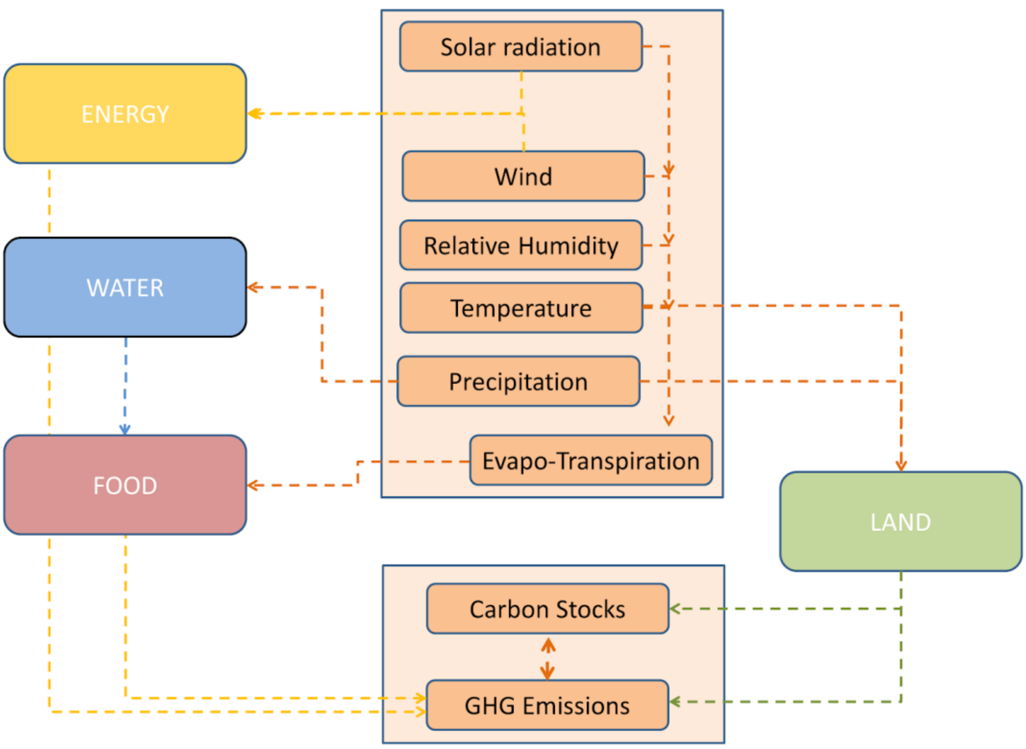


Figure 3.1.5: Conceptual model. The Climate sector for Sardinia

Land

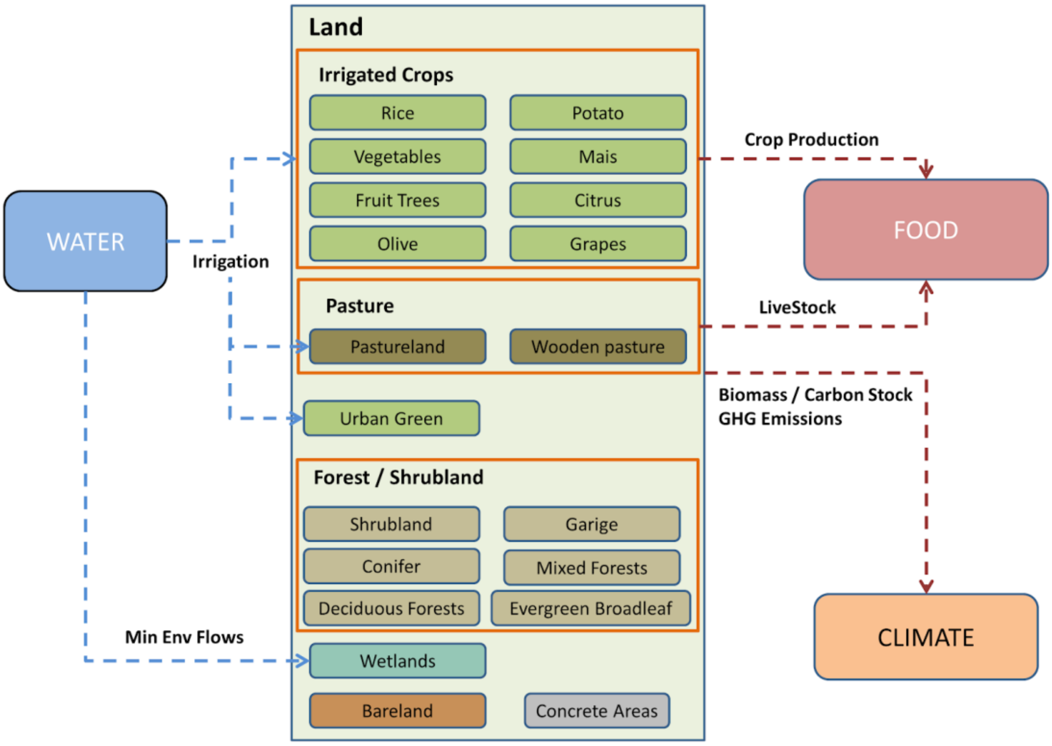


Figure 3.1.6: Conceptual model. The Land Sector for Sardinia

Land uses are tied to various Nexus component. In general, land availability is quite large in Sardinia given to its low population density. However, given the semi-arid conditions, relevant land productivity is necessarily in needs of other resources, such as water, energy and labour. Land uses are primarily responsible to carbon emissions and sinking, in addition to emission due to energy consumption, and are main drivers for crop production and livestock, and thus food security (Figures XXX).

Different socio-economic variables influence trends and mostly demand over the NEXUS sectors (Figure.

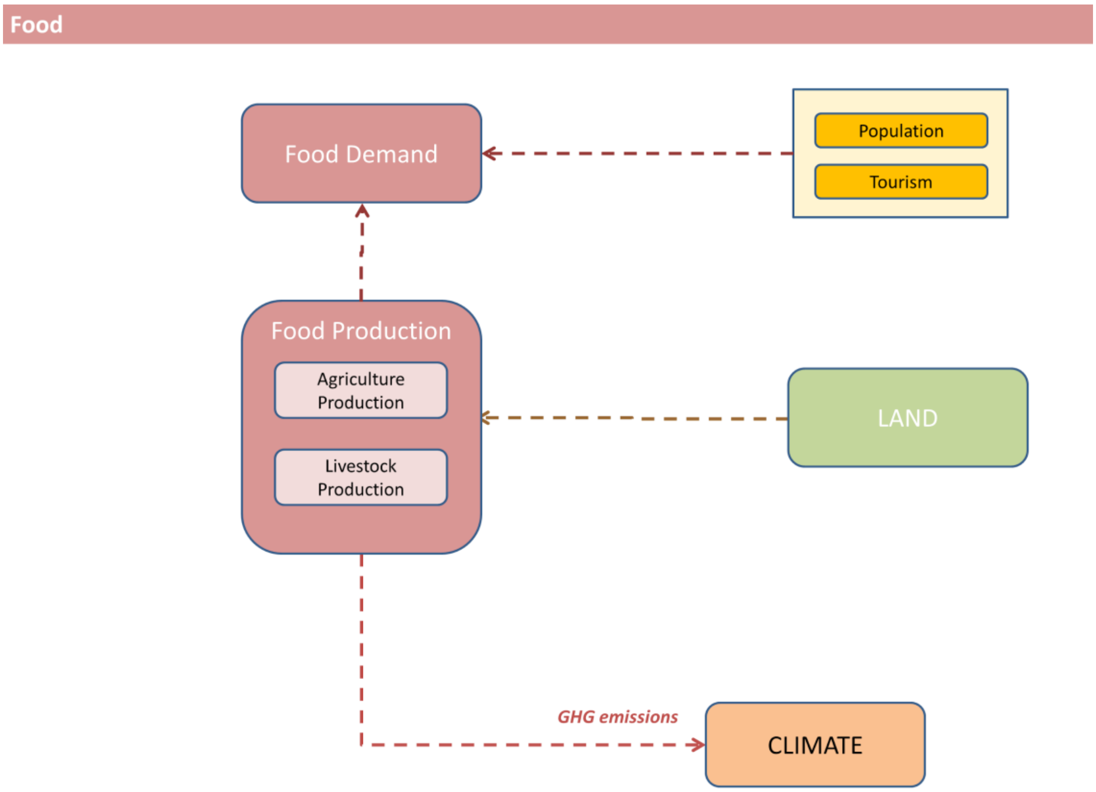


Figure 3.1.7: Conceptual model: The food sector for Sardinia

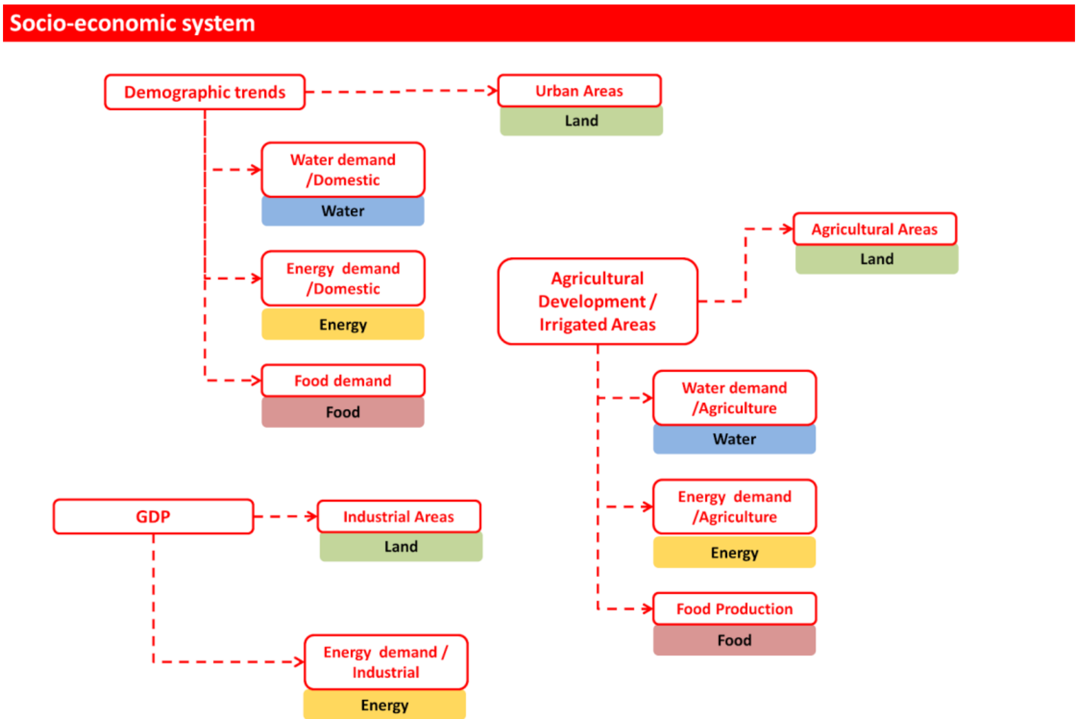


Figure 3.1.8: Conceptual model. The Socio-economic system for Sardinia

Data from thematic models provide projected changes of irrigated area by crop (CAPRI), energy production and demand by sector (E3ME), socio-economic factors (GTAP). All other data are from local Sardinian sources.

3.1.3 Description of the developed system dynamics model

The top-level SDM model for Sardinia, showing the five main nexus sectors and being driven by population and, uniquely, tourism, is shown in Figure 3.1.9.

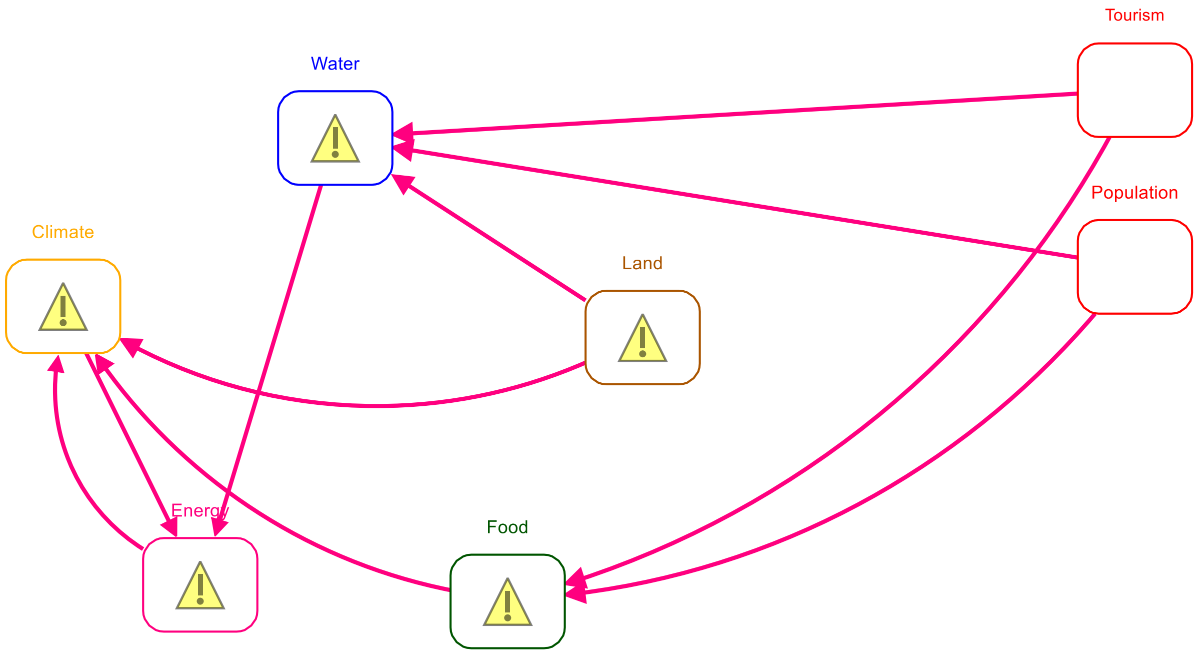


Figure 3.1.9: Top-level SDM for Sardinia. Note that uniquely, the nexus sectors in this case study are also driven by (changes in) tourism.

The water sector submodel is shown in Figure 3.1.10. For this Case Study, the focus is on quantifying the water balance of major water supply reservoirs on the island, and this balance forms the core of the model. Water availability is governed by surface water inflow to reservoirs, which is calculated as a function of basin surface area, precipitation, and a runoff coefficient. A proportion of surface water flow is reserved for environmental flows, and as such is not available for consumption. Water is consumed from the reservoirs by evaporation losses, discharges to hydropower, spillway releases when reservoirs levels get too high, and water demand from the crop, tourism, domestic and industrial sectors. Crop water demand is determined by estimating the water demands of 13 crops, and is a function of crop area and crop water demand per unit area (Figure 3.1.11). Tourist and domestic water demand is calculated from knowledge of the number of tourists and residents, and the per-capita tourist and residential water demand respectively (Figure 3.1.12).

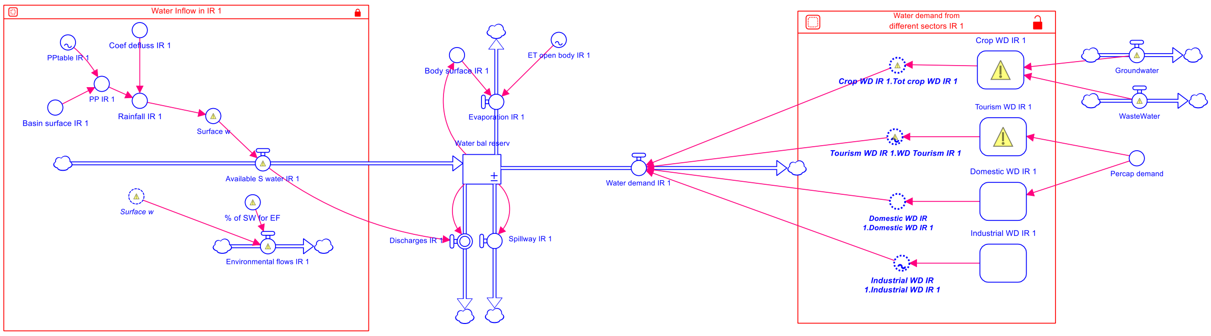


Figure 3.1.10: Water sector submodel for the Sardinian case study

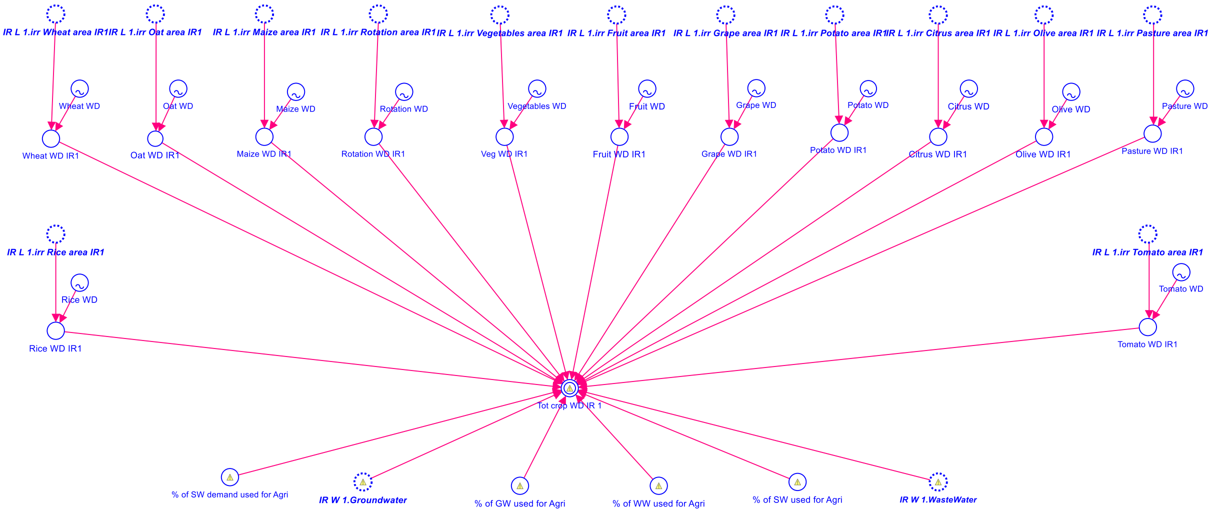


Figure 3.1.11: The crop-water demand part of the water sector submodel for Sardinia.

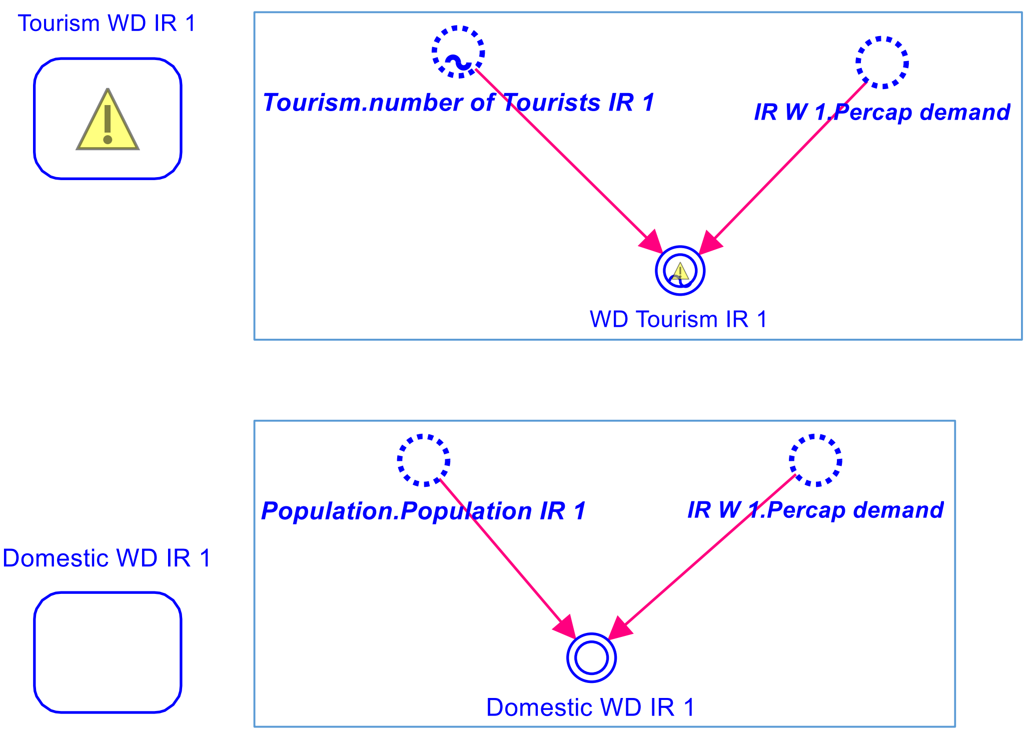


Figure 3.1.12: The tourist (top) and domestic (bottom) water demand models for Sardinia.

As irrigated agriculture on Sardinia is a priority concern regarding water demand, the land sector submodel focuses on crop areas, especially for irrigated crops, although the areas of rain-fed crops is also accounted for, as is the area of forests and the urban extent (Figure 3.1.13). Changes are tracked over time, and are used to re-calculate irrigated crop water demand.

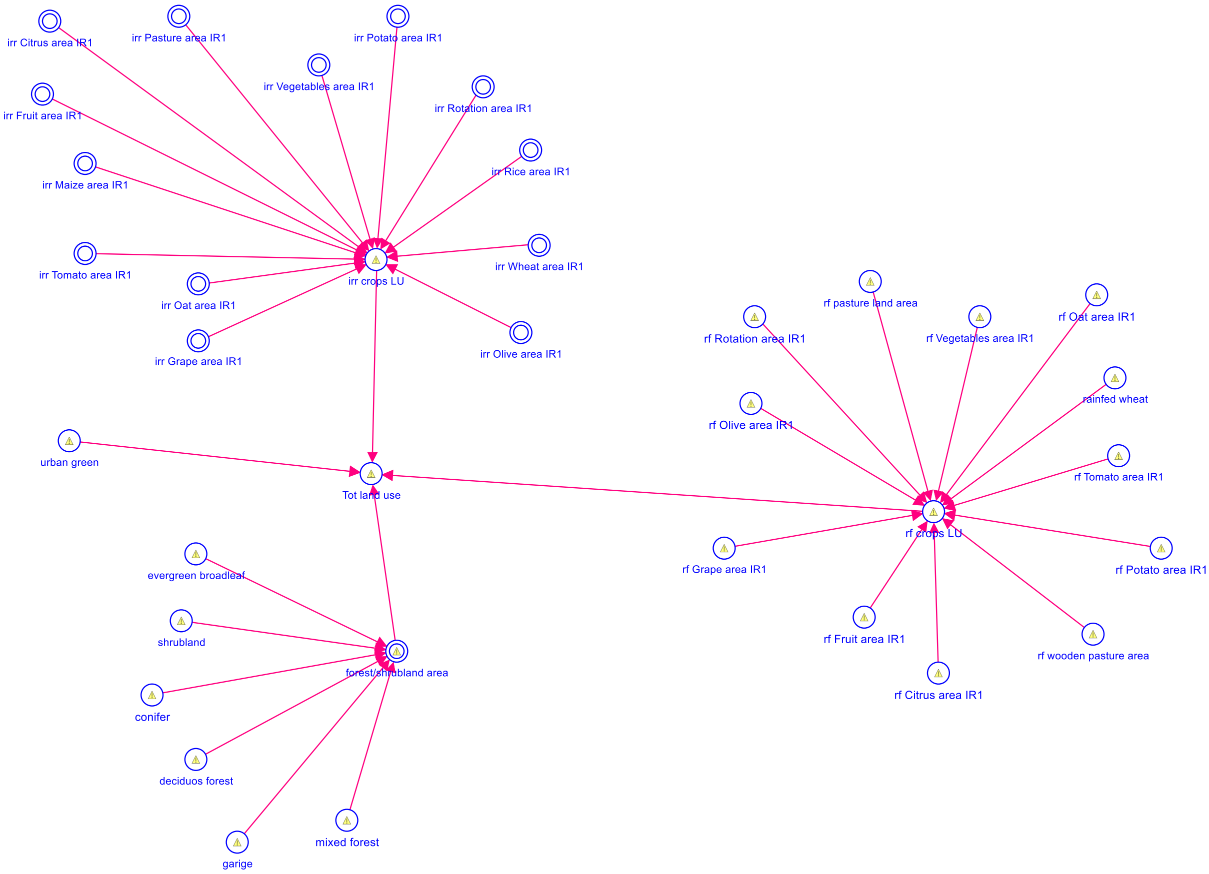


Figure 3.1.13: The land sector submodel for the Sardinia case study.

The food sector has not been extensively developed, not being a primary concern for the case study (Figure 3.1.14). Production is the sum of crop and livestock production, and food consumption is accounted for from both the local population and form tourists.

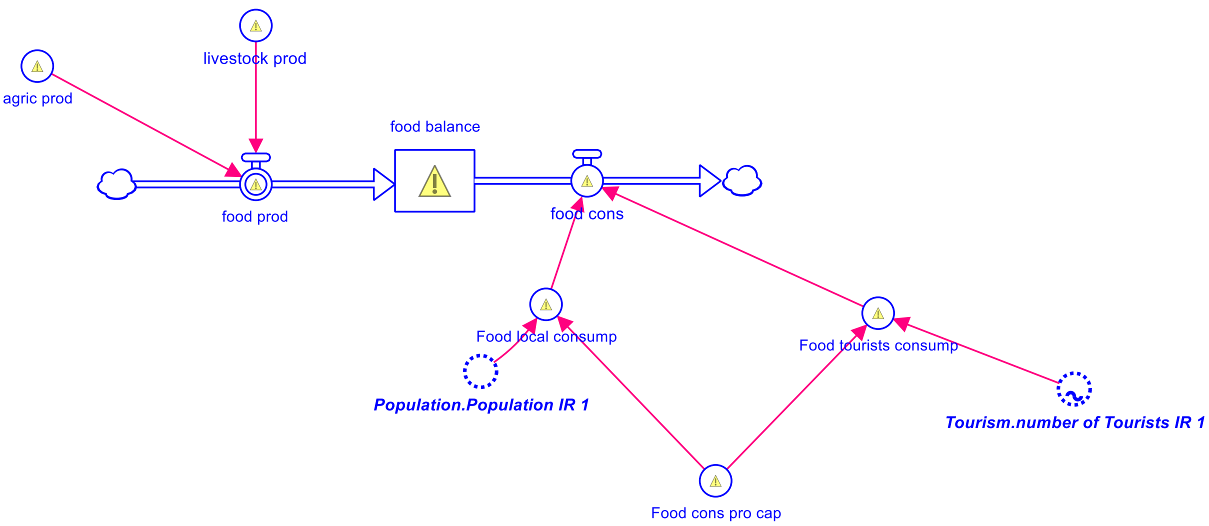


Figure 3.1.14: The food sector submodel for the Sardinia cases study.

The Sardinian energy sector sub model is developed in significant detail (Figure 3.1.15. The primary and secondary energy sectors, as well the heat production are further developed (Figure 3.1.16), and demand from five sectors is also developed in further detail (Figure 3.1.17). At the top level, energy is available from many primary and secondary sources, including electricity and heat energy. A small proportion is exported. Energy is demanded by five main economic sectors (agriculture, domestic, industry, transport and the tertiary sector), and is addition, the energy demands of water pumping and water treatment are explicitly modelled.

In terms of primary energy (Figure 3.1.16), energy sources include coal, oil, methane, propane and biogass. Heating energy comes from oil, biomass, methane and propane sources, while electricity derives from hydropower, wind, solar, coal, oil and methane sources.

For demand, domestic demand of different energy sources is accounted for. In agriculture, only electricity and oil energy sources are considered. Transport deals with solely with liquid fuels (oils), and electric vehicles are negligible.

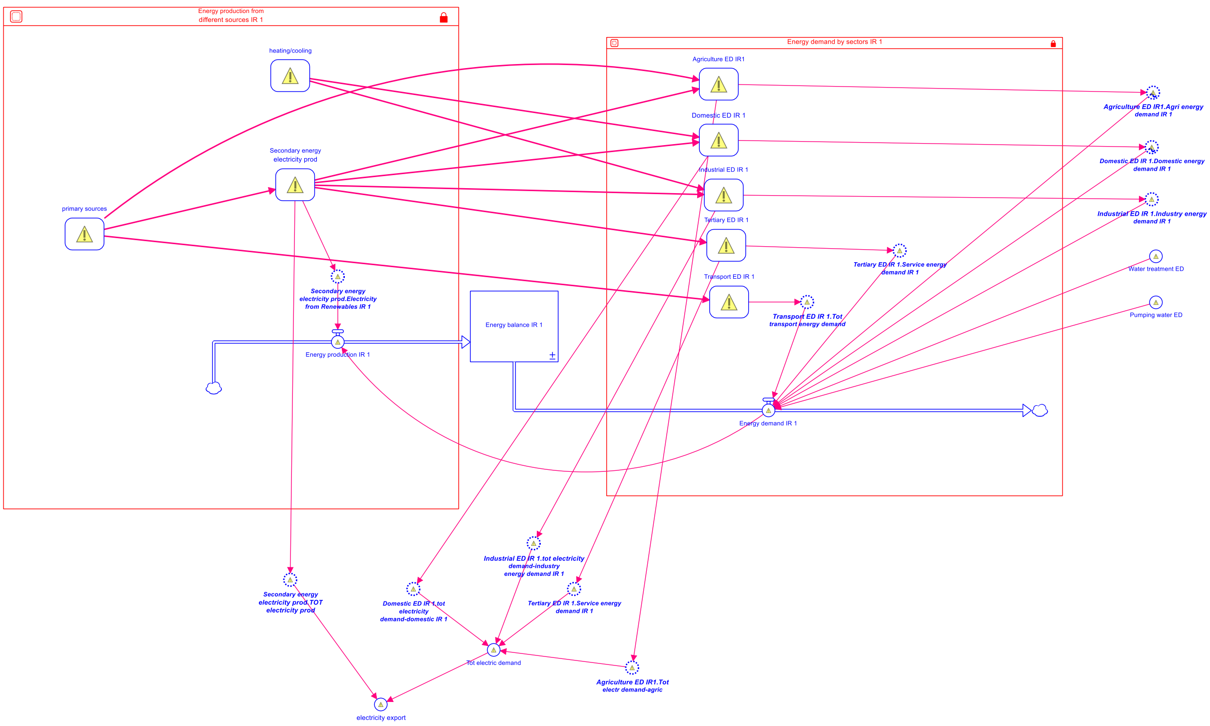


Figure 3.1.15: Top-level energy sector submodel for the Sardinia case study.

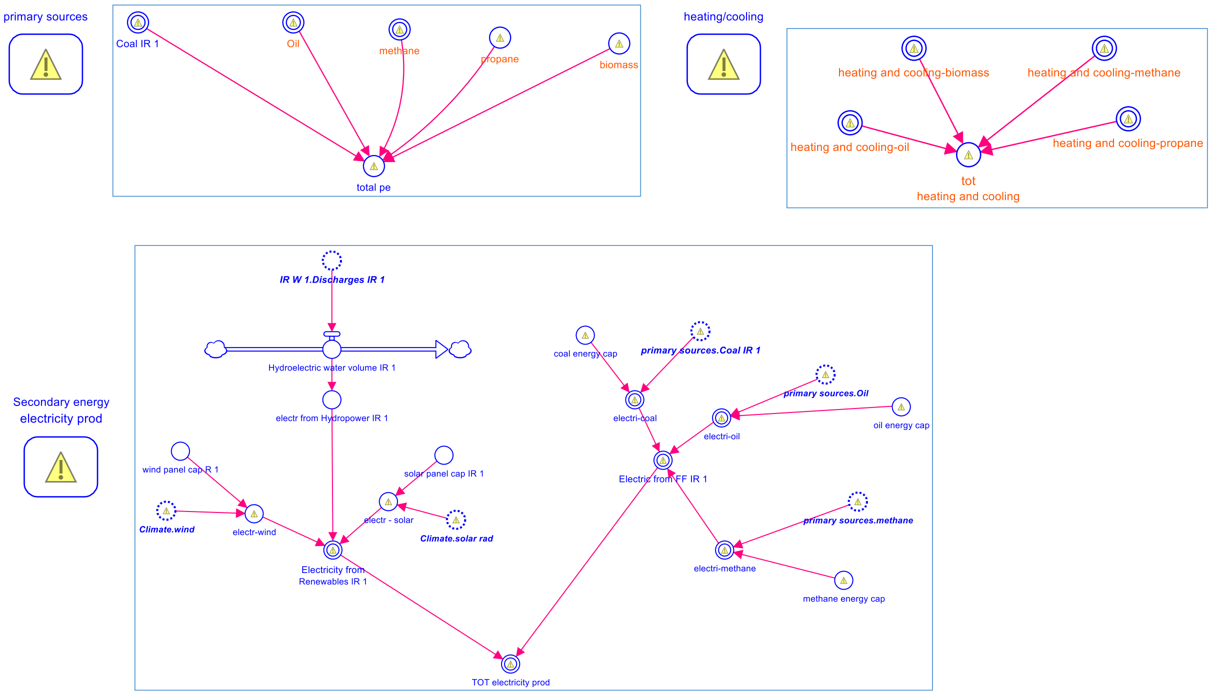


Figure 3.1.16: Detailed models for primary (top left), secondary electricity (bottom) and heat (top right) energy production in Sardinia.

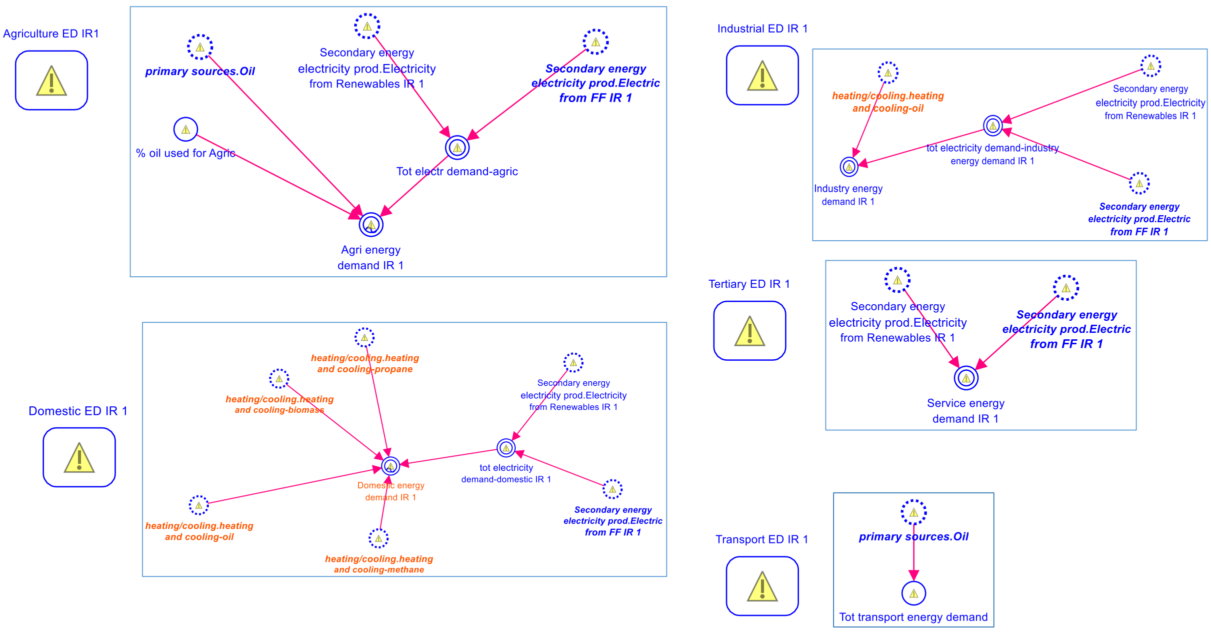


Figure 3.1.17: Electricity demand models for the agriculture (top left), domestic (bottom left), industry (top right), tertiary (middle right), and transport (bottom right) sectors for Sardinia.

Finally, the climate sector (Figure 3.1.18) consider emissions and sequestration of GHGs to arrive at a GHG balance for Sardinia. Emissions come from food production, heating energy, and electricity production from coal, oil and methane, while sequestration is possible from forest and pasture lands.

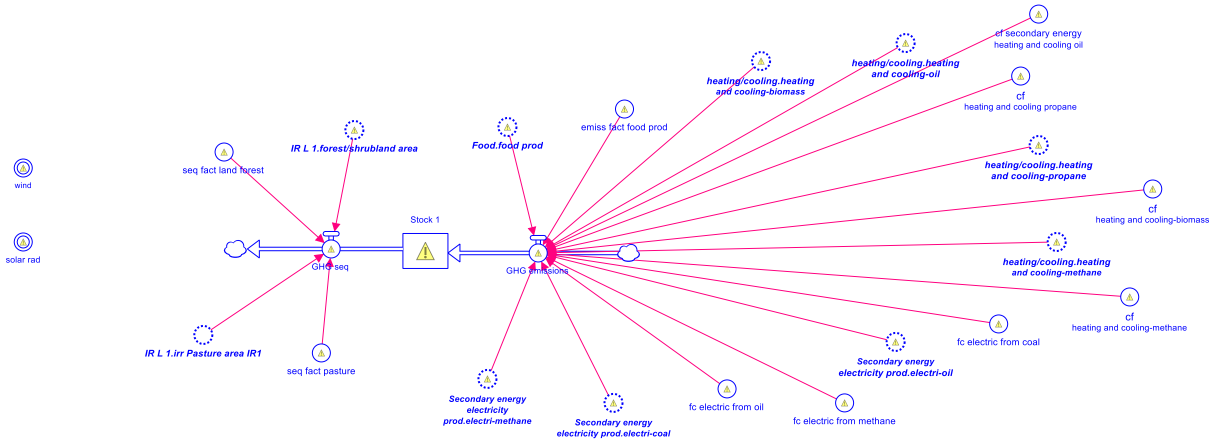


Figure 3.1.18: The climate sector submodel for the Sardinia case study.

3.2 Andalusia case study

3.2.1 Short description of the case study

Andalusia is an autonomous region located in Southern Spain (Figure 3.2.1). It has a total area of 8.76 million hectares (17.4% of the Spanish territory) of which half is Utilized Agricultural Area (UAA), including one million hectares of irrigated land (Massot 2016). Andalusia´s population is approximately 8,4 million people (2015). Andalusia is the second largest region in Spain and the fourth largest region in EU28. It´s orographic and hydrographic features, climate types and biodiversity vary considerably (Massot 2016). In Andalusia, the primary sector, including agriculture, accounts for 5.5% and employs 263.1 thousand people (AWUs or Annual Work Units) in 2017 (Junta de Andalucía 2018). In particular, olive oil, both in terms of turnover (5292 million Euro) and value added (662 million Euro) is crucial for Andalusia´s agri-food industry, with exports worth of 2 288 400.70 thousand Euro, making Andalusia the global market leader for olive oil (Massot 2016).

The gross water demand is 3357 hm^3 taken into consideration the efficiency of water transport, distribution and application (type of irrigation system). Approximately 74% of the irrigated land in Andalusia currently uses localised irrigation systems, 17% drop irrigation and to a lesser extent sprinkler irrigation. Irrigation agriculture derives approximately 64% of the agricultural production in Andalusia, and has also high socioeconomic importance (generates 63% of agricultural employment and 67% of farm income) (Massot 2016). While irrigation agriculture is crucial for Andalusia´s socioeconomic development, it also puts pressure on the limited water resources in the province. Andalusia has a negative water balance and, in some areas, faces problems of erosion (with risk of desertification).

Irrigated land in the region is mainly concentrated in the Guadalquivir RBD (856429 ha). The Guadalquivir RBD is the main river basin of Andalusia with a watershed area of 51500 km^2, that represents 58.8% of the geographic area of Andalusia. Irrigation water is largely drawn from the Guadalquivir river, the longest river in Andalusia and the fifth longest in Spain with 657 km. Total water demand in the Guadalquivir RBD is estimated to be 3815 hm^3 in 2015 with agriculture being the main water user with 3356 hm^3 (88% of the total demand). With regard to the origin of water, approximately 2498 hm^3 correspond to surface water (74.0% of the total water demand) and approximately 913 hm^3 to groundwater (26% of the total water demand). The Guadalquivir RBD includes approximately 86% of the total irrigated land in Andalusia, of which olive trees are the most predominant (52%), followed by extensive crops (30%), fruit trees (7%) and rice (4%). The olive groves, which are mostly located in the Guadalquivir RBD, are the largest farming system in Andalusia. They account for 25% of total UAA and 42.6% of holdings in Andalusia, with often highly mechanized production and irrigation systems.

Regarding efficient energy use in irrigation facilities, high energy costs are a huge conundrum for irrigators (Lopez-Gunn et al. 2012). As a result of modernization of the irrigation system, the Spanish water delivery system was changed from surface irrigation to pressurized systems. This required the installation of electric pump systems to guarantee sprinklers or drip irrigation to function properly. Energy has, thus, turned into an essential resource for irrigation agriculture with huge increases in energy consumption. Moreover, the Ministry of Industry subsidized energy for irrigation with a special rate (R rate) until July 2008. After July 2008, the energy market was liberated and brought about higher (unsubsidized) energy prices for irrigators to the benefit of power companies (González-Cebollada 2015).

Against these trade-offs in the WEF nexus and the importance of irrigation agriculture in Andalusia, the Andalusian case study assesses the economic aspects of the agricultural sector and respective land use changes. Key indicators to be assessed for the production of olives (irrigated and rainfed), cereals (irrigated and rainfed), wine (irrigated and rainfed), sunflowers (irrigated and rainfed), and citrus fruits (irrigated) include income (Eur ha^{-1}), utilized agricultural area (UAA) (1000 hectares), supply (1000 t), per hectare water use (m3 ha^{-1}), and energy consumed per unit of irrigated area (kWh ha^{-1}). Moreover, water demand from reservoir (surface water) and groundwater is assessed, as well as energy production and consumption.

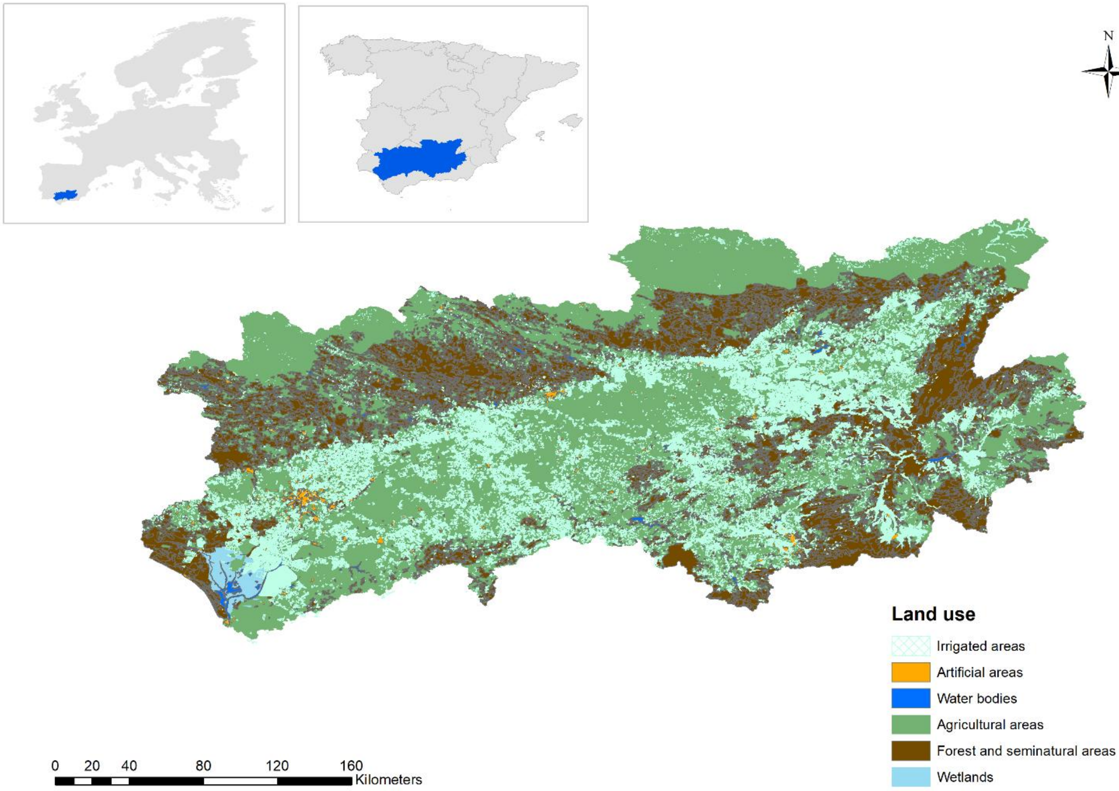


Figure 3.2.1: Map showing the SIM4NEXUS Andalusian case study.

3.2.2 Evolution and description of the conceptual diagram

Similar to the other case studies, this section describes the evolution of the conceptual diagram. The first version of the conceptual model (Figure 3.2.2 and Figure 3.2.3) was developed based on information gathered through interviews with stakeholders from the water, energy and food sectors in Andalusia. Bilateral interviews were conducted by phone or face-to-face following seven guiding questions that helped to get a preliminary understanding of main nexus challenges in Andalusia (see project Deliverable D5.2 - The Main Nexus Challenges in Andalusia-Spain for more details).

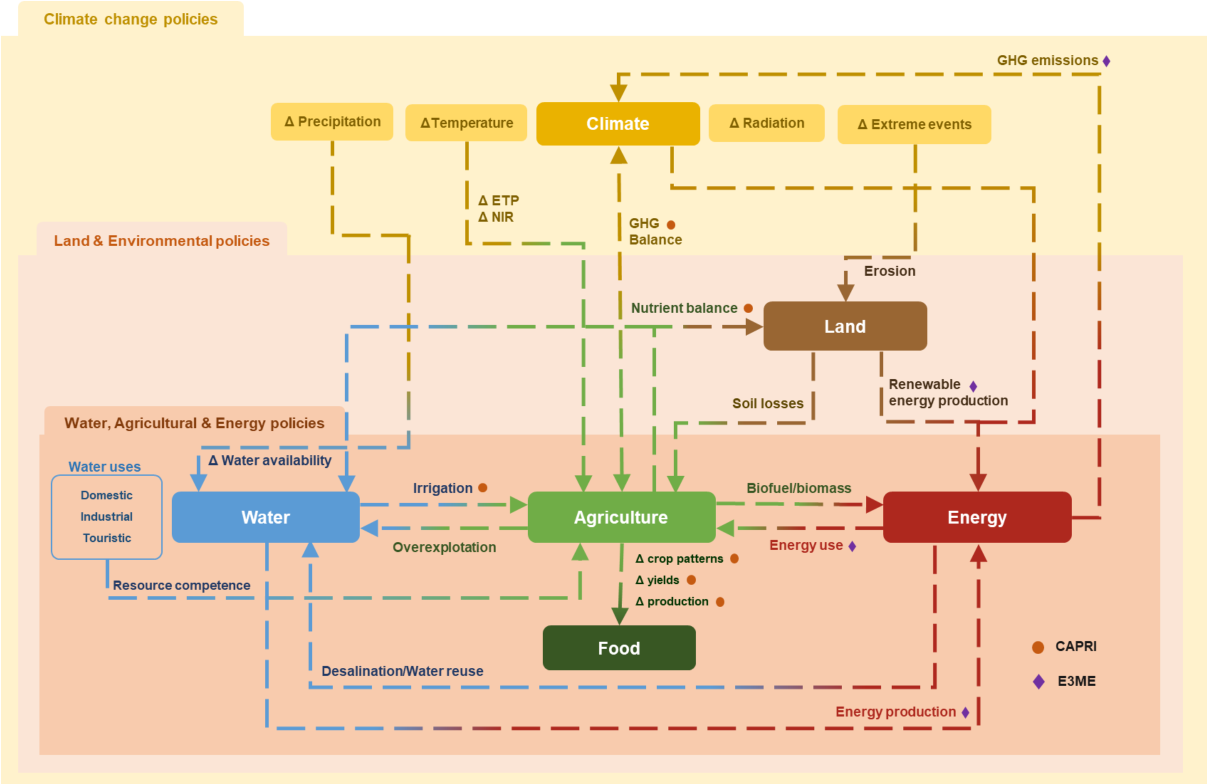


Figure 3.2.2: First version of the conceptual model for all Andalusian Nexus components.

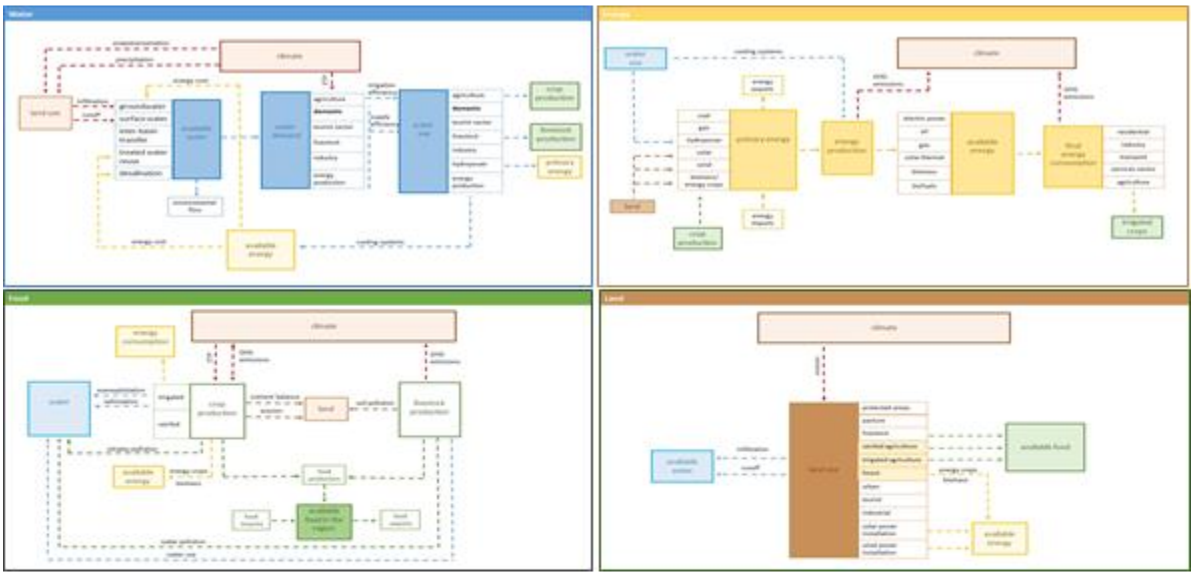


Figure 3.2.3: First version of the Andalusian conceptual model: water, energy, food and land sub-models. This figure shows the general view, while each sector is shown in more detail in other figures.

The validation of the conceptual model was performed through a stakeholder workshop held in Seville in October 2017. The methodology of Fuzzy Cognitive Mapping (FCM) was applied to elicit stakeholder's knowledge on the nexus. Each participant developed a cognitive map considering the main interrelations in the water-energy-food nexus in Andalusia according to their views. Participants unrestrictedly selected variables in the map and depicted causal relationships between them using arrows. Causal relationships were further detailed with a sign that reflects a positive (+) or negative (-) relationship and a weight between 0 and 1 (Figure 3.2.4). The eleven individual maps obtained were then processed and analysed to extract the key factors and interdependencies in the nexus. To that end, variables from individual maps were processed to eliminate similar names and less repeated variables were aggregated into wider categories according to similarities. Each individual map was converted into matrix form by using the variables and magnitude of the causal relationship. All individual matrices were merged into an augmented matrix to create a group map, which represents the views of all the participants. The analysis of matrix indices enabled to identify the main variables and interactions in the group map. Additionally, this exercise constituted an extremely great opportunity to gain insight into the system performance by running preliminary scenarios using the FCM software FCMapper (for further information, please see Martinez et al. 2018). Results from the analysis were used to refine the first version of the conceptual model with the introduction of new variables and interrelations.

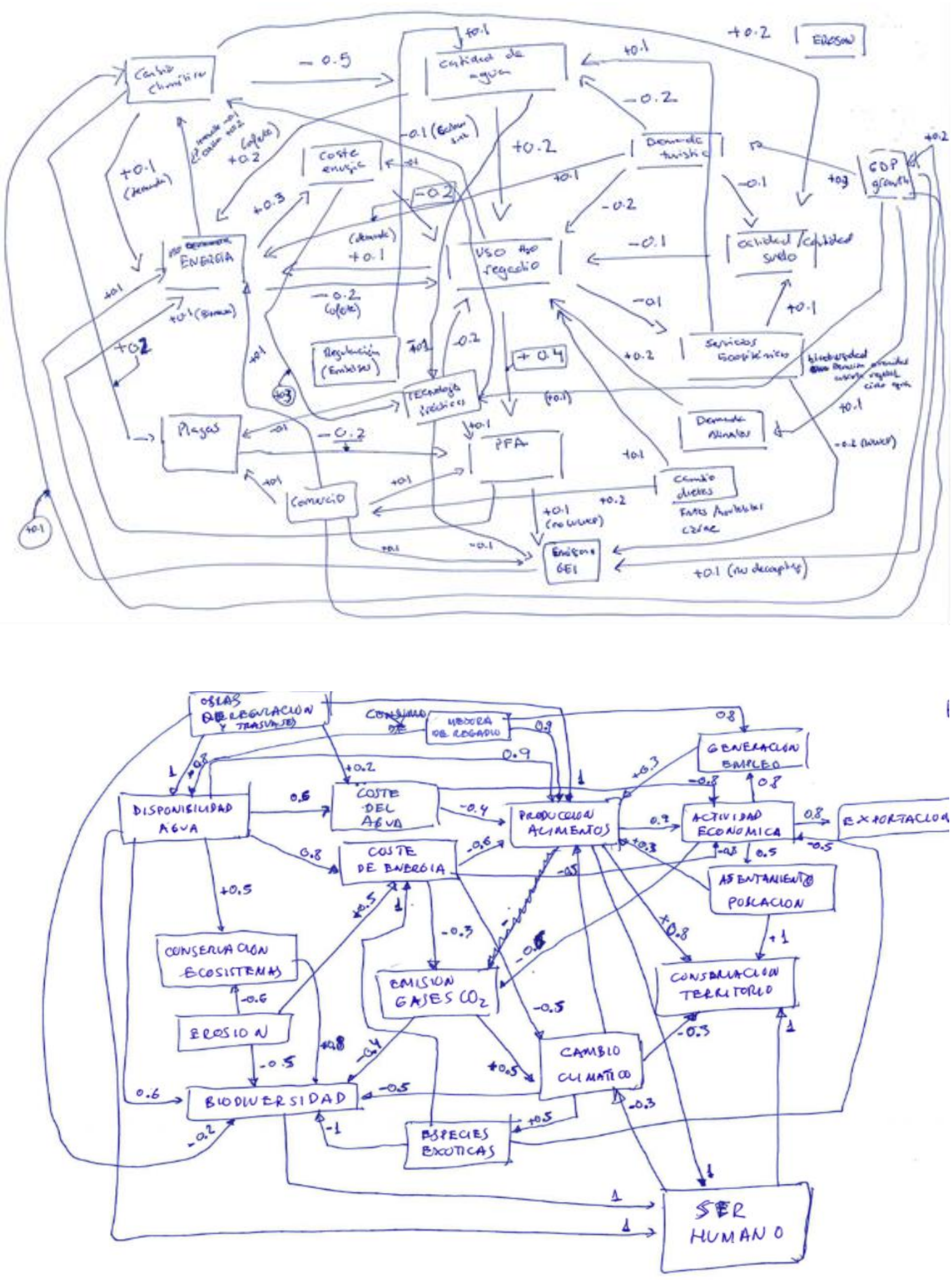


Figure 3.2.4: Examples of individual maps drawn by stakeholders.

The validated version of the conceptual model is presented in the following Figures. The water sub-model (Figure 3.2.5) attempts to capture climate change effects on water availability and their implications for the economic sectors, with special focus on irrigation and energy production. Environmental concerns such as water quality and environmental flow are also reflected. Furthermore, energy needs for water abstraction, desalination and reutilisation are included.

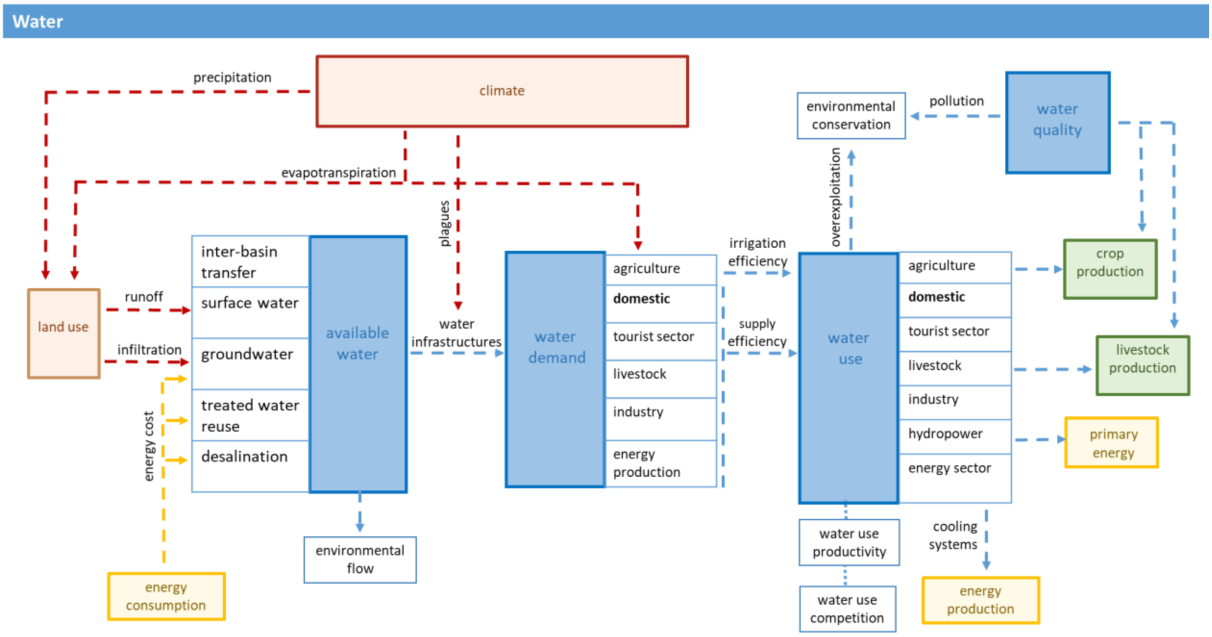


Figure 3.2.5: Validated Andalusia Conceptual model for water.

Figure 3.2.6 presents the energy sub-model where the main energy sources (renewable and non-renewable) and energy consumption sectors are represented. Water is required to produce energy (hydropower and cooling systems), as well as land and bioenergy crops. On the other side, energy is needed for irrigation. Another important interrelation depicts impacts of the energy sector on climate through greenhouse gas emissions.

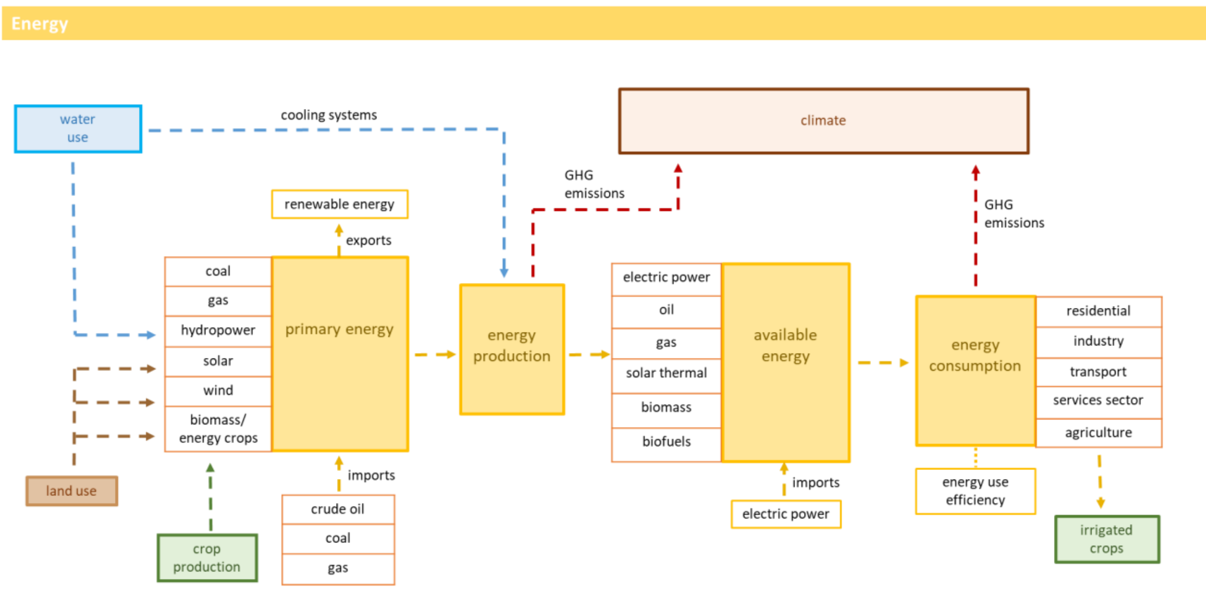


Figure 3.2.6: Validated Andalusia Conceptual model for energy.

Figure 3.2.7 shows the food sub-model with a number of interdependencies between the different nexus sector. Whereas water is essential for crop and livestock production, agricultural activities might lead to overexploitation and water quality degradation. Energy is a key factor in irrigation in Andalusia because of the high-energy dependence of pressure irrigation systems and the elevated energy prices. Agriculture is highly sensitive to climate change and, at the same time, is an important contributor to greenhouse gas emissions, mainly methane and nitrous oxide.

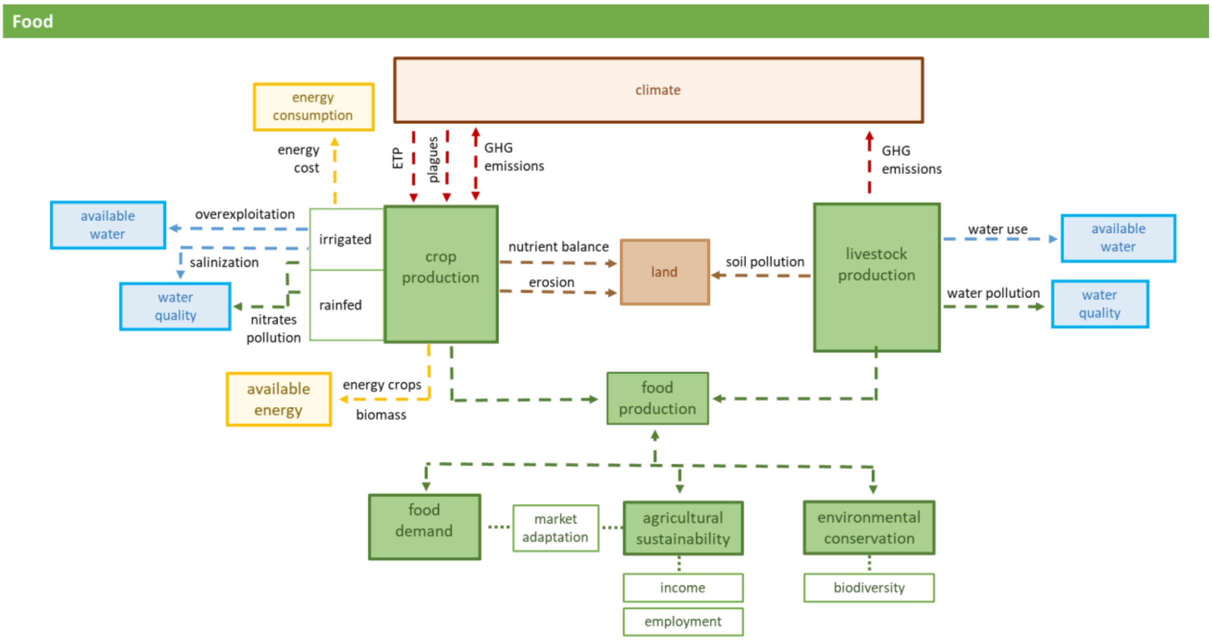


Figure 3.2.7: Validated Andalusia Conceptual model for food/agriculture.

Figure 3.2.8 represents the land sub-model with the main types of land uses and their interrelations with the nexus sectors. Land is crucial for agricultural production but also to energy production. Climate affects land mainly through erosion and land contributes to climate change mitigation as a carbon sink (e.g. forest). Water availability is linked to land through infiltration and runoff, whereas water quality is affected by the different types of land use.

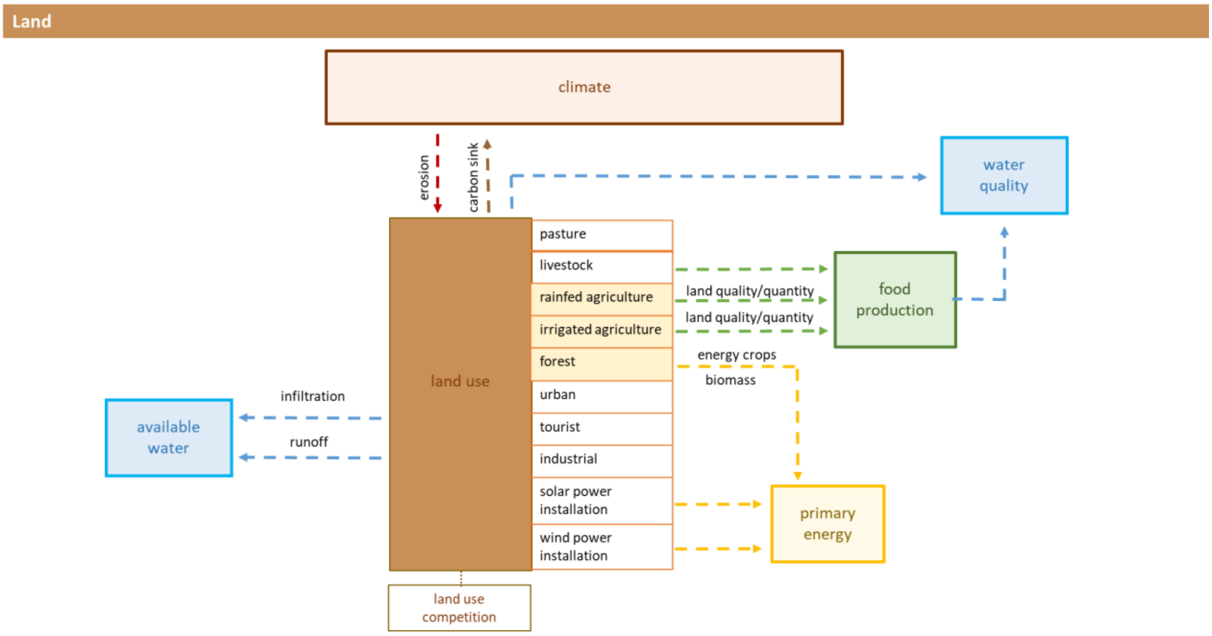


Figure 3.2.8: Validated Andalusia Conceptual model for land use.

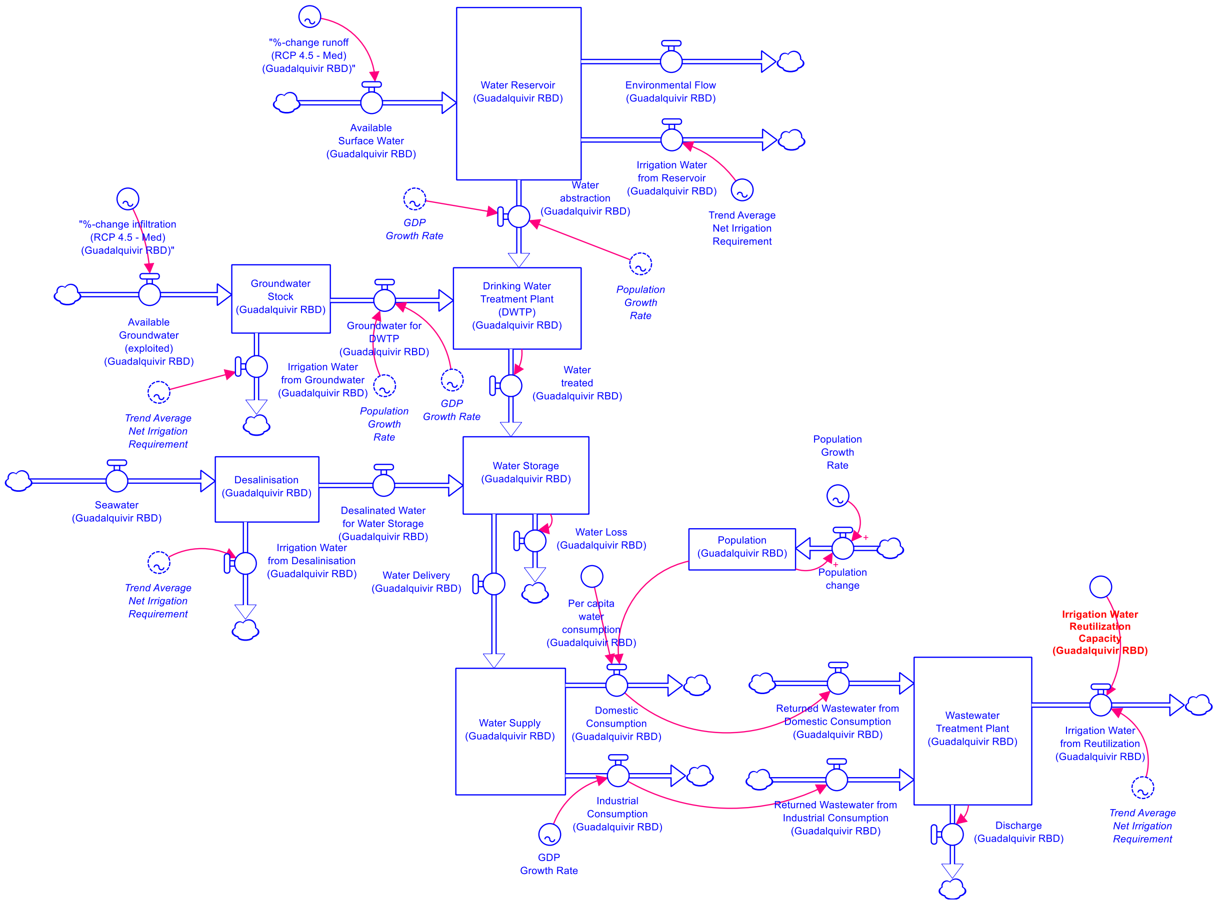
3.2.3 Description of the developed system dynamics model

This section describes the SDM representing the WEF nexus and links to land use for the Andalusian case study. Sub-sections 3.2.3.1 to 3.2.3.4 describe the water, energy, food/agriculture, and land use models, respectively. The specific formulas and data used in the model are available upon request. The data used for the water model are largely drawn from local statistical sources. Moreover, irrigation consumption data and projections that are used in the sub-model for irrigation water balance are drawn from CAPRI, a sectorial model largely used for analysing the food/agriculture sector. For the energy model, the major data are drawn from E3ME, a sectorial model for assessing climate and energy policy on economic activity and employment. For the food/agriculture and land use model, data are also taken from CAPRI or from local statistical sources.

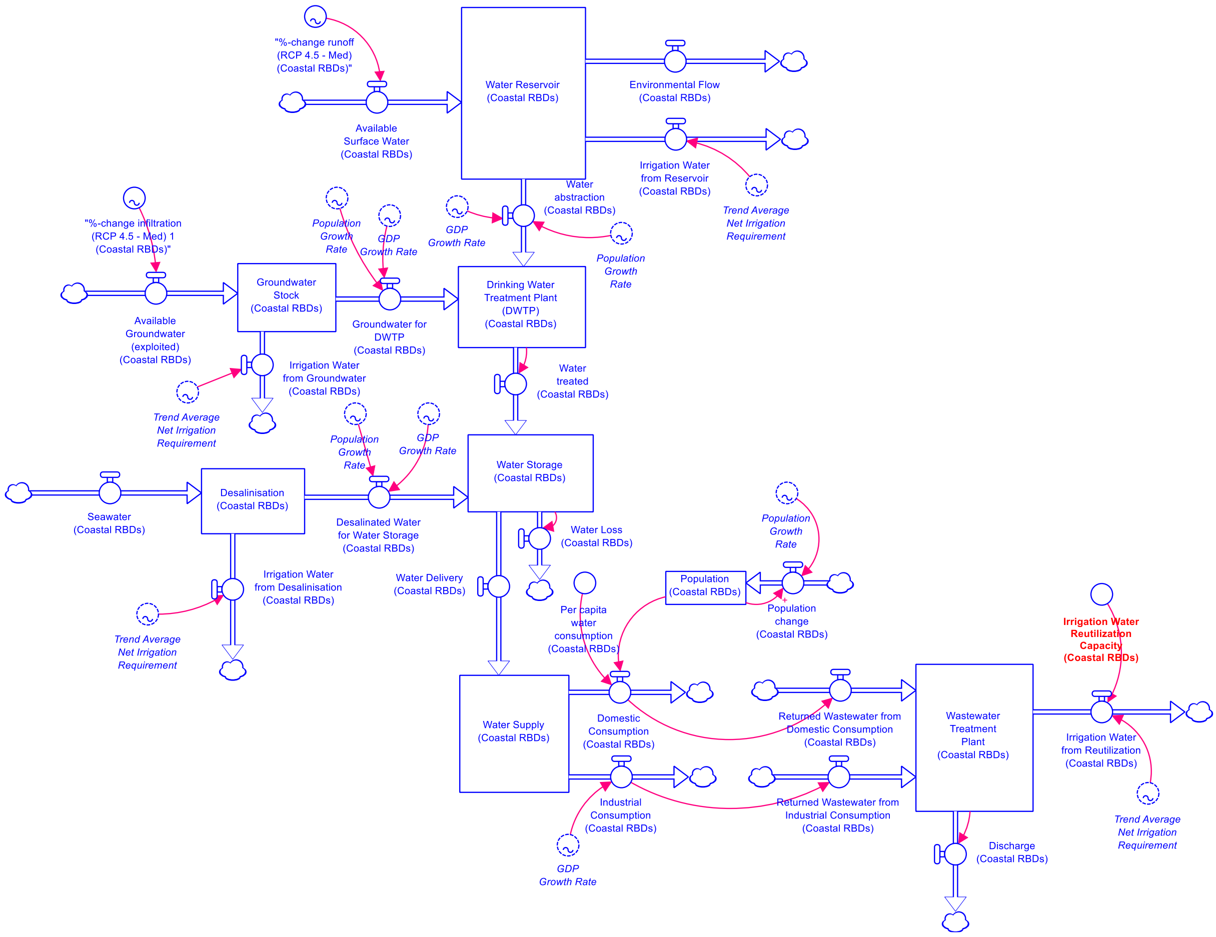
3.2.3.1 The water model

The water model, which is shown in Figure 3.2.9 considers two water models, one for the Guadalquivir RBD (Figure 3.2.9a), one for the coastal RBD (Figure 3.2.9b), and an irrigation water balance (Figure 3.2.9c). The structure of the two water models is identical but the data are specific for the Guadalquivir RBD and the coastal RBDs, which combines the three RBDs (Mediterranean, Guadalete-Barbate, Tinto-Odiel-Piedras). The water model includes major incoming and outgoing water flows, and focuses on irrigation water supply from different sources represented in the sub-models. Starting with the sub-model for surface water, the water reservoir stock increases by the incoming surface water that depends on the runoff and decreases by the outgoing surface flow. The outgoing surface water is an inflow to the water reservoir stock, which is decreased by environmental flows, irrigation water uses from reservoir, and water abstraction. The water abstracted from the water reservoir is an inflow to the Drinking Water Treatment Plant (DWTP) together with the outgoing groundwater flow. The outgoing flow from DWTP is the treated water that is then stored (water storage) and available for water supply. Another sub-model is used for groundwater stock, where incoming groundwater flow depends on infiltration. Subtracted from the groundwater stock is the outgoing groundwater flow that is delivered to the DWTP and the groundwater used for irrigation. Water storage, another interlinked sub-model, is then defined by an inflow of treated water and desalinated water and an outflow from delivered water (for water supply) and water loss. Regarding desalinated water, there is an additional sub-model included. The stock-variable of desalinisation is defined by the inflow of seawater and outflows of irrigation water and desalinated water used for storage. The delivered water is an inflow to the next sub-model of water supply stock, which is used for domestic and industrial water consumption where domestic consumption depends on per capita water consumption multiplied by population. The population stock is determined by the initial population plus population change, which depends on the population growth rate. Next, the sub-model of water reutilisation from domestic and industrial consumption is considered. Both domestic and industrial water could potentially be reutilized and be treated in a wastewater treatment plant, where returned wastewater from domestic and industrial consumption increase the stock of treated wastewater, discharge and irrigation water from reutilization decrease the stock of treated wastewater.

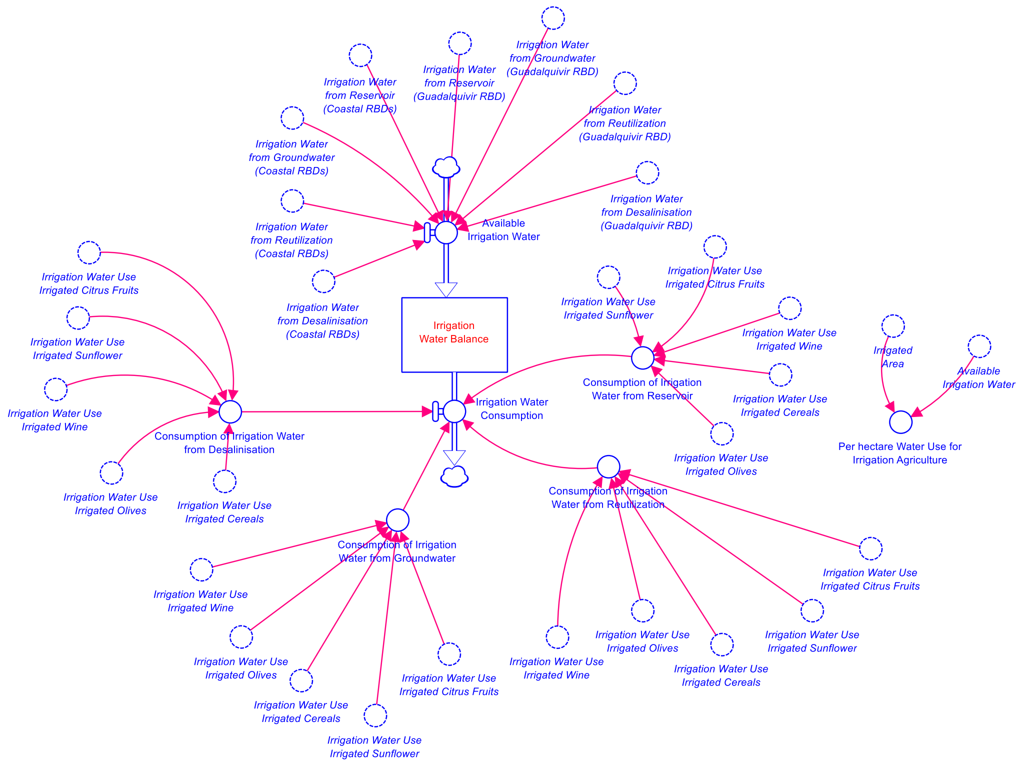
Given the importance of water used for irrigation agriculture, we use an additional sub-model for the water balance of irrigation water, which is defined by the sum of available irrigation water (taken from the water sub-models for the Guadalquivir and coastal RBDs) minus the sum of irrigation water consumed (taken from the food/agricultural model). The consumption of irrigation water is based on the water consumed for irrigation for growing different kinds of agricultural commodities depending on available sources of irrigation water (from reservoir (surface water), groundwater, desalinisation, and reutilization), as given in the respective sub-models mentioned earlier. The three available sources of irrigation water are linked to the irrigation water used per commodity. In the current version of the SDM, irrigation water used for olives for oil, cereals, wine, sunflower, and citrus fruit production are considered (hereafter we refer to olives for oil by using olives). Irrigation water used for the different crops is directly linked to the food/agriculture sub-models for each commodity. Sub-models for different commodities are used to better account for differences in irrigation water use. Per hectare water use of irrigation agriculture (m^3 ha^{-1}) is calculated by dividing available irrigation water by irrigated area.



a: Water model for the Guadalquivir RBD



b: Water model for the coastal RBDs

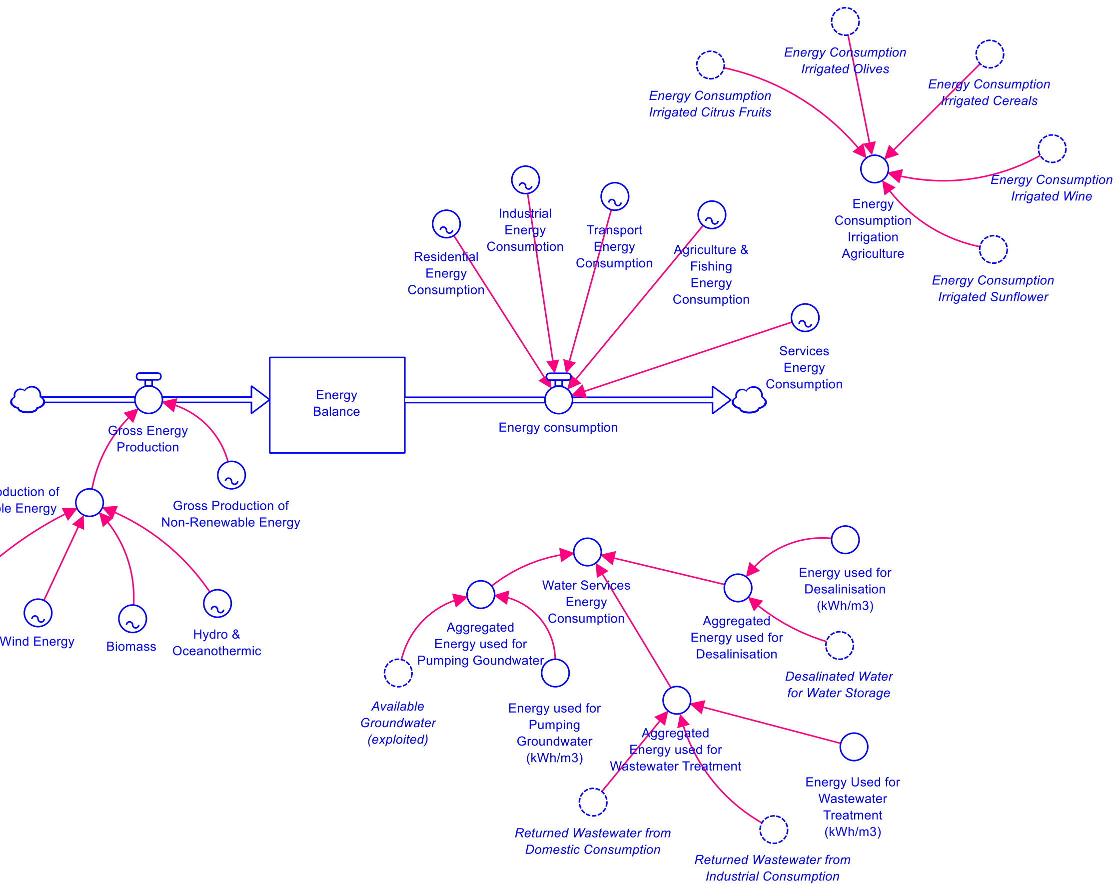


c: Irrigation water balance

Figure 3.2.9: Stock-and-flow diagrams for the water model.

3.2.3.2 The energy model

The energy model, which is shown in Figure 3.2.10, comprises an energy balance model that combines calculations of energy generation (inflow) and energy consumption (outflow). Energy generation depends on renewable energy generation and non-renewable energy generation. Renewable energy generation is further divided into solar energy, wind energy, biomass, and hydro and oceanothermic energy. Energy consumption depends on residential energy consumption, industrial energy consumption, transport energy consumption, agriculture & fishing energy consumption, services energy consumption. Two additional sub-models for energy consumption from irrigation agriculture, which is linked to the food/agriculture model and energy consumption for water services, which is linked to the water model, are included. In the current version of the SDM, energy consumption for irrigated olives, cereals, wine, sunflower, and citrus fruit production is calculated (see food/agriculture model). Water Services Energy Consumption is divided into energy used for pumping groundwater, which is linked to the outgoing groundwater flow in the water model multiplied by energy used for pumping groundwater (kWh m^{-3}), and energy used for wastewater treatment, which is linked to returned wastewater from domestic and industrial consumption of the water model multiplied by energy used for wastewater treatment (kWh m^{-3}). The energy consumed per unit of irrigated area (kWh ha^{-1}) is calculated by dividing energy consumption in irrigation agriculture by the irrigated area. Similarly, the energy consumed per unit of irrigated area (kWh ha^{-1}) is calculated for the crops considered in the SDM.



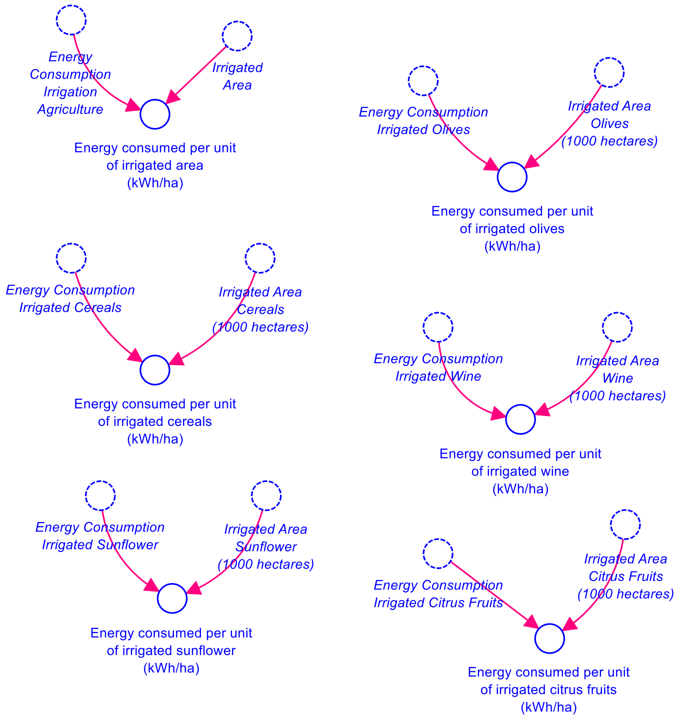


Figure 3.2.10: Stock-and-flow diagram for the energy model.

3.2.3.3 The food/agriculture model

The food/agriculture model focuses on the economic aspects of the agricultural sector. Figure 3.2.11 shows the food/agriculture model for the production of irrigated and rain-fed olives. The model is equally applied to the other commodities considered in the SDM. It includes calculations for production costs, revenues and gross profits (including premiums) of the crops considered. Except for citrus fruits production, which is produced with irrigation only, all other commodities (olives, cereals, wine, and sunflower) include separate sub-models for rain-fed and irrigated production. Rain-fed and irrigated production are separated to account for differences in water and energy costs from irrigation. Irrigation water use is linked to the water model; energy consumption to the energy model; and area used for agricultural production to the land use model. Income (Eur ha^{-1}), supply (1000 t), per hectare water use (m^3 ha^{-1}), water productivity, and energy productivity are calculated for the commodities considered.

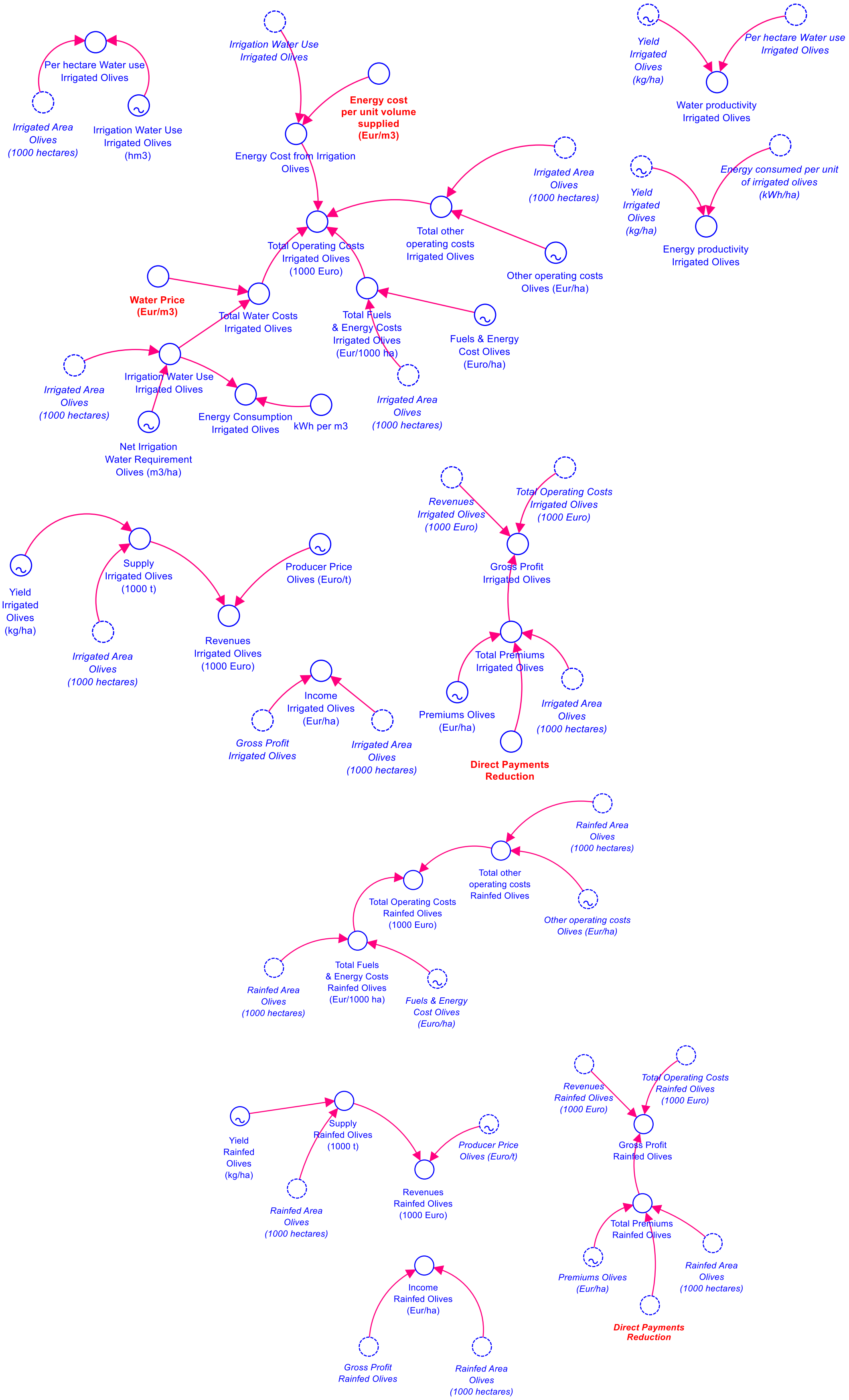
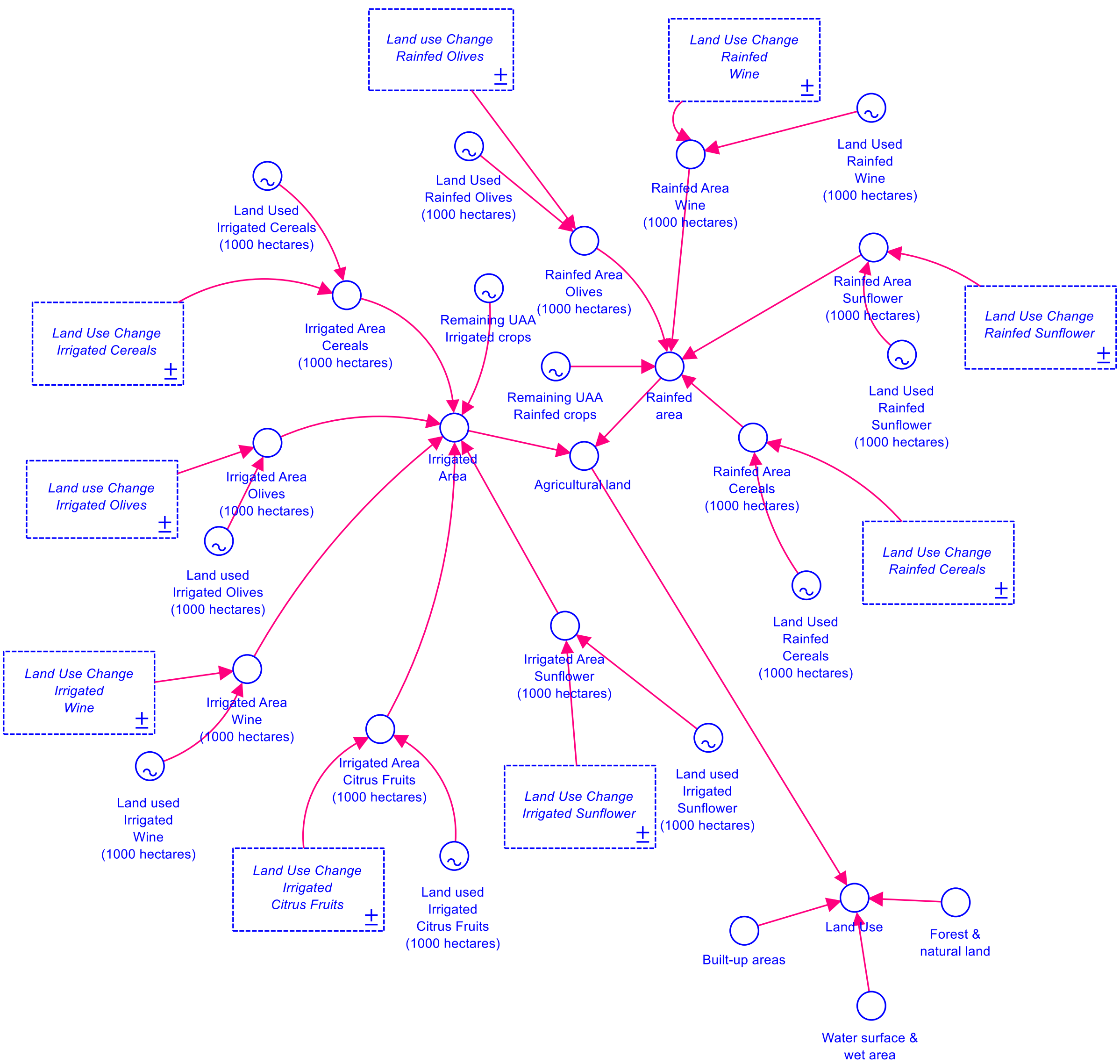


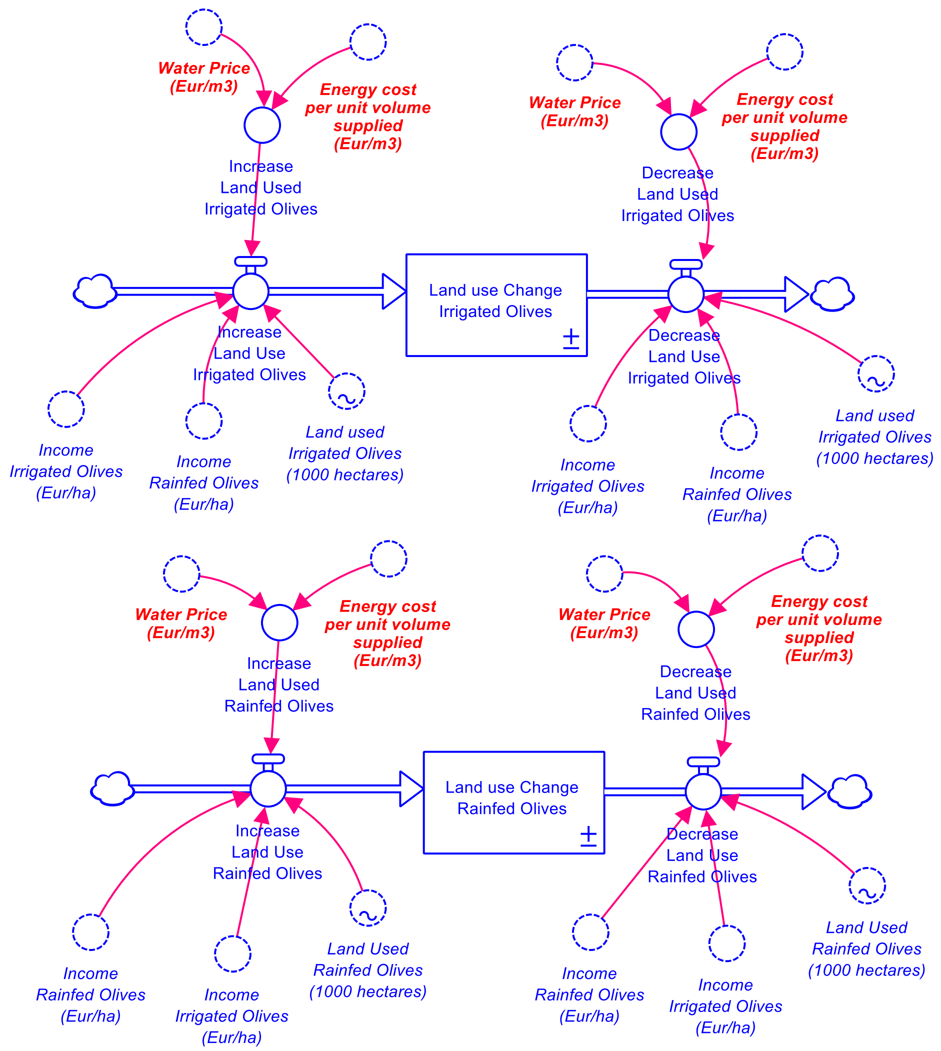
Figure 3.2.11: Stock-and-flow diagram for the food/agriculture model – example of irrigated and rainfed olive production.

3.2.3.4 The land use model

The land use model is shown in Figure 3.2.12. The core of the model includes land use (Figure 10a), which is the sum of agricultural land, built-up areas, water surface and wet area, and forest and natural land. Agricultural land is further divided into irrigated and rain-fed area with specific consideration of the irrigated and rain-fed areas, linked to the calculation of operating costs, water use, and revenues in the food/agriculture model, for the different crops considered. The logical expression to define land use change is based on the assumption that the commodity (shown in Figure 3.2.12b for the example of olives) with higher income (Eur ha^{-1}) is produced and that the land used for the commodity with higher income (Eur ha^{-1}) is increased by one percent and the land used for the commodity with lower income (Eur ha^{-1}) is decreased by one percent. With sensitivity analysis of water and energy price, it can then be analyzed for the different commodities (olives, cereals, wine, and sunflower) whether irrigated production remains profitable or rain-fed production is preferred. For citrus fruits, which are only produced with irrigation, a similar logic applies: if land used for citrus fruit production increases or decreases depends on whether income (Eur ha^{-1}) from citrus fruit production is positive or negative, respectively.



a: Land use model



b: Land use change model

Figure 3.2.12: Stock-and-flow diagram for the land use model – for land use change example of irrigated and rain-fed olive production.

3.3 UK case study

3.3.1 Short description of the case study

The UK Case Study covers the region of the South West of England which is under the operational control of South West Water Ltd. The area roughly approximates to the UKK30 and UKK43 NUTS boundaries Devon and Cornwall, covering an area of approximately 10,300 km^2. There are 1.7 million residents in the region, with the majority of the population (45%) located in just 13 urban centres.

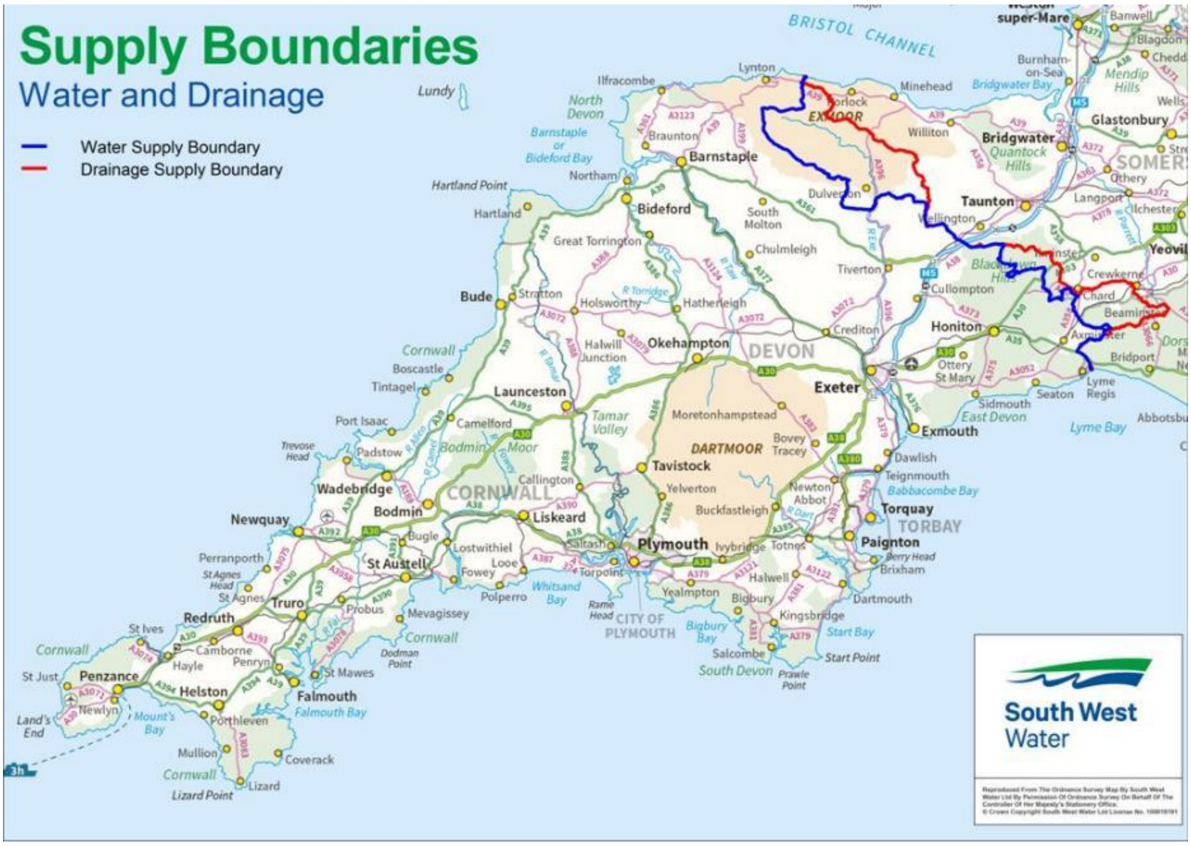


Figure 3.3.1: South West Water operational area

The main aim of the project is to better understand the complex interactions of the Nexus components in the South-West region and develop a decision support framework to facilitate integrated resource management. The UK case study has been prepared in partnership between South West Water Ltd (SWW) and the University of Exeter (UNEXE). Both partners have a strong interest in water and energy. As a water services provider, SWW has a special interest in the influencing factors on the water sector. It is, therefore, the resource and policy interactions between these sectors which form the focus for investigation.

To put the focus of the study into context, the delivery of drinking water and wastewater services are inextricably linked to significant demand for energy and primary resources arising from the natural environment. Further, it is becoming evident that the growing pressures of climate change and population growth heighten the need for efficiency and integrated solutions. Within this setting the UK water industry regulators expect drinking water and wastewater service providers to undertake suitable planning actives to ensure the ongoing delivery of services. In 2007 the Water Resource Management Planning Regulations came into force enacting amendments to the Water Act, which for the first time placed a statutory obligation on water companies to prepare and maintain a Water Resource

Management Plan (WRMP). The main objective of the WRMP being to communicate a water company's intention to manage the balance of supply and demand of drinking water over a 25-year time horizon. It is now expected a similar obligation will be placed upon wastewater service providers in the near future. In anticipation of this requirement, many wastewater companies have prepared and published draft plans following the newly introduced framework for Drainage and Wastewater Management Plan (DWMP). While the WRMP and DWMP are not formally aligned there are numerous linkages between the provisions of the two services, and an integrated approach to planning is likely to improve the overall service level.

Due to the inherent complexity of the urban water cycle, a systems-thinking approach has been suggested by the regulators. When such an approach is taken it quickly becomes evident that the urban water cycle is, in fact, a component of, and entirely dependent upon, a larger supply chain system. Developing this philosophy along a logical route results in a framing similar to that of the water, energy food nexus. The Water-Energy-Food Nexus as a conceptual framework to examine the interdependencies arising from the supply of resources has gained increasing prominence in academic research. However, despite the growing body of literature, few real-world case studies, or examples of the practical application of the approach are available. It is hoped, therefore, that the UK SIM4NEXUS case study will provide a valuable insight for UK utilities, and point the way towards an integrated approach that goes beyond the requirements of DWMP and WRMP.

Energy is the other primary focus of the case study and faces similar challenges to the water sector. The economic regulators of the UK utilities sectors are instructed by the government to minimise the unit cost of all utilities to domestic customers, while at the same time requiring an increase in service level, resilience and environmental performance.

A significant trade-off to be explored is centred on the aim of energy decarbonisation, and the prioritisation of either nuclear or renewable energy, which have both been identified as low carbon solutions. The South-west region of the UK has England's largest natural resource of wind and solar energy, with the greatest installed capacity. The southwest peninsula also has the most accessible offshore renewable resources in England including wave, tidal and wind, which is largely unexploited. The conflict, therefore, arises as the south-west has been chosen as the location for the next major nuclear energy installation, Hinkley Point.

Nuclear energy, while excellent at providing very consistent base-load output has a minimal ability to respond rapidly to fluctuations in demand. This is incongruent with the government's objective of creating a flexible energy network and the intermittent nature of renewables, which fluctuate with the available resource. Furthermore, the baseload output of the nuclear energy station will potentially act as a bottleneck limiting the capacity of the transmission/distribution network to accept more renewable energy generation. It is believed that this, and other, the grid capacity challenge can be mitigated by reinforcement of the network but at a significant capital cost. For nuclear and renewables to coexist in the southwest, there is a much-heightened need for mechanisms to attenuate the temporal disparities between supply and demand and increase network capacity. To compound the complexity of the problem at a national level, both new nuclear and renewables are subsidised via the same funding mechanism "Contracts for Difference", accessing the same budgetary resource. Therefore both economic and technical dimensions play a role in the trade-off between nuclear and renewables.

Synergies with water management are created through raw water resource providing an opportunity for hydropower generation. This option is suitable to the region, although there are high capital costs of new plant, and the economically viable resource is mostly fully exploited.

Synergies could also be created by changing land use and water management practices. Upstream catchment management and paid ecosystem services, for example, would improve surface water quality and reduce the energy demand of drinking water treatment. A pioneering programme undertaken by South West Water, of rewetting moorland and improving farming practices have potential benefits to surface water quality and biodiversity. However, the benefits of such schemes are difficult to quantify, and the feasibility of maintaining such paid ecosystem agreements may be challenged. Similarly, synergies could be established through Sustainable Urban Drainage Systems (SUDS), aimed at reducing surface flood risks, sewer flood risk and sewer storm flow. This concept is not a new one and is effective at minimising wastewater pumping, treatment and consequently energy demand. Southwest water has an engagement program with local authorities and housing developers to implement SUDS, through jointly funded programmes. This helps to overcome some of the main barriers to full exploitation which arise due to the high capital cost for retrofit, and the complex issues surrounding responsibility of ownership and maintenance. Also, there is a significant challenge since economic benefits are not usually seen by those financing SUDs, and or the payback periods can be long and difficult to calculate.

There are potential synergies from water to land and energy, since anaerobic digestion of sewage sludge generates methane gas suitable for energy use, and composted sludge cake from anaerobic digestion of sludge is rich in phosphates and nitrogen. When disposed to agricultural land, composted sludge cake can provide valuable fertiliser, offsetting the need for fertilisers from other sources and reducing energy consumption. Sludge passed to anaerobic digestion remains at a relatively low proportion within South West, and the majority of sludge is 'limed', which is of lower agricultural value. The main barriers to further exploitation are the logistic challenge of sludge transport to centralised anaerobic digested treatment and the capital costs to build a treatment plant.

Synergies between water and energy could be created by improving resilience or security of energy supply. Energy supply in the south-west UK is critical to the water services in this region. It would enhance the resilience and security of water, but high capital costs are a barrier to further exploitation. The utility sectors have several commonalities in terms of the general challenges they face, which can also be expanded to the food sector; equality, security of supply and environmental sustainability. These interlinked objectives are often described as a resource trilemma due to the inherent competition and inevitable need for compromise. The conceptual understanding of the resource trilemma frames the nexus question as a whole and forms the basis of the modelling approach. The grouping of water, energy and food as resource-based sectors, challenged by the trilemma, set them aside from the land and climate sectors, which can both be considered as environmental sectors. From a policy perspective, this view is also relevant as we have identified very few policy mechanisms which are exclusively tied to land or climate. Where this is a desire to influence either of these sectors, policy instruments are typically applied within the specific resource sectors likely to impact those environmental sectors.

Focusing on SWW's operational area and within the context outlined above, the case study addresses how legislation, policy and strategic planning can be aligned to;

1. Support sustainable agriculture and the provision of Water and Energy services in a region with significant environmental sensitivities and the UK's largest tourism region.

2. Recognise the need for resilience in the face of climate change, population growth and an increasingly competitive market place.

Findings from the case study have been used to develop the Systems Dynamic Model (SDM) of the linkages between water, land, food, energy, and climate in the South West (UK) region. The SDM will facilitate detailed scenario-based analysis and learning opportunities which will support both business planning and stakeholder engagement. Furthermore, SWW intends to use the project outputs to positively influence regulatory policies in support of the UK Governments wider ambitions and to demonstrate a strategic approach to business planning that considers "end-to-end" resource management.

Specific areas of investigation that the SDM will facilitate include:

- end-to-end resource management
- improved utilisation and deployment of low carbon energy
- the impact of land use change and farming practices
- resilience to climate change and population growth

In line with the wider S4N project the SDM has been developed to operate over a time horizon of 2020 to 2050. To better suit resource planning, the model employs monthly time steps. Impact analysis is achieved by manipulation of control variables embedded within the model which simulate the policy objectives that have been identified as being relevant to each sector.

3.3.2 Evolution and description of the conceptual diagram

The conceptual model presented here follows from the initial conceptual model prepared for the Deliverable 5.2 South West UK case study report and feedback from the first stakeholder workshop. See Figure 3.3.2 and Figure 3.3.3 which show the early conceptual model.

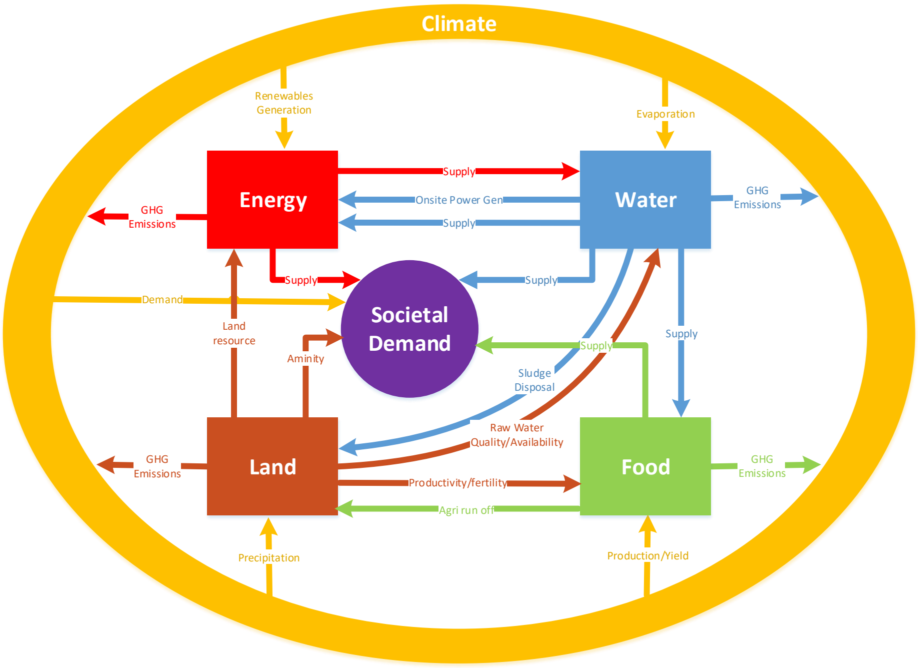


Figure 3.3.2 High level conceptual model

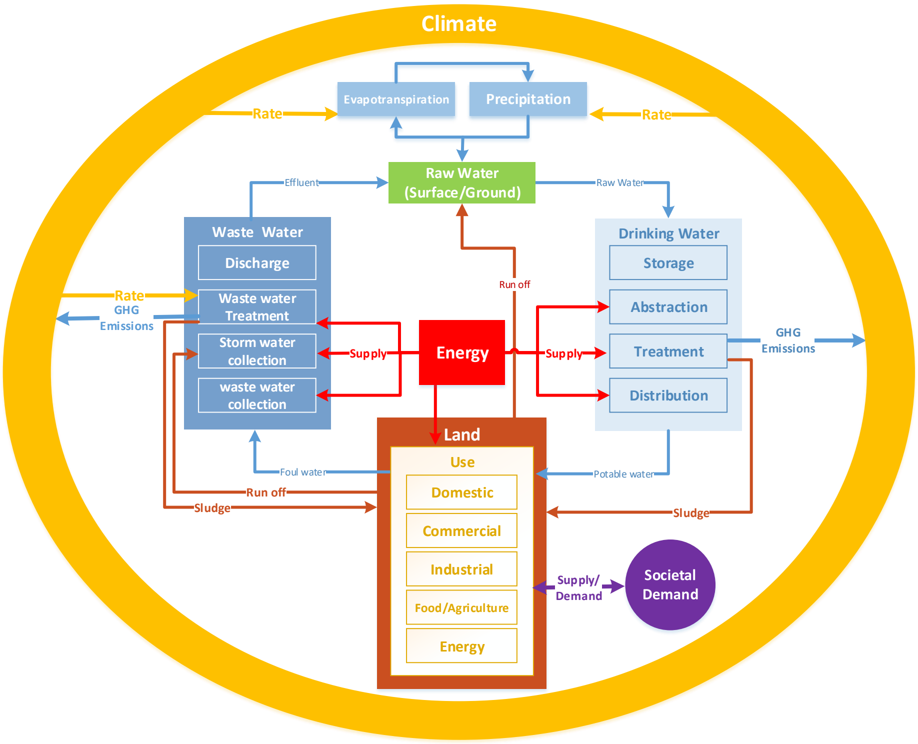


Figure 3.3.3: Conceptual model (early version) in more detail

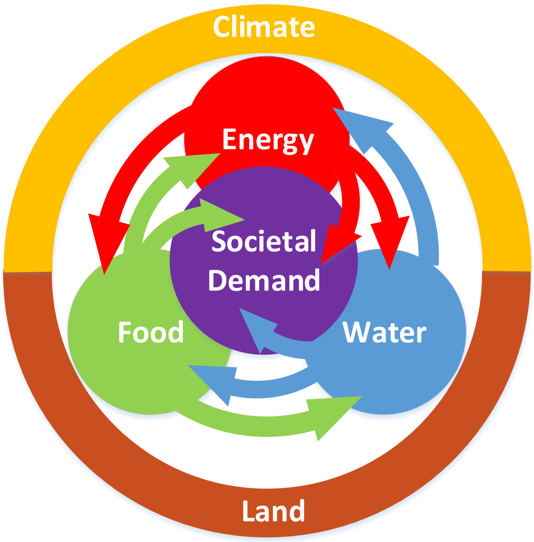


Figure 3.3.4: Simple context nexus

Figure 3.3.4 attempts to highlight the distinction between the two types of nexus sectors;

Resource sectors: The sectors Water, Energy and Food, represent the provision of resources which are in some way; won from the environment, stored, transported and consumed.

Environmental sectors: The sectors Land and Climate represent the environment in which the resource sectors exist or operate, and are the receptors to emissions arising from those sectors.

In all of these simple diagrams, arrows radiating from the sectors represent resource flows, in response to a demand signal generated in the receiving sector. Due to a necessity for increased detail, much of the additional work on the conceptual model has been undertaken directly within the Stella Architect software environment. Simple visualisations of each process have been developed to support user understanding, validate model interactions, and communicate the base functionality of the modelling environment.

3.3.3 Description of the developed system dynamics model

From a functional perspective, the SDM assumes a demand-led philosophy, whereby the flow of resources to meet direct societal demands (i.e. demands associated with domestic, commercial and industrial activities), and the flow of resources between individual sectors are the primary driving factors. While the demand-led approach dominates, in several situations, the model uses a supply-led approach where raw resource availability becomes the driving force, for example in the case of renewable energy generation or land use.

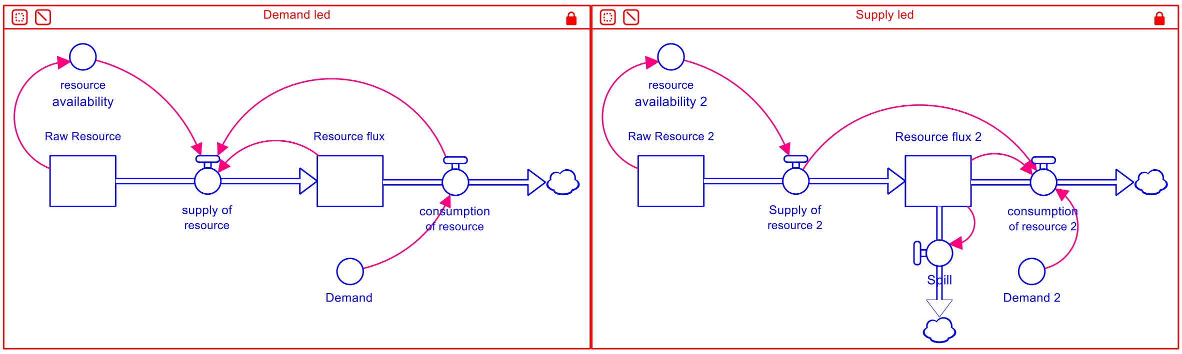


Figure 3.3.5: demand led vs supply led resource component in SDM

In both philosophies supply and demand together control the ultimate consumption of resources. However, there is a priority in terms of where the driving control signal originates and the subsequent balance of resources.

Under the demand-led philosophy, demand initially drives consumption which sends a control signal to resource supply. The intention is for supply to meet demand, resulting in no over-supply or accumulation of the resource flux stock. In this example, the availability of resource acts as a limiting factor upon supply, but the nominal assumption is that supply exceeds demand.

Under the supply-led philosophy, the nominal assumption is that demand exceeds supply and resources are supplied immediately upon resources becoming available. Where demand does not match supply, this results in uncontrolled over-supply and resources accumulating in the resource flux stock, or being spilt as waste.

From the standpoint of the nexus existing to meet societal demand, the resource flows between sectors can be seen as system losses, as they are resources which are not made available to meet society's demands but are consumed by the system. Therefore an efficient nexus model seeks to minimise the cross-sector supply and demand flow while maximising the availability of those resources to society.
A significant amount of data has been provided by South West Water for the operational and resource management characteristics of drinking water and wastewater systems. Further detailed historical energy consumption statistics from the UK government has been used for the modelling of the energy and land systems. This is further supported by thematic models E3ME and CAPRI to determine primary aspects of societal demand and agricultural activity.

VARIABLES

The model has been built to understand the impact of policy decisions influencing individual sector variables. To that end, several variables are included in each module to act as control dials. These variables are as follows:

WATER

- environmental flow rate from the strategic reservoirs
- minimum volume of reservoirs
- water infrastructure condition, as a leakage rate per kilometre of network
- drinking water quality
- wastewater effluent quality
- wastewater infrastructure condition, as a saline/ground water infiltration factor

ENERGY

- transmission and distribution network capacity
- the operational status of Hinkley point (nuclear facility)
- installed capacity of all generating technologies
- the capacity factor of all generating technologies

LAND

- planning policy – development on greenbelt
- land-use change
- waste management, recycling, recovery and landfill
- combined surface drainage
- sustainable urban drainage

METRICS

Amongst the numerous objectives of the nexus approach, resource efficiency and decarbonisation are the priorities. Therefore the two primary metrics to track performance are:

1. Total CO2 emissions; *and*
2. the ratio between the total resources supplied by each sector and resources directly consumed by societal demand.

Within each sector, more specific objectives and metrics are considered, based on the priorities identified during the case study. The water sector, for example, is highly concerned about strategic storage of raw water, and sustainable rates of abstraction from surface water bodies. To address these areas of interest, these variables, become performance metrics which are tracked over time in the SDM. An overall health indicator for each sector is considered by evaluating the effectiveness of meeting total demand. This health indicator is then increased or decreased according to the positive or negative impact implied on other sectors, i.e., CO_2 emissions. The financial implications of policy decisions taken within a sector, and the knock-on effect of the policy decision in other sectors, is inherently considered in the modelling. This is done by evaluating the total expenditure (CAPEX plus OPEX) impacts from the baseline level.

TOP LEVEL VIEW

The highest level view of the model is illustrated in Figure 3.3.6 which is a screenshot taken from within the stellar architect platform, showing the two county-based subdivisions of the South West Water operational area, Devon and Cornwall. Within this environment each module incorporates a graphical representation of the region in question for illustrative purposes. The cross-boundary import/export of resources between the two regions is indicated by the arrows that lead from one module to the other.

Figure 3.3.6: high level view of the SDM

REGIONAL MODULE - NEXUS MODEL

Each regional module is a structurally identical nexus model, comprising 6 sub models, which describe the interactions between society and the nexus sectors for that region, Figure 3.3.7. The use of individual nexus models per regional boundary enables region-specific data to be applied so that the unique circumstances of each county (region) can be taken into consideration. This approach, in theory, could be applied to further regional disaggregation, perhaps using catchment areas or other jurisdictional boundaries.

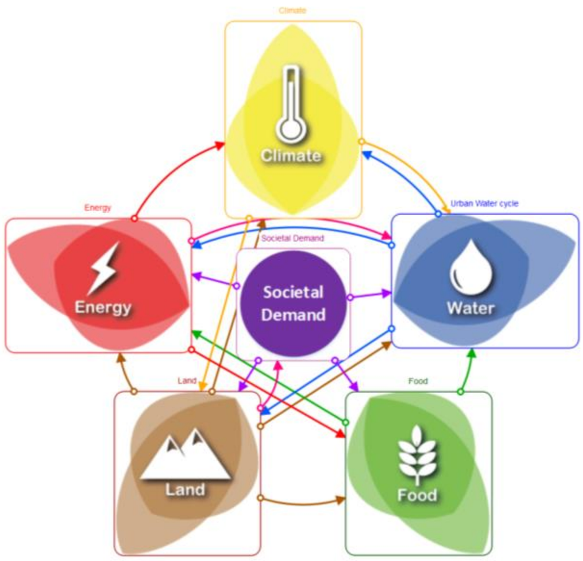


Figure 3.3.7: The nexus model

SPECIFIC LINKAGES:

LAND TO ENERGY: - WASTE TRANSPORT FUEL DEMAND

Within the Land module, waste management is considered, and the transport of municipal and other waste materials is calculated to generate a transport fuel demand upon the Energy sector.

LAND TO FOOD: - LAND UTILISATION FOR AGRICULTURAL PRODUCTION

Within the Land module, land utilisation per agricultural activity is calculated; this data is used by the Food module to calculate raw food productivity.

LAND TO WATER: - RAW WATER QUALITY AND SURFACE DRAINAGE

Within the Land module flow rates and water quality of surface run-off and drainage are calculated for the various land use types. This data is passed to the water module for use within the drinking water and wastewater calculations.

LAND TO SOCIETAL DEMAND: - LAND UTILISATION OF THE HOUSING AND HOUSING DEMAND

The Land module calculates the total area of land utilised for residential housing; this data is used by the Societal Demand module to calculate housing demand due to the population.

LAND TO CLIMATE: - GREENHOUSE GAS EMISSIONS AND SEQUESTRATION FROM LAND-USE

The land module calculates the total area of land utilised for agricultural activities and natural amenity. This data is utilised by the climate module to determine net greenhouse gas emissions from land-use.

FOOD TO WATER AND ENERGY: - IRRIGATION, LIVESTOCK AND FOOD PROCESSING DEMAND

Within The Food Module water and energy demand for arable farming, livestock, transport and food processing is calculated based on land utilisation and productivity. This data is passed to the Energy and Water sectors as demands.

WATER TO ENERGY: - ENERGY DEMAND FOR WATER TRANSPORT AND TREATMENT

Within the Water Module, the whole urban water cycle is considered which calculates numerous energy demands between treatment and transportation of water. This data is passed to the energy sector as a demand.

WATER TO LAND: - SLUDGE DISPOSAL

Wastewater and drinking water treatment give rise to various sludge streams which are disposed to land. The volume of sludge is calculated within the Water module and passed to the Land module.

WATER TO CLIMATE: - PROCESS AND FUGITIVE EMISSIONS

The Water module calculates volumes of sludge produced, chemicals consumed and energy demand, each of these have associated greenhouse gas emissions which are calculated within the Climate module.

3.3.3.1 Water Sector Submodel

The water sector sub model is subdivided into drinking-water and wastewater supply chains which when linked via raw water resources describe the urban water cycle.

Drinking water module

Demand analysis process

Description – Overall Water demand is a core component of the water sector. It is a summation of the raw water demand from domestic, agricultural, industrial and commercial sectors. Determining demand levels requires an analysis of population and land use factors. These factors are overlaid with the consumption of the land user or resident and the growth or decline of the specific land use itself. The demand for water is highly seasonal with a significant increase in summer months. This seasonality is most strongly seen in domestic and agricultural contexts, where heat drives an increase in water use for drinking and washing. This is further exaggerated in the southwest due to an influx of tourists. To account for this the model uses a seasonal demand curve derived from SWW operation data which peaks in the summer months. In addition to this raw demand, an allowance is made from system leakage (losses) which is variable and dependent on policy decisions.

Inputs – Population (Pop)/ Per Capita Consumption (L/Pop/d) / Seasonal curve summer (dimensionless)/ Land use area (by type) (km^2) / Water consumption (by type) (L/hds) / Food processing demand (ML/d) / agriculture self-supply (ML/d) / leakage losses (dimensionless)
Prior processes interactions: None

Outputs – Demand (by type) (ML/d)

Subsequent process interactions: Water treatment / Wastewater treatment / Raw Water Availability / River Abstraction / Reservoir Abstraction / Borehole Supply
Policy decision variables – Growth / Behaviours / leakage

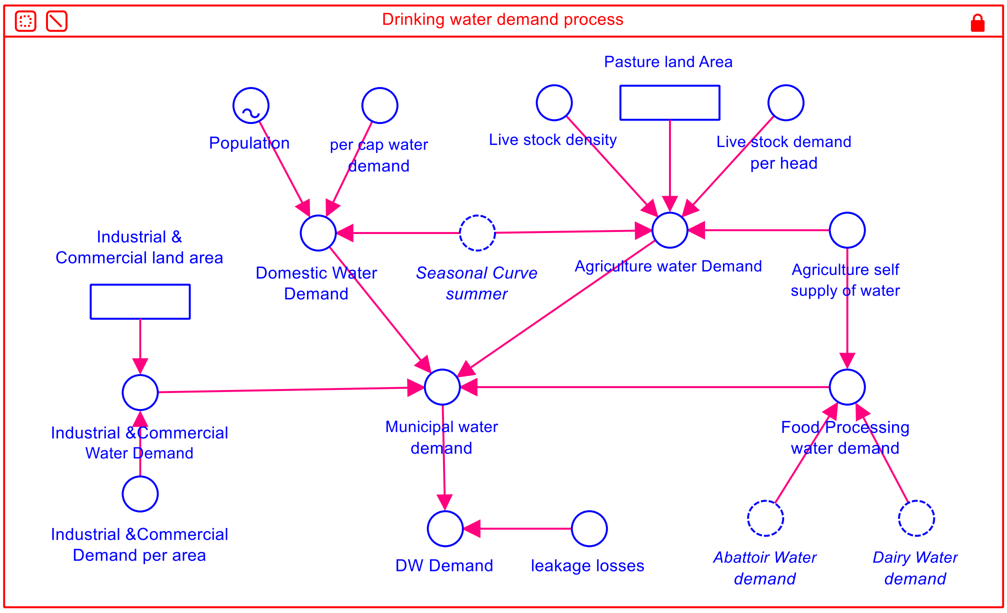


Figure 3.3.8: Drinking water demand process

Raw water availability process

Description - Water availability is considered at the most strategic level of modelling, by evaluating the complex relationship between demand and three potential water sources; 1. River abstraction; 2. Reservoir storage; *and* 3. Borehole supply. Where demand exceeds the sum of available water across the three sources, after making appropriate consideration to their specific constraints, then a supply deficit is said to exist.
The model abstraction priorities follow the order;
1. River Abstraction>2. Reservoir Abstraction> 3. Borehole Abstraction

Inputs – Demand (ML/d) / River abstraction volume (ML/d) / reservoir storage volume (ML/d) / borehole supply volume (ML/d)

Prior processes interactions: River abstraction process / Reservoir abstraction process / borehole supply process

Outputs – River abstraction demand (ML/d) / reservoir storage demand (ML/d) / borehole supply (ML/d) demand

Subsequent process interactions: Water Treatment process

Policy decision variables – None

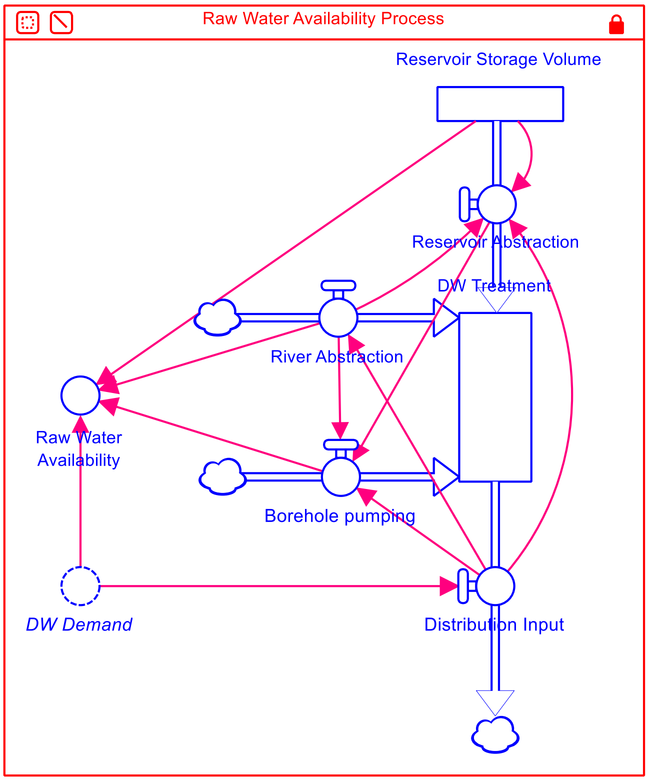


Figure 3.3.9: Raw water availability process

Reservoir storage process

Description – This process represents the volume of stored water held within the Strategic Reservoirs of the region. Within South West water's operational area there are three strategic reservoirs, Colliford in Cornwall then Roadford and Wimbleball both in Devon.

The strategic reservoirs are fed by surface water flow from across the region which is described by the *Catchment flow* data sets. The two main flows leaving the *Reservoir* that occur irrespective of demand are losses (due to evaporation) and environmental flows. Evaporation losses are influenced by climatic variables, average wind speed and temperature. Whereas environmental flow is required to maintain downstream river health and is specified by the regulations that implement the Water Framework Directive. There is a potential to manipulate these flows by policy adjustments i.e. following Brexit.

The *Abstraction* volume is the primary draw of raw water resource from the reservoir to meet drinking water demand. The application of a *minimum reservoir volume* is established as the central management variable to control reservoir level and can be adjusted according to policy or operational decisions. Abstraction flow also adds the potential for hydropower generation or conversely pumping energy demand depending on the specific circumstances of the network.

Where more than one reservoir exists within the regional boundary, the model attempts to maintain an equal distribution by drawing down each reservoir based on their current percentage full. Where demand is higher than useable reservoir volume, we acknowledge a supply shortfall from the reservoir sources.

Inputs – Demand (ML/d) / River abstraction volume (ML/d) / River flow (ML/d) / Reservoir capacity (ML/d) / Environmental flow (ML/d)

Prior processes interactions: Demand process / River abstraction process

Outputs – Reservoir abstraction volume (ML/d) / reservoir storage (ML/d) / reservoir spill volume (ML/d)

Subsequent process interactions: Raw water availability process / Borehole supply volume process

Policy decision variables – Environmental flow / Reservoir capacity

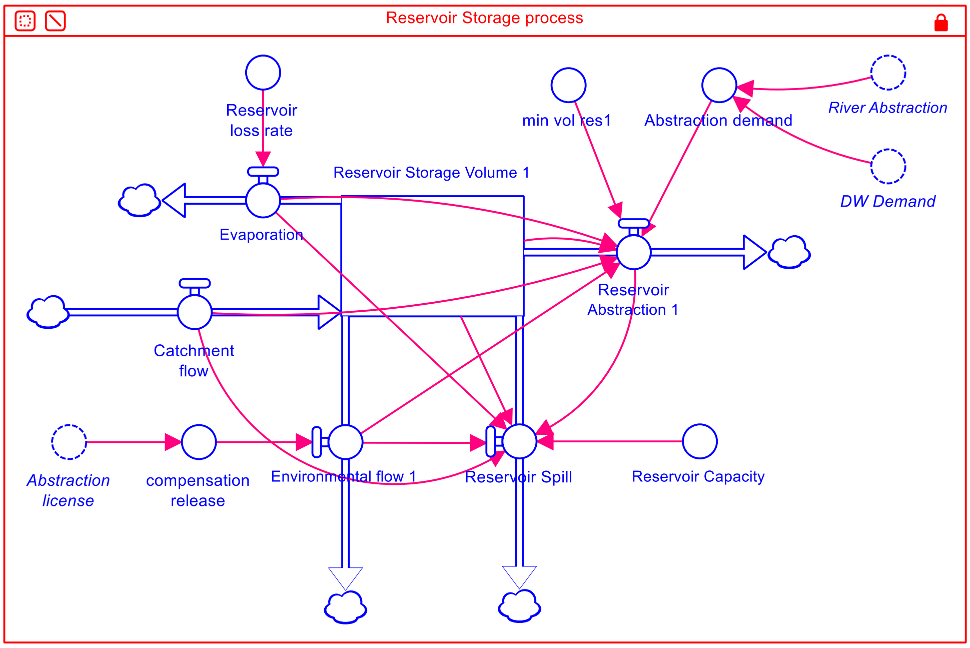


Figure 3.3.10: reservoir storage process

Borehole supply process

Description – The final water resource used to supply drinking water treatment is via *borehole pumping* of the *Groundwater Resource* stock. Borehole pumping incurs a significant operational cost due to the large energy requirement to lift from the body of water. It is therefore a less desirable resource than surface water from an operational cost perspective. However, groundwater is a valuable alternative when demand exceeds the supply of surface water, and it typically incurs lower chemical demands during the treatment process due to the partially treated nature of the source waters.
The borehole abstraction volume is used to bridge the shortfall in demand once river and reservoir abstractions are maximised. In the event, that the required borehole abstraction volume needed to bridge this demands, exceeds the abstraction limit of the borehole, then a total supply shortfall is observed.

Inputs – Demand (ML/d) / River abstraction volume (ML/d) / Reservoir abstraction volume (ML/d) / Borehole abstraction limit. (ML/d)

Prior processes interactions: Demand process / River abstraction process / Reservoir abstraction process

Outputs – Borehole supply volume (ML/d)

Subsequent process interactions: Raw water availability process

Policy decision variables – Borehole abstraction limit

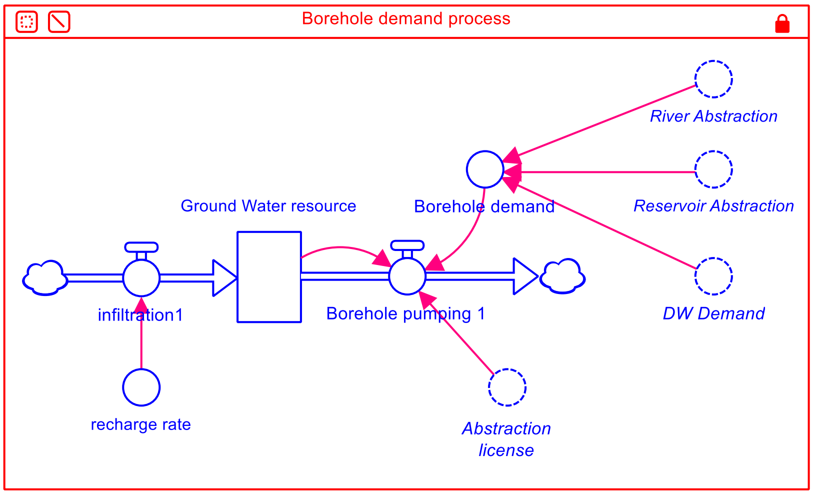


Figure 3.3.11: Borehole demand process

Drinking water treatment process

Description - The *Drinking Water Treatment* process models the chemical and energy demands associated with treating source waters. It uses factors based on the source of water being treated to determine the chemical and energy demands. Chemical and energy coefficients are considered for raw water abstraction and network supply infrastructure to derive the overall drinking water chemical and energy demands from source to tap. Policy decisions around improving or relaxing water treatment standards can be modelled in this process by increasing or decreasing the chemical and energy coefficients.

Inputs – River abstraction volume (ML/d) / Borehole supply volume (ML/d) / reservoir abstraction volume (ML/d) / Demand (ML/d) / Treatment Chemical & Energy coefficients (kg/ML) / Energy coefficients for river, reservoir & borehole abstraction (kWh/ML)

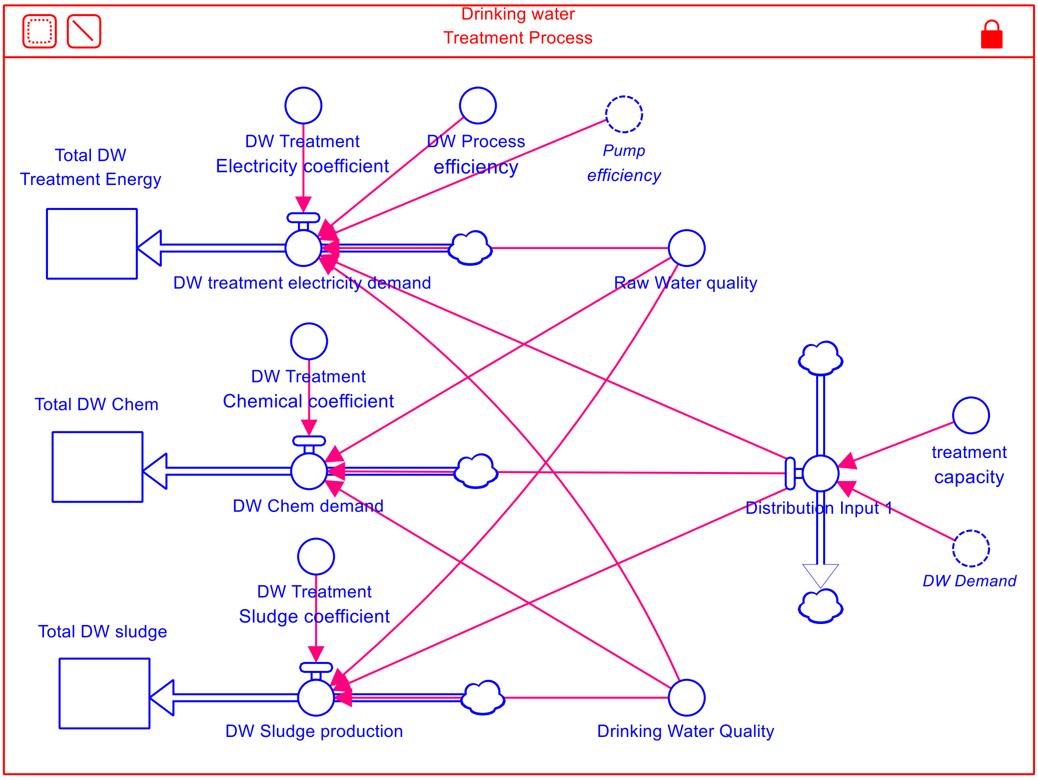
Prior processes interactions: River abstraction process / Reservoir abstraction process / Borehole supply volume process / Demand process

Outputs – Energy demand (kWh) / Chemical demand (kg)

Subsequent process interactions: Energy process / Land & Environment process

Policy decision variables – Treatment Quality via increases to Energy & Chemical coefficients

Figure 3.3.12: Drinking water treatment process



Waste Water Module

Wastewater process

Description - The primary flow into the *Wastewater* stock is the flow of consumed water from the municipal supply which equals the main drinking water demand. The model assumes that for every unit of drinking water supplied and consumed, one unit of foul water is generated. It is acknowledged that this is not entirely correct, however, due to the difficulty of metering foul wastewater flow and the assumed relationship between drinking water and foul water used for sewage billing, this seems a reasonable approximation. The other flow rates into the wastewater stock are primarily due to external environmental factors. These are represented as a surface water drainage volume and intrusion rates resulting from infrastructure in poor condition that is located in either saline or high ground water

environments. Therefore *Saline intrusion*, *surface water intrusion,* and *surface drainage* are potential opportunities for network improvements that would reduce the wastewater volume to treatment.
All wastewater that is generated is passed to the *wastewater treatment* stock which represents the total aggregated wastewater requiring treatment. Due to capacity constraints or operational service fluctuations, not all wastewater is treated, and this is modelled within the 'environmental discharge process'. The Drainage Network flow represents wastewater within the network which hasn't been rejected due to capacity constraints and is being passed to wastewater treatment.

Inputs – Municipal demand (ML/d) / Area of land (by type)(km^2) / Surface drainage coefficient (ML/km^2) / Climate change factor (dimensionless) / River flow rate (ML/d) / Intrusion rate (saline & ground water) (L/km/d) / Network length (km) / Network % in (coastal area & below water table)

Prior processes interactions: Land & environment process / Demand process

Outputs – Wastewater Volume via Drainage network flow and CSO flow (ML/d)

Subsequent process interactions: Environmental discharge process

Policy decision variables – Area of land (by type) / Surface drainage coefficient / Saline & groundwater intrusion rates

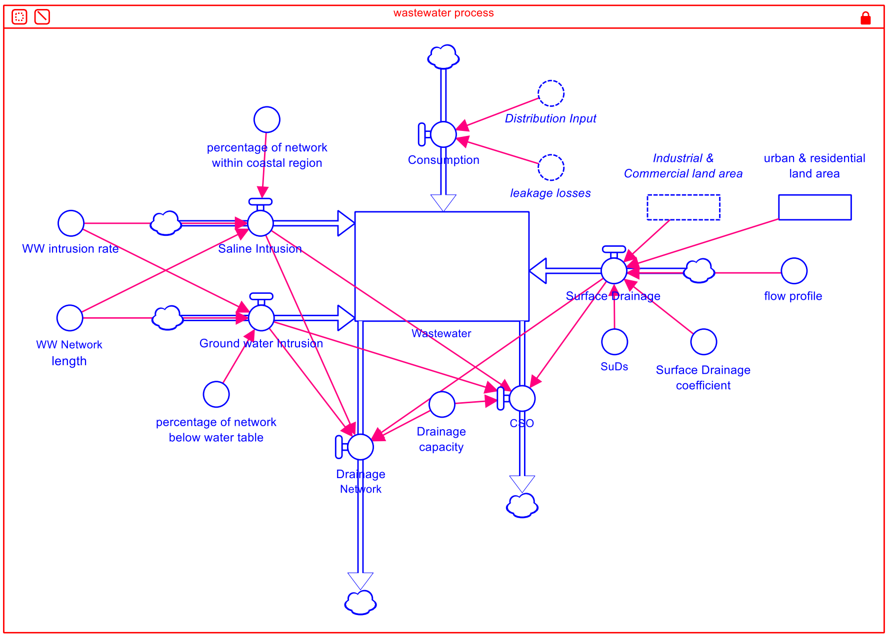


Figure 3.3.13: Wastewater process

Waste water treatment process

The *Treated flow* represents the treatment process itself and is driven primarily by the *drainage network* flow. An addition flow into the process comes from commercial waste handling, the majority of which arises from food processing. The commercial waste flow can be stored temporally on site, and feed into the treatment process gradually to avoid exceeding treatment capacity. Treatment capacity can theoretically be exceeded by inflow from the drainage network, when this occurs the additional flow bypasses treatment and is discharged directly, see untreated discharge process.

Using the same approach as the drinking water treatment module, chemical & energy demand alongside sludge production are calculated using a per-flow coefficients derive from SWW data.

Inputs – Drainage network flow (ML/d) / Dairy wastewater (ML/d) / Abattoir wastewater (ML/d) / per-flow coefficients for energy, chemicals and sludge (kWh/ML, kg/ML, kg/ML)
Prior processes interactions: wastewater process

Outputs – Treated discharge and flow Bypass flow (ML/d)

Subsequent process interactions: Environmental discharge process

Policy decision variables – treatment capacity / effluent quality / process efficiency / pump efficiency / percentage of sludge sent to CHP

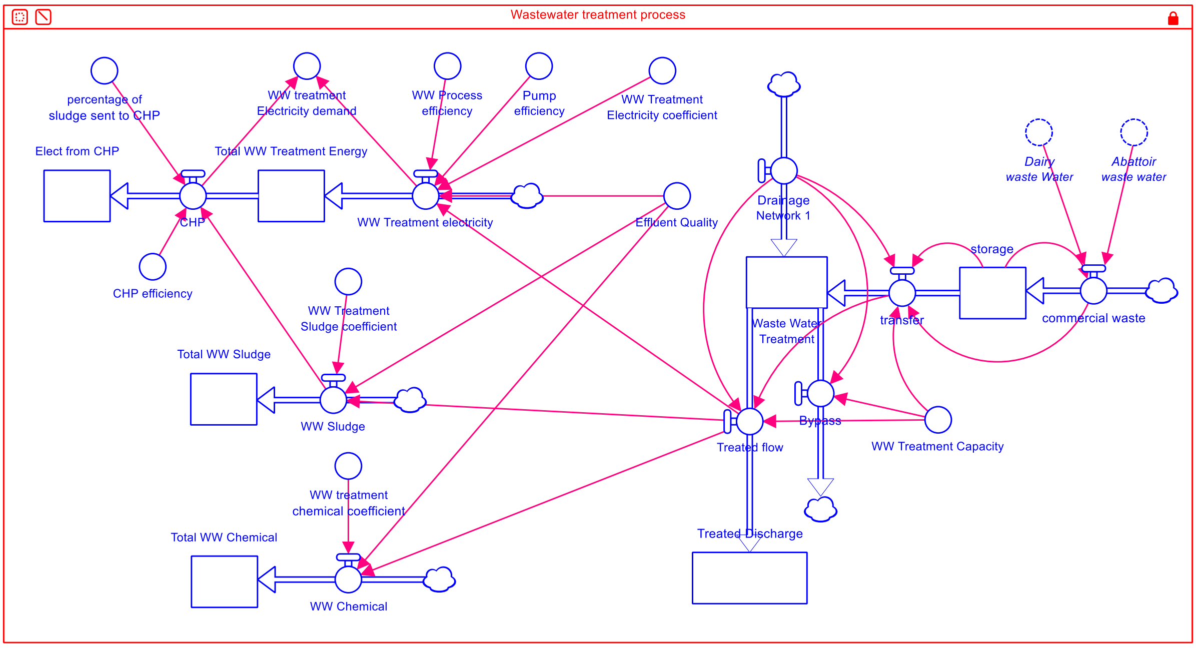


Figure 3.3.14: Wastewater treatment process

Untreated discharge process

Description – As previously acknowledged, not all flows in the wastewater network can be treated. This arises from either insufficient capacity of the drainage network or insufficient capacity of the treatment works itself. In the first instance, excess wastewater is discharged to the environment via combined sewer overflows (CSO). Typically, this occurs due to high volumes of surface water in the network and therefore the concentration of sewage is relatively low. In the latter instance, the flow to treatment would exceed the treatment capacity of the wastewater treatment works. Again, this would only occur during storm events, and the environmental discharge is pre-screened to minimise environmental impact. These untreated discharges are highly undesirable and great effort is made to avoid their occurrence. Discharge events are also reportable to the environmental regulator and used as performance metrics across the industry.

Inputs – Wastewater volume (ML/d) / Treatment capacity (ML/d) / Drainage capacity (ML/d)

Prior processes interactions: Wastewater volume process

Outputs – Treated water volume (ML/d) / Uncontrolled discharge volume (ML/d)

Subsequent process interactions: Land & environment process

Policy decision variables – Drainage capacity / Treatment capacity

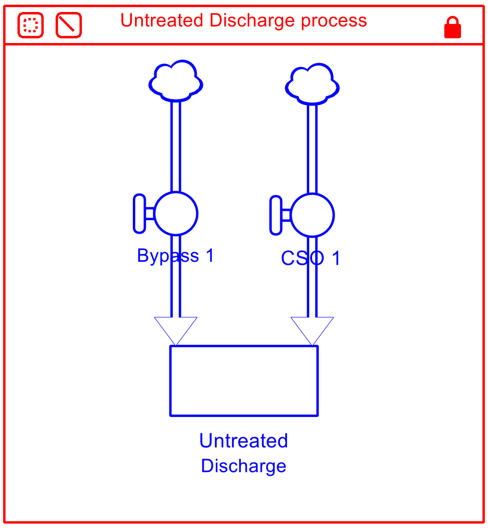


Figure 3.3.15: Untreated discharge process

Description of datasets and policy variables

River flows and catchment flows: is taken from SWW's historical data of the rivers abstraction points, reservoir catchment in flows and from the Centre for ecology & Hydrology (CEH) "Future Flows" data set.
Losses rates: including leakage and evaporation will be taken from SWW's historical data
Environmental flow prescribed flow and Abstraction limit: are provided by Environment Agency (EA) regulations for specific rivers. This is a crucial management variable and may be modified by policies within the model.
Minimum volume of reservoir: Is initially taken from SWW's Drinking Water Resource Management Plan. However, this is a crucial management variable and may be modified by policies within the model.
Aquifer and *groundwater recharge:* will be provided by South West water's Drinking Water Resource Management Plan.
For both drinking water and wastewater treatment several operational characteristics are directly linked to flow rate. Within the model these are; chemicals demand, sludge production and energy demand. Historical data will be used to determine the correlation between flow and these three characteristics for the treatment sites within the spatially defined boundaries. The averaged per flow of each variable will then be applied as coefficients. It is possible to apply percentage-based multipliers to these coefficients to simulate improvement or degradation to service performance in accordance with model scenarios or policy decisions.
Drinking water quality: is specified by the Drinking Water Quality Regulations and has a direct impact on chemical and energy demand. To a lesser extent sludge production arising from drinking water

treatment is also a by-product of legislative changes. Policy decisions to amend these regulations can be implemented in the model by manipulation of this coefficient.

Surface Water Quality: is calculated in the Land module using a mass balance approach from the various surface water run-offs within the region. The model calculates an averaged value for water quality across the whole spatial boundary and does not examine individual river tributaries. It will be possible to manually adjust *surface water quality* to examine sensitives and upstream scenarios.

Network km and *Leakage per km:* provide SWW data about the distribution network within the spatial boundary. Leakage is manipulated by percentage-based multipliers to simulate improvement or degradation to service performance following model scenarios or policy decisions.

The *Saline intrusion* and *surface water intrusion* flows into the *wastewater* stock represent the intrusion of unwanted water flow into the drainage network; this is in effect the opposite of leakage.

WW intrusion rate: Within the model, this is considered as a rate, per unitary length of the network and is provided by initially by SWW data. Contributing factors to this included age of the pipe, the material of the pipe, the stability of ground and recent groundworks etc.

WW network km: is the total wastewater network length within the spatial boundary; this will be found using GIS analysis of SWW data.

Coastal region: this will describe the percentage of the wastewater network within the boundary which is close to or below sea level and within a certain distance of tidal waters. This will be determined by GIS analysis of SWW data.

Sea level: will be used in conjunction with the coastal region to determine the rate of saline intrusion. Sea level rises a predicted impact of climate change and time series data from the thematic models will be used to plot this.

Water table depth: is the primary driver of groundwater intrusion into the drainage network, this data will be provided by SWW and water framework directive groundwater catchments via GIS analysis.

Surface drainage: much of the impermeable surface within urban and commercial areas of the south-west region is connected to the drainage network, adding stormwater flow to wastewater treatment. The total impermeable area within the spatial boundary will be calculated within the land use module, and via GIS analysis, this data will drive surface drainage flow.

Effluent consent: the effluent consent specifies the quality to which wastewater must be treated before discharge to a natural watercourse; this has a direct impact on energy/chemical demand sludge production and the aquatic environment. As effluent consent is largely determined by implementations of the WFD the model will provide a valuable opportunity to analyse the implications of policy decisions and operational decisions that altar consent standards.

3.3.3.2 Energy Sector Submodel

The energy sector sub model seeks to examine the balancing of supply and demand of electrical and thermal energy within the region. All forms of renewable energy generation within the south-west region are included as well as all forms of fossil fuel and grid electricity import.

The energy subsector model is the first example of a supply lead philosophy taking precedence within the whole Nexus SDM. The supply lead approach is appropriate due to the nature of renewable energy generation, in that for the majority of cases energy is generated as the resource becomes available. For example, photovoltaic solar energy only generates when it's "sunny", and if it is in an operational condition, it always generates when it's sunny. In its current state, the Distribution Network Operator (DNO) has limited ability to curtail generation from renewable energy suppliers and only a small percentage of generators connected to the network have arrangements in place to facilitate this. This, however, is likely to change in the coming years as DNO's switch to a Distribution System Operator model whereby they become responsible for balancing arrangements. The SDM, therefore, provides an opportunity to examine strategies for enhancing the utilisation of renewable energy generation so that curtailment of generation can be optimised as a strategic level. The model considers that renewable energy is generated in two modalities *constrained* and *unconstrained*.

The energy sector model is subdivided into three modules representing: 1.Local Electricity from renewable Energy, 2. The Distribution and Transmission Network, *and* 3. Thermal Energy.

Data and variables used in the model

Digest of UK Energy Statistics (DUKES) and the Renewable Energy Planning Database (REPD) provided by the UK government are used for historic baseline energy generation data, the installed capacity, and capacity factor. Forecast coefficient representing changes to installed capacity are derived from E3ME. Western Power Distribution (WPD), the regional electricity distribution operator, have provided network capacity analysis data.

Energy demands process

Description: As with the water sector, demand is a core component of the Energy sector, and it is a summation of the energy demand from domestic, agricultural, industrial and commercial sectors, and crucially also the water sector.
Within the energy sector, a further distinction is required due to the different sources of energy and their ultimate use. For simplicity sake the SDM focus on Electricity and thermal energy, transport energy is largely ignored.
Following the same approach to the water sector, energy demand is determined by analysis of population and land use factors.
The demand for energy is highly seasonal with a significant increase in winter months. This is driven by the reduction in ambient temperature giving rise to a direct heating load for space and water heating. To account for this, the model uses a seasonal demand curve derived from National Grid data which peaks in the winter months.

Inputs – Population (Pop) / Per Capita Consumption (kWh/Pop/d)/ Seasonal curve winter (dimensionless) / Land use area (by type) (km^2) / energy consumption (by type) (kWh) / Food processing demand (kWh) / agricultural demand (kWh) / self-supply from renewables (kWh) / water sector electricity demand (kWh)

Prior processes interactions: none

Outputs – Demand (by type) (kWh)

Subsequent process interactions: Local Distribution network process

Policy decision variables – Growth / Behaviours / efficiency / self-supply of renewable energy

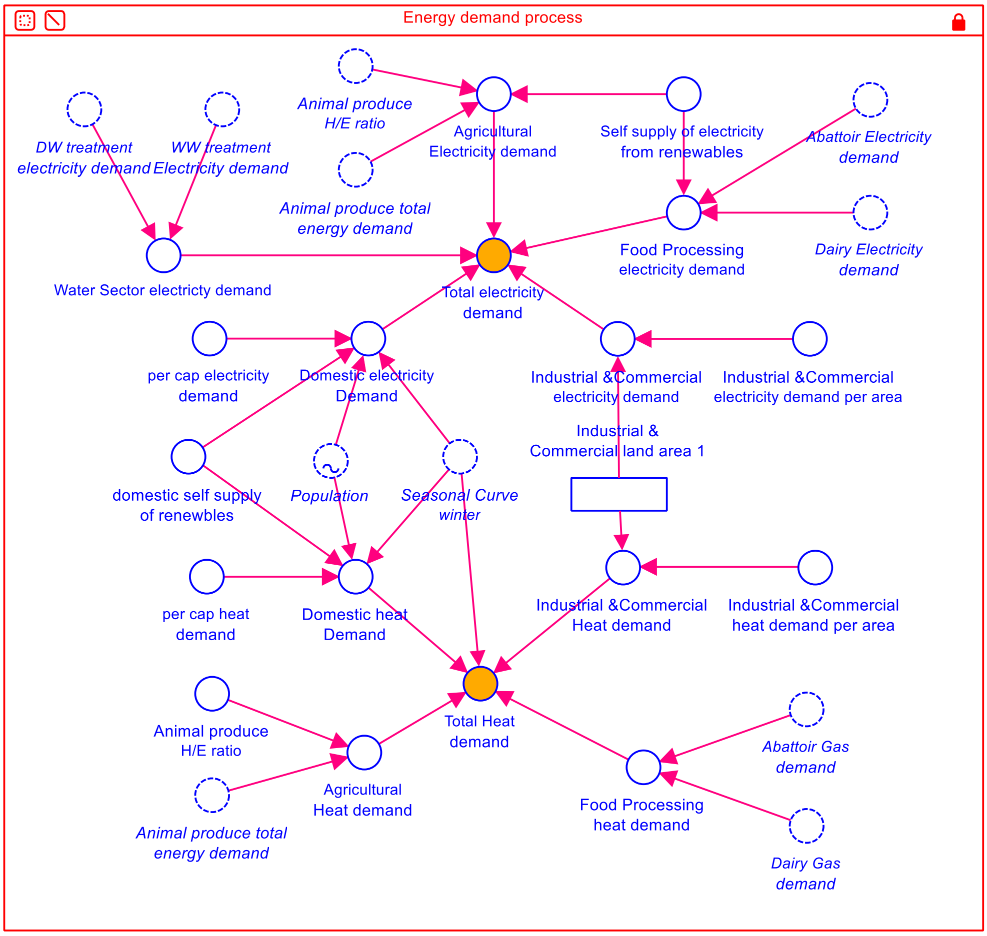


Figure 3.3.16: Energy demands process

Distribution and transmission network module

Local transmission network process

Description – At the centre of the energy sector model is the local distribution network process which models the basic the activities of the distribution network operator (DNO). The distribution network receives locally generated electricity and imported electricity from the transmission network which it then distributes to end-users of all types.

The central stock Local Electricity Network receives flow from the following sources: 1. *unconstrained renewable electricity into Supply*, 2. *constrained renewable electricity into supply*, 3. *transmission Grid electricity Import and* 4. *local CCGT*. The primary flow exiting the stock is Total Local Electricity Consumed which meets local electricity demand. Grid Electricity Export represents electricity generated locally but not consumed and exported back onto the transmission network. The primary function of this process is to balance supply and demand ensuring that demand arising from across the nexus is met through a combination of these electricity sources.

As mentioned previously a supply lead philosophy dominates much of this part of the model, where electricity generated from renewable energy sources enters the distribution network irrespective of demand. This is also true of electricity generated from the local Combined Cycle Gas Turbine (CCGT), which attempts to operate in a baseload modality. The balancing activity is achieved by comparing the instantaneous supply of electricity against local demand. When a surplus occurs the additional volume is exported onto the transmission network, conversely when a deficit occurs the shortfall volume is imported.

Inputs – unconstrained renewable electricity into supply (kWh) / constrained renewable electricity into supply (kWh) / transmission grid electricity import (kWh) / Local CCGT (kWh) / Total Electricity demand (kWh)

Prior processes interactions: constrained renewable energy generation / unconstrained renewable energy generation / Transmission Network Capacity Process

Outputs – Transmission grid electricity export (kWh) / total local electricity consumed (kWh)

Subsequent process interactions: GHG emissions process
Policy decision variables –

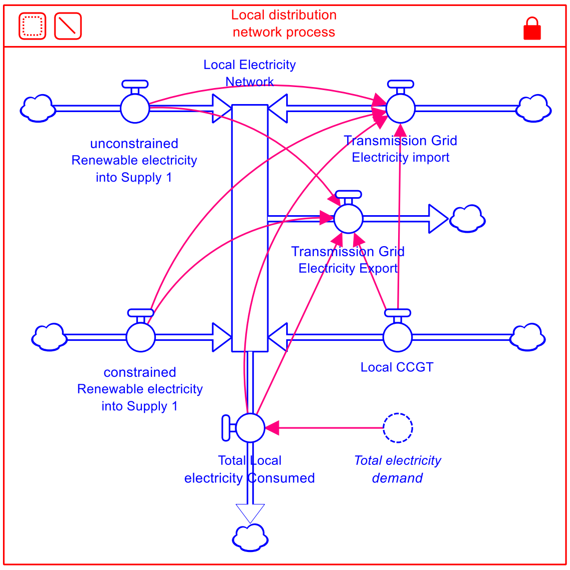


Figure 3.3.17: Local distribution process

Transmission network capacity process

Description – The flow of imported and exported electricity between the local distribution network and the transmission network is limited by the available capacity of the interconnection between the two, and it can be heavily influenced by large scale energy generators. This is of particular importance because this capacity facilitates the effective use of locally generated energy and enables regional energy security. To model this relationship an addition check process is included which monitors the volume of import/export against effective transmission network capacity. When a network capacity is exceeded a curtailment signal throttles energy generation.   The operational status of the planned nuclear plant Hinkley point and the proposed enhancement to network capacity are major influencing factors in the process

Inputs – Operational status of Hinkley Point (dimensionless) / Presence of balancing mechanisms (dimensionless) / transmission network capacity (kW)

Prior processes interactions: none

Outputs – generation curtailment signal (dimensionless)

Subsequent process interactions: Local Distribution network process / GHG emissions process

Policy decision variables – Operational status of Hinkley Point / Presence of balancing mechanisms / transmission network capacity

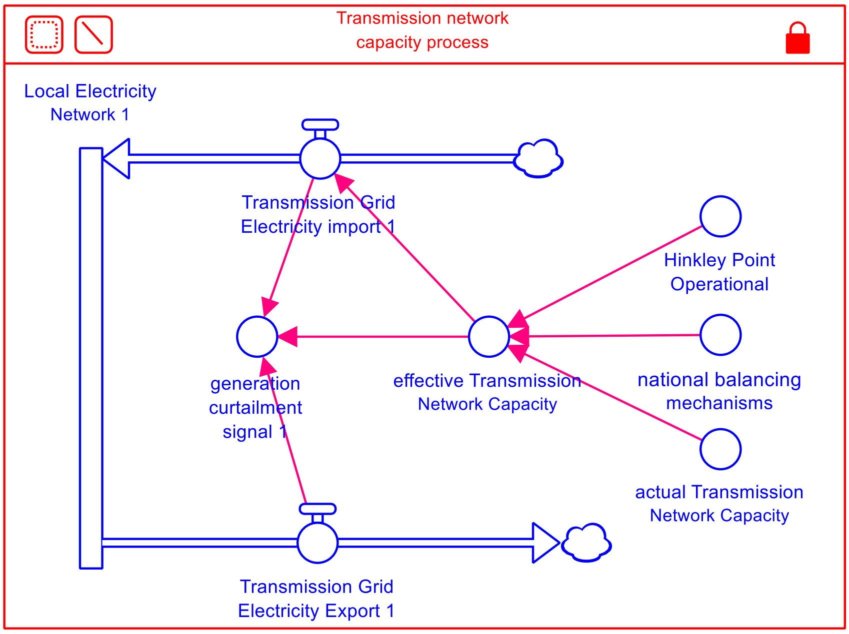


Figure 3.3.18: Transmission network capacity process

Local electricity from renewable energy module

Unconstrained renewable electricity process

Description – the unconstrained modality, which is applied to solar, wind and hydro, assumes that all energy generated by the available resource is supplied into the distribution network without curtailment and is not constrained by offtake demand. This situation is only possible while renewable energy generation supply is nominally lower than demand and while sufficient capacity within the distribution network exists. It is worth noting that constraints within the distribution and transmission network do currently exist and are limiting the development of new generating capacity, hence the inclusion of the 2 modalities.
All forms of unconstrained renewable energy generation are described in terms of; *Installed Capacity* and *Capacity Factor,* with a *seasonal curve* that varies output over the year. This approach enables all three variables to change with time. In the case of a *seasonal curve,* this may change as a result of climate change, i.e. it becomes windier or less sunny. Installed capacity describes the total megawatt generating capacity of all aggregated assets of that type in the spatial boundary. As the policy to deploy more or less generating assets changes over time so will the installed capacity figure. The capacity factor describes the relationship between actual generation and potential generation of the asset; therefore with improved efficiency or different management philosophy, the capacity factor may improve or

decline over time. The volume of energy generated in the time step by each technology is found by multiplying the 3 variables by the hours in the month.

Inputs – Installed Capacity per technology (wind, solar, hydro) (kW) / Capacity factor per technology (wind, solar, hydro) (dimensionless) / seasonal curve (dimensionless)

Prior processes interactions: none

Outputs – unconstrained renewable electric into supply flow (kWh)

Subsequent process interactions: Local Distribution network process

Policy decision variables – Installed Capacity / Capacity factor

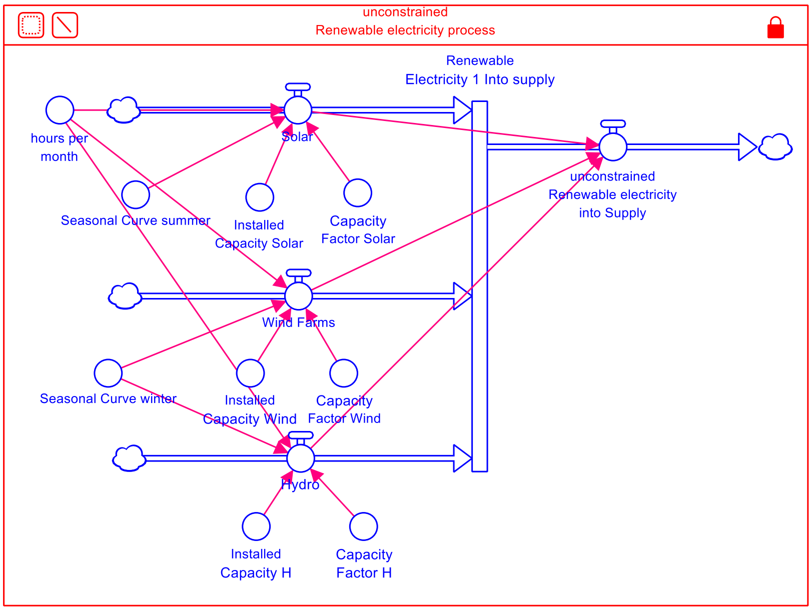


Figure 3.3.19: Unconstrained renewable energy process

Constrained renewable electricity process

Description – To account for the growing need for load balancing, the model includes a constrained modality for generating technologies which are inherently capable of energy storage, thus allowing, a response to a curtailment signal without spilling of resource. These technologies can further be characterised as being combustion based generating technologies. Each technology is described in terms of *installed Capacity* and *Capacity factor* in a similar approach to unconstrained renewables. Again following the same approach the volume of energy generated in the time step by each technology is found by multiplying the 2 variables by the hours in the month.
The *load curtailment signal* is as a management variable which when triggered by 'unconstrained renewable generation' exceeding the network capacity, acts to limit the volume of energy generated by the constrained technologies. The effect is to throttle back supply of electricity up to the capacity threshold, rather than fully shutting down the generating technologies. This approach is taken as the temporal resolution distorts the impact of multiple short term shutdown events.

Inputs – Installed Capacity per technology (EfW, Biomass, Landfill gas, AD) (kW) / Capacity factor per technology (EfW, Biomass, Landfill gas, AD) (dimensionless) / presence balancing mechanisms within the network (dimensionless) / capacity of Network storage (kWh) / Distribution network capacity (kW)

Prior processes interactions: unconstrained renewable electricity process

Outputs –Constrained renewable electric into supply flow (kWh)

Subsequent process interactions: Local Distribution network process

Policy decision variables – Installed Capacity / Capacity factor / network storage / local balancing mechanisms / Distribution network capacity

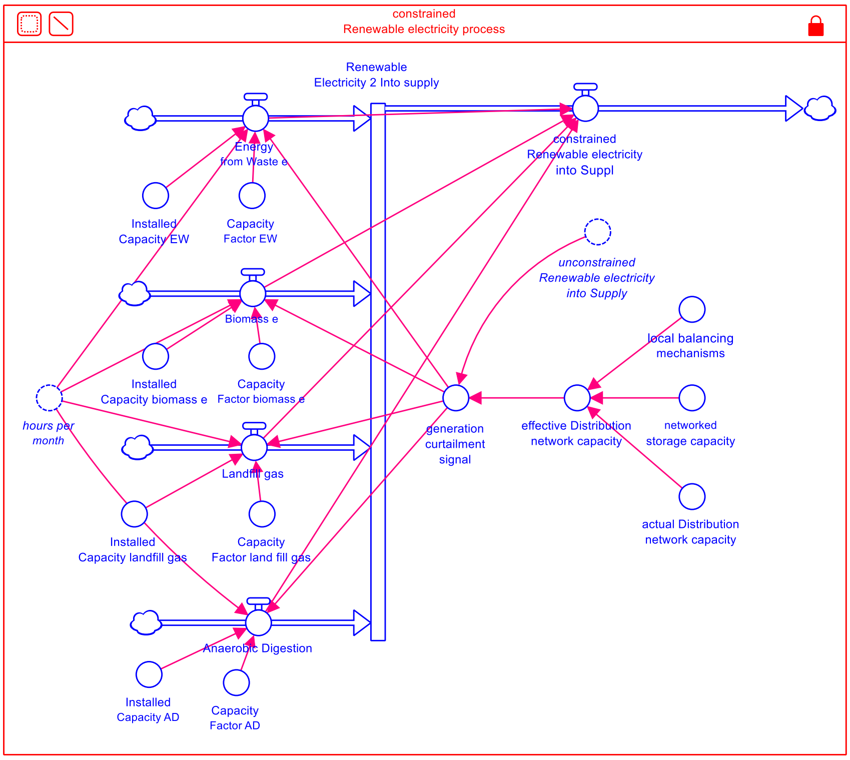


Figure 3.3.20: Constrained renewable energy process

Renewables land use process

Description – The land use associated with renewable energy generation is considered in the model by focusing on solar and wind technologies only. This is because the energy density of these technologies is such that land area per MW of capacity makes a significant impact to land resources. The other generating technologies have much higher energy density and a correspondingly low footprint. Furthermore, these technologies are often located within or immediately alongside existing industrial activities.

Commercial scale wind energy uses land on two levels, firstly the actual physical footprint of individual plant components, and secondly the arrogated area when turbines are grouped into wind farms. These two land uses are very different in both terms of scale and impact. The direct footprint of wind farm plant is relatively small, and is less variable or a per MW basis (usually measured in terms of m^2 per

MW), but it excludes all other land uses in its immediate location. The aggregated wind farm area, however, is much larger and significantly more variable of a per MW basis (typically measured in terms of Ha per MW). The aggregated wind farm area is much less exclusive to other land use activities and can incorporate agriculture and even solar energy generation. However, exclusion zones can inhibit activities beyond the physical footprint. To account for these two land uses, coefficients and land areas for each level are included, this is based upon historical wind land use statistics from UK government.
The land demand for ground-mounted solar energy plant is very consistent and has a linear relationship to generating capacity. Solar energy farms are more exclusive in terms of other land use within their immediate foot print, but are less demanding in terms of the surrounding land use and do not conflict with other land uses beyond their direct footprint.

Inputs – wind farm land density (MW/km^2) / wind energy direct land use (MW/m^2) / solar energy land density (MW/km^2)

Prior processes interactions: unconstrained Renewable electricity process

Outputs – solar energy land use (km^2) / wind farm land use (km^2) / land demand for renewables (km^2)

Subsequent process interactions: Land use process

Policy decision variables – wind farm land density / solar energy land density

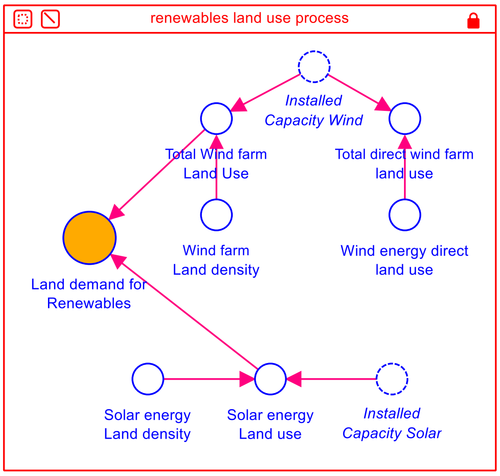


Figure 3.3.21: Renewables land use process

Thermal energy module

Heat energy process

Description- A significant proportion of the energy demand in the south-west region (UK) is in the form of heat for a range of purposes. Because all of the heat conversion technologies are entirely dispatchable and in many instances, multiple fuel types are used on the same site, a demand-led philosophy is appropriate. Heat is supplied to meet demand by each fuel type based on the percentage of the total installed heating capacity, modified by a capacity factor that fuel type.

Inputs – heating energy demand (kWh)

Prior processes interactions: Demand process

Outputs – volume of heat supplied by fuel source (kWh) / volume of fuel consumed by fuel type (kWh)

Subsequent process interactions: GHG emissions process

Policy decision variables – installed capacity by fuel type (kW) / capacity factor by fuel type (dimensionless)

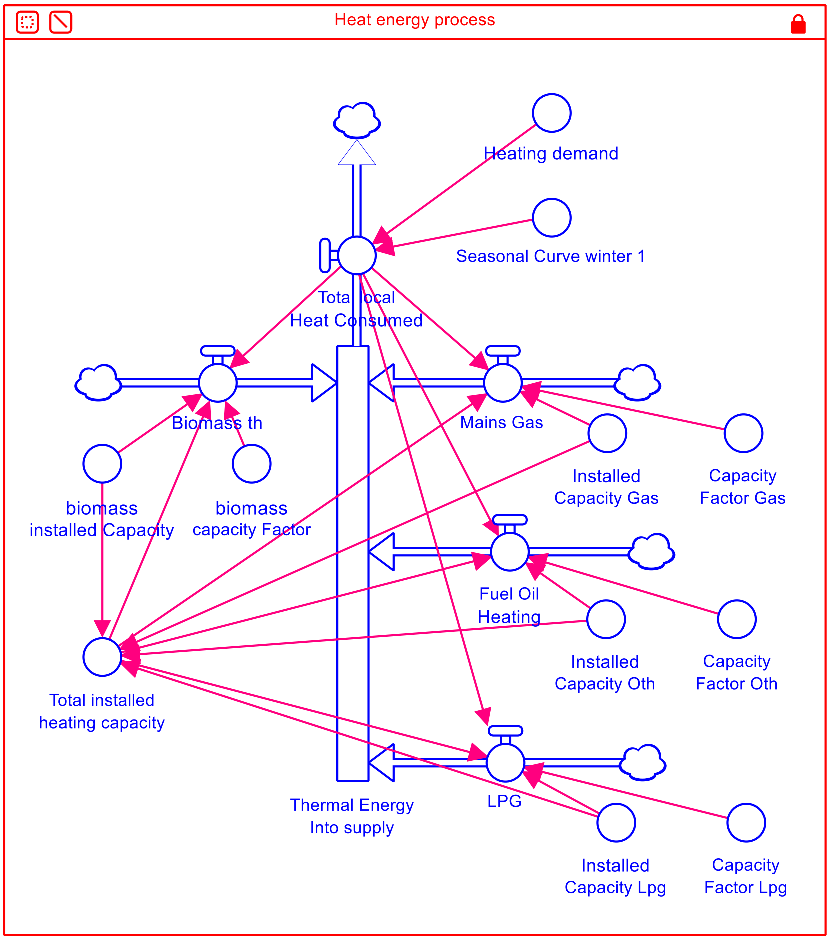


Figure 3.3.22: Heat energy process

3.3.3.3 Land Sector Submodel

Land use module

The model approach is to assume that the total available land resource within the spatial boundary is finite and exists in one of seven states;

1. Residential and Urban Area: this describes all land that is used for residential housing and the immediately associated activities.
    a. Urban Green space; is a sub category parallel to residential and urban area is that describes the area of parks and grassed areas within the urban environment.

2. Commercial and industrial Area: describes the land area used by industrial and commercial activities within the region.
3. Brownfield Area: describes the area of land which has previously been occupied by some form of residential, commercial or industrial activity, but that has been cleared ready for new development.
4. Greenfield Area: describes the area of land which has not been previously developed but has been allocated as available for development.
5. Agricultural Area: describes the area of land where all agricultural activities occur. This area is used to calculate more specific agricultural uses based on utilisation data from the CAPRI thematic model.
    a. Land for dedicated energy crops, is a sub category parallel to both Agriculture Area and Forestry Area, which describes land area utilised for dedicated energy crops
    b. Land for solar, is a sub category parallel Agriculture Area which describes the area of land used for ground mount solar energy.
6. Forestry Area: describes the area of woodland and forestry, all types of are considered managed, unmanaged, broad leaf and coniferous, however, short rotation coppice is not included as this is especially a cropping regime.
7. Natural habitat: describes all remaining unutilised land which has not been included in the other categories.

The initial value of all stocks in this module is set using data from GIS analysis of the region. Using these categories, the model simulates the transition from one state to another based on policy decisions or forecast data. This is a highly simplified model and intentionally excludes from the analysis of particular land types, such as ancient woodland, sites of special scientific interest and other areas designated as unavailable for land use change.

Residential and urban area process

Description- This process utilises a demand-led approach but it is heavily constrained by the availability of land supplied from the adjoining stocks. While it can be assumed that in most cases demand will exceed supply, potentially justifying a supply-led approach, this would result in unrealistic behaviour in the rare situation of supply exceeding demand.

The primary driving force in this process is *housing demand and policy*, which drives the flow of resource along the *redevelopment of brownfield,* and *development of greenfield* flows, thus supplying the *Residential and Urban Area* stock. The strongest relationship among the stocks is between *Residential and Urban Area* and *Brownfield Area* where there is a near constant transition between these two states, potentially even within the same time step. The model prioritises housing development on greenfield land as this is typically easier and more cost-effective for housing developers to use. When insufficient greenfield land is available to meet demand, brown field land is used.

The *creation of green space* flow into the *urban greenspace stock* is driven by the rate of development on either brownfield or greenfield land, and ultimately by a greenspace policy, represented by the *greenspace percentage* variable. The *loss of urban greenspace* flow is also driven by the *greenspace percentage* variable applied to, the current values of the *urban green space* stock and the *residential and urban Area* stock. The objective of the *greenspace percentage* variable is therefore to maintain the value of the *urban green space* stock.

The *Demolition* flow represents residential and urban area being cleared of buildings ready for redevelopment and a transition into brownfield land. This flow is essential within the model, as it enables the housing stock to be adjusted, potentially enabling changes to housing density. The *Demolition* flow is driven by the *rate of demolition* variable.

All variables are initially set based on historical data from land management statistics provided by the local County Councils in the southwest region. When the model is running the variables become subject to policy decisions increasing or decreasing their value which are at the control of the user.

Inputs – Housing demand including policy / Greenspace percentage / Rate of demolition

Prior processes interactions: Housing demand and policy process

Outputs – Residential and Urban Area / urban green space /

Subsequent process interactions: water and energy demand processes

Policy decision variables – Housing demand including policy / Greenspace percentage / Rate of demolition

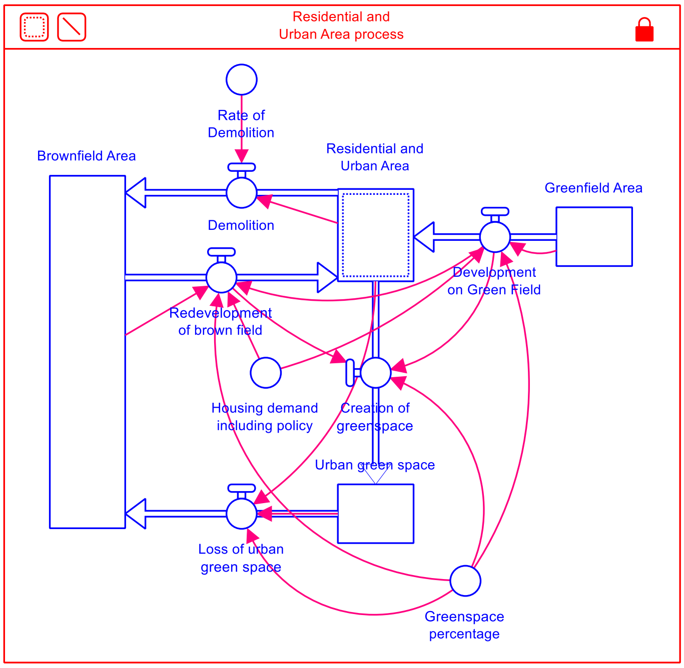


Figure 3.3.23: Residential and urban area process

Housing demand process

Description- Housing demand arises from a complex interplay of socioeconomic and policy-based factors. Intuitively the primary driving force is population growth and immigration to the region, however, planning policies regarding housing density are an underlying driver. The SDM takes a highly simplified approach based upon a policy defined housing density, which is used to calculate two component areas, which are summed to find housing demand area. The two components are the area required to house the new population, and the area required to house population displaced following demolition.

Inputs – residential and urban area (km^2) / population (Pop) / demolition (km^2) / new development housing density (Pop/km^2)

Prior processes interactions: Residential and Urban Area process /

Outputs – Housing demand including policy (km^2)

Subsequent process interactions: Residential and Urban Area process

Policy decision variables new development housing density

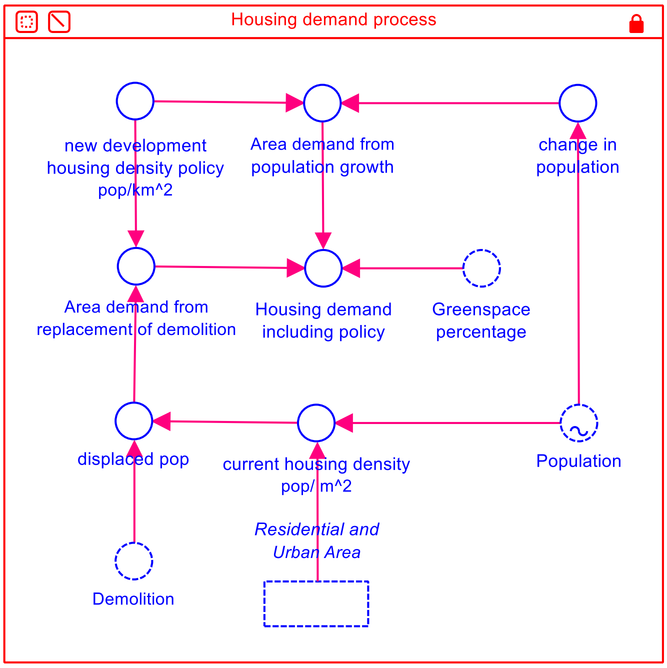


Figure 3.3.24: Housing demand process

Commercial and industrial area process

Description - The *Commercial and industrial Area* stock and its relationships to the *Brownfield Area* and *Greenfield Areas* stocks follow the same model as that of *Residential and Urban Area*. In that, there is a constant transition between the commercial area and brownfield due to redevelopment and a highly regulated supply of greenfield land based on planning policy. Within this process, the simile to *Demolition* and its associated control variable is *Decommissioning* and *Rate of decommissioning,* which act to transfer land resource from the commercial area into brownfield. All variables are initially set based on historical data from land management statistics provided by the County Councils. When the model is running the variables become subject to policy decisions increasing or decreasing their value.

Inputs – commercial demand including policy (km^2) / Greenspace percentage (dimensionless) / Rate of decommissioning (km^2/d)

Prior processes interactions: demand process

Outputs – Commercial and industrial Area (km^2)

Subsequent process interactions: Residential and Urban Area process / water and energy demand processes

Policy decision variables – commercial demand including policy / Greenspace percentage / Rate of decommissioning

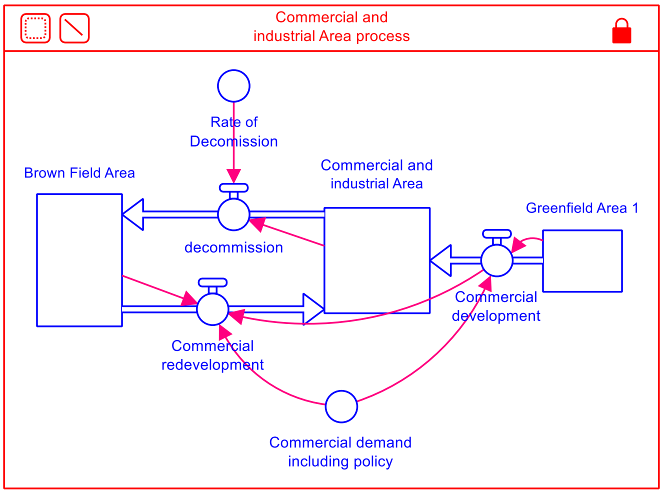


Figure 3.3.25: Commercial and industrial area process

Primary land resource process

Description – the primary land resource process attempts to model the transition of land use between agriculture, forestry and natural habitat. In the UK, forests/woodlands and natural habitats are protected from land use change. However as these protections are policy driven legal frameworks rather than a physical barrier, were those policy mechanisms to change, land resources would quickly be impacted due to agriculture expansion. Under the current policy climate, there are weak drivers in place to stimulate the transition of agricultural land into both natural habitat and forestry/woodland. These policies set the initial flow rates and act as the baseline for model runs. When the model is running policy variables for Forestry and Natural habitat increase or decrease these rates, and where negative values are used, they allow for the transition of forestry and natural habitat into agricultural land.

The *Dedicated energy crop area* stock represents agricultural land given over to the production of dedicated energy crops. The distinction of dedicated energy crop is made because these crops cannot be used for food production, so should be separated from normal arable crops which may be diverted to either food or energy use. Furthermore, dedicated energy crops are typically grown in long term monoculture, taking several years of uninterrupted cultivation to reach peak productivity. The transition of resource between the *Agricultural Area* and the *Land for dedicated energy crop* stocks is driven by a policy variable allowing flow in either direction.

Inputs – Forestry Policy (dimensionless) / Natural habitat policy (dimensionless) / Energy crop policy (dimensionless)

Prior processes interactions: Policy processes

Outputs – Agricultural land Area (km^2) / Natural habitat Area (km^2) / Forestry Area (km^2) / Dedicated energy crop area (km^2)

Subsequent process interactions: Agricultural land utilisation / land run-off / GHG emissions / Energy demand / Water demand

Policy decision variables – Forestry Policy / Natural habitat policy / Energy crop policy

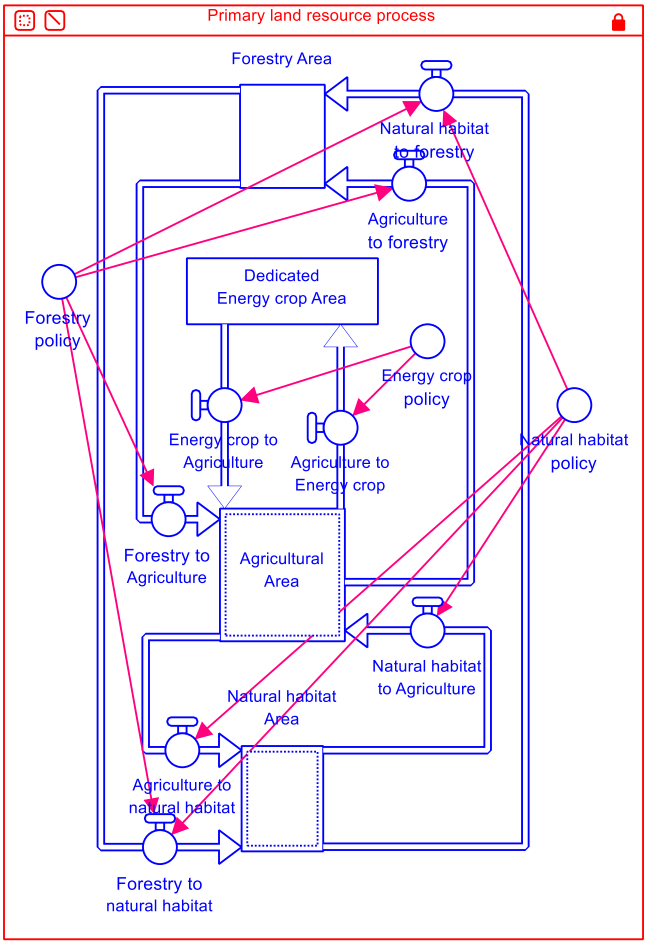


Figure 3.3.26: Primary land resource process

Greenfield development process

Description – Greenfield land made available for development is highly sort after by land developers of all types and must be tightly controlled because this is a practically irreversible transition. The *Greenfield development policy* acts as the main driving force enabling the flow of land resource into the *greenfield area* stock. The flows of forestry and natural habitat land into the greenfield stock are further limited by those respective polices. Flow is only enabled when they have been set into a negative state by the user during a model run. As with the other land use processes, the initial flow rates for these policies are set based on land use statistics and act as the baseline that are modified by the user during model runs.

Inputs – Forestry Policy (dimensionless) / Natural habitat policy (dimensionless) / Greenfield development policy (dimensionless)

Prior processes interactions: Policy processes

Outputs – greenfield area (km^2) / forestry area (km^2) / agriculture area (km^2) / natural habitat area (km^2)

Subsequent process interactions: Agricultural land utilisation / land run-off / GHG emissions / Energy demand / Water demand / Commercial and industrial Area process / urban and residential land process

Policy decision variables – Forestry Policy / Natural habitat policy / Greenfield development policy

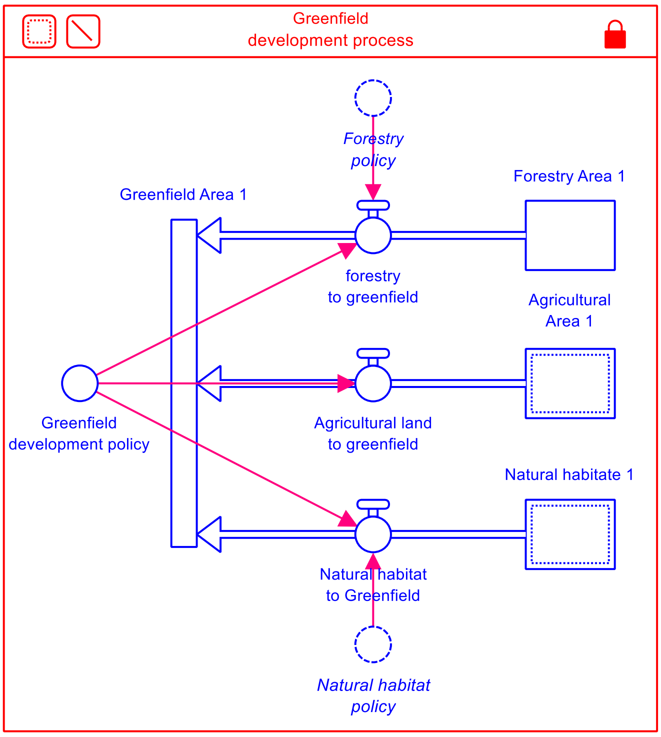


Figure 3.3.27: Greenfield development process

Land for solar development process

Description – The land for solar stock represents the area of agricultural land given over to ground mount solar energy. The *Solar energy land use* variable controls the rate of flow between development and decommissioning such that the *Land for Solar* stock equals the *Solar energy Land use* variable, as calculated in the *land for renewable energy* process.

Inputs – Solar energy land use (km^2)

Prior processes interactions: land for renewable energy

Outputs – Land for Solar energy (km^2) / Agriculture Area (km^2)

Subsequent process interactions: Primary land resource process

Policy decision variables - none

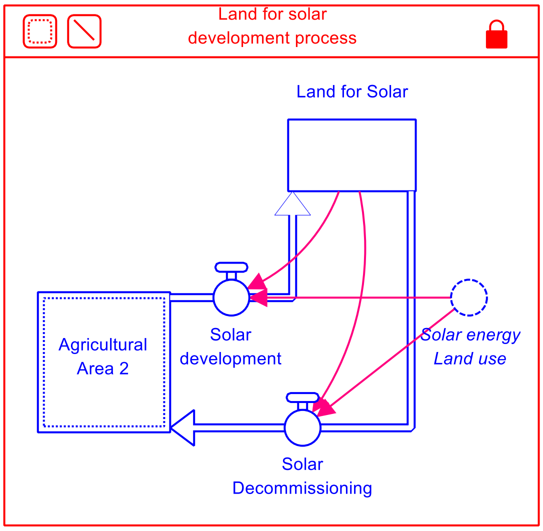


Figure 3.3.28: Land for solar development

Agricultural utilisation process

Description – Utilisation of agricultural land is driven most strongly by economics, this ultimately influences farmers, who attempt to generate profit from a speculative view on future crop prices. The reality of this process is highly nuanced and requires a detailed economic analysis that is beyond the scope of the SDM. Therefore, to account for this mechanic the SDM integrates data from CAPRI describing detailed agricultural land use, and the calculated area of productive agricultural land.

Within the SDM the *Agricultural Area* stock, which is calculated in the *primary land resource process,* and is used to describe the total land use under all agricultural activities is used as the basis. Data extracted from CAPRI is restructured using interpolation to provide monthly values for; Utilized agricultural area; *Arable Area*; *Pasture Area; Cereal Area;* Oil seed Area; *Vegetables and permeant crops area; other crops; and* set *aside area.* Each of the land uses is found as a percentage of the total Utilized agricultural area, rather than absolute values.
The SDM then calculates the area of each land use based on the *Agriculture Area* stock value, to provide land use over time. There are two major groups of agricultural activity: 1. *Arable Area; and* 2.*Pasture Area*. The *Arable Area* is further sub divided into *Cereal Area*; Oil seed Area; *Vegetables and permeant crops area*; *other crops;* and, set *aside/non-productive area.* Pasture Area describes land used for the raising of livestock which is considered in more detail in other processes. The approach outlined here enables the SDM to control the gross volume of agriculture land, and CAPRI to forecast the specific more detailed agricultural land use.

Inputs – CAPRI data (dimensionless)

Prior processes interactions: land for renewable energy

Outputs – Arable Area (km^2) / Pasture Area (km^2) / Cereal Area (km^2) / Oil seed Area (km^2) / Vegetables and permeant crops area (km^2) / other crops(km^2) / set aside area (km^2)

Subsequent process interactions: Food processing / Land run-off / water demand / energy demand

Policy decision variables – na

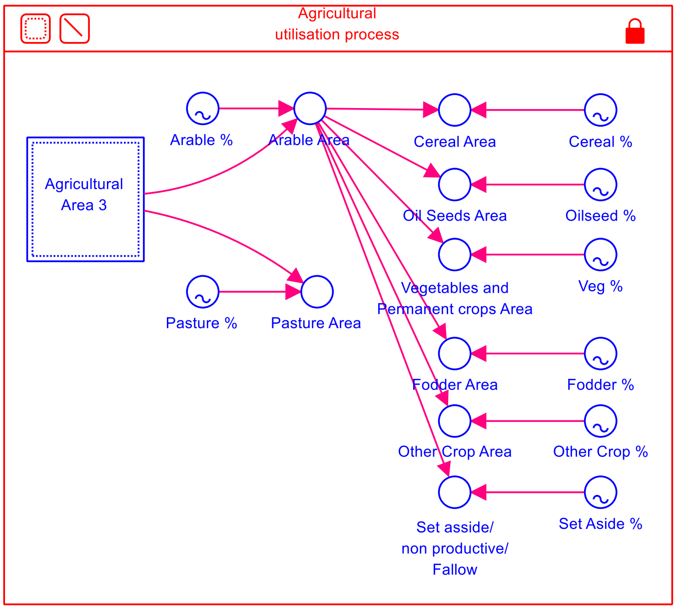


Figure 3.3.29: Agricultural utilisation process

Forestry composition process

Description – the *forestry area* stock describes the total combined area of forest and woodland. Without specific composition of the tree types, the initial value of the stock is taken from GIS analysis. To provide more detail, the model uses the gross area of forestry and divides it based upon the categories of Broadleaf, Coniferous and Mixed, using data from the UK forestry commission's National Forestry Inventory.

Inputs – percentage forestry coverage of; Broadleaf, Coniferous and Mixed, (dimensionless)

Prior processes interactions: Primary land resource process

Outputs – Broadleaf Area (km^2) / Coniferous Area (km^2) / Mixed Area (km^2)

Subsequent process interactions: GHG emissions / natural capital / Run-off

Policy decision variables: none

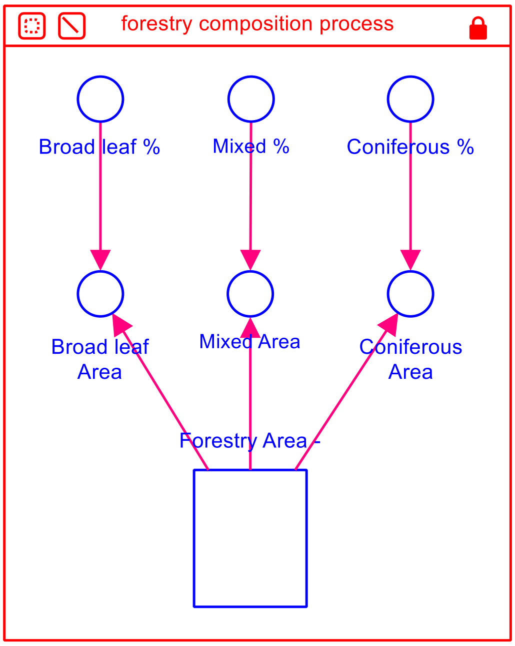


Figure 3.3.30: Forestry composition process

Surface water runoff

Primary land resource run-off water quality process

The water quality module uses a mass balance approach to approximate an aggregated surface water quality arising from the primary land resource. The model considers the surface area of each land use and associated water quality coefficients, which are based on an assumed water quality index. Developed urban and industrial areas are excluded as these are assumed to be connected to the wastewater drainage network. This is a highly simplified model and does not consider detailed or specific site data but seeks to give an average view of the whole spatial boundary. Therefore to provide a more detailed view, further subdivision of the spatial boundary would be necessary, and in theory, could be extended adfinitem.

Inputs – percentage forestry coverage of; Broadleaf, Coniferous and Mixed, (dimensionless)

Prior processes interactions: Primary land resource process / Agricultural utilisation process / forestry composition process

Outputs – Forestry run-off water quality (dimensionless) / Agricultural run-off water quality (dimensionless) / Natural habitat run-off water quality (dimensionless) / Dedicated Energy crop run-off water quality (dimensionless) / Primary land resource run-off water quality (dimensionless)

Subsequent process interactions: natural capital / raw water quality (drinking water)

Policy decision variables: none

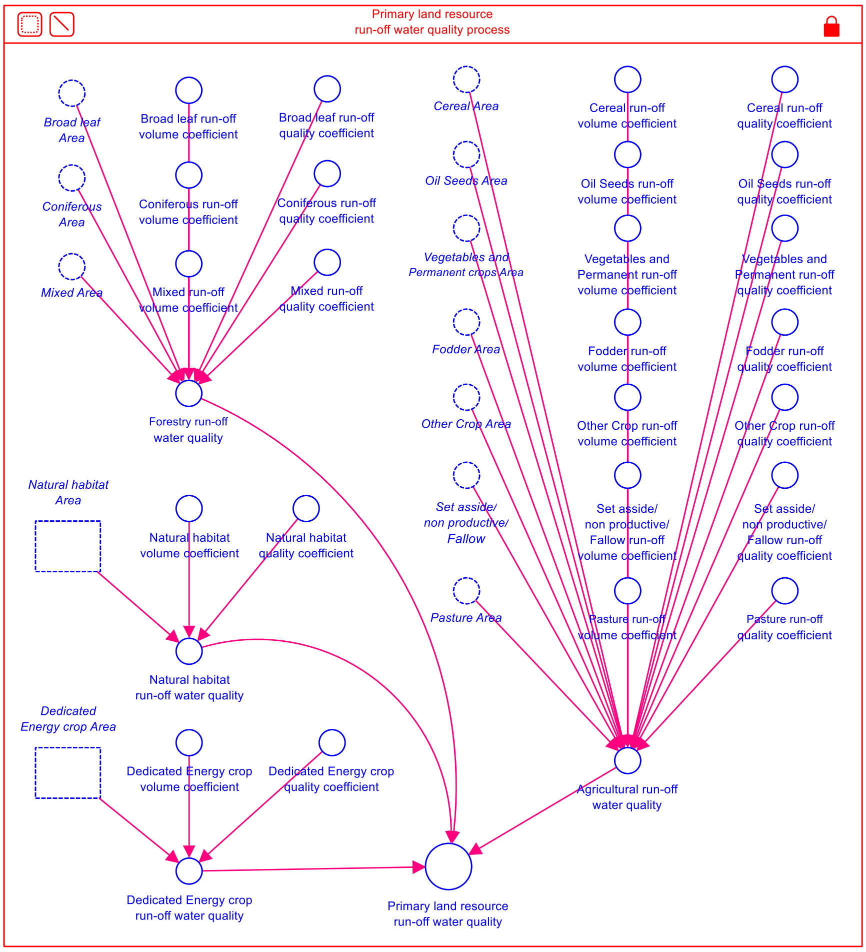


Figure 3.3.31: Primary land resource run-off water quality process

Waste management module

Waste management process

The waste management module is an elementary view of waste generated within the region and the ultimate routes for recovery.

The *municipal waste* flow represents the total mass of waste arising from the resident population and other commercial and industrial activities. Residential waste is calculated based on a *waste production per capita* coefficient and *Population* data table, waste production statistics from the UK government provide per capita data. Commercial and industrial waste is calculated based on the current area of land utilised by commercial and industrial activity, a waste production coefficient, and GDP from the E3ME data table. The combined municipal waste flow is then passed to one of three routes of final disposal, recycling, thermal recovery, and landfill, which are prioritised in that order.

Sludge generated by drinking water and waste water treatment is either disposed to agricultural land or landfill depending on sludge quality and the availability of agricultural land.

Inputs – Commercial and Industrial Area (km^2) / waste production coefficient (dimensionless) / GDP (dimensionless), waste production per capita (kg/Pop/d) /DW sludge (tonnes) / WW Sludge (tonnes)

Prior processes interactions: Commercial and industrial are process / Drinking water treatment process / wastewater treatment process

Outputs –recycled (Tonne) / thermally recovered (Tonne) / waste to land fill (Tonne) / sludge to land fill (Tonne) /

Subsequent process interactions: natural capital / raw water quality (drinking water)

Policy decision variables: rate of recycling / rate of thermal recovery / behaviour

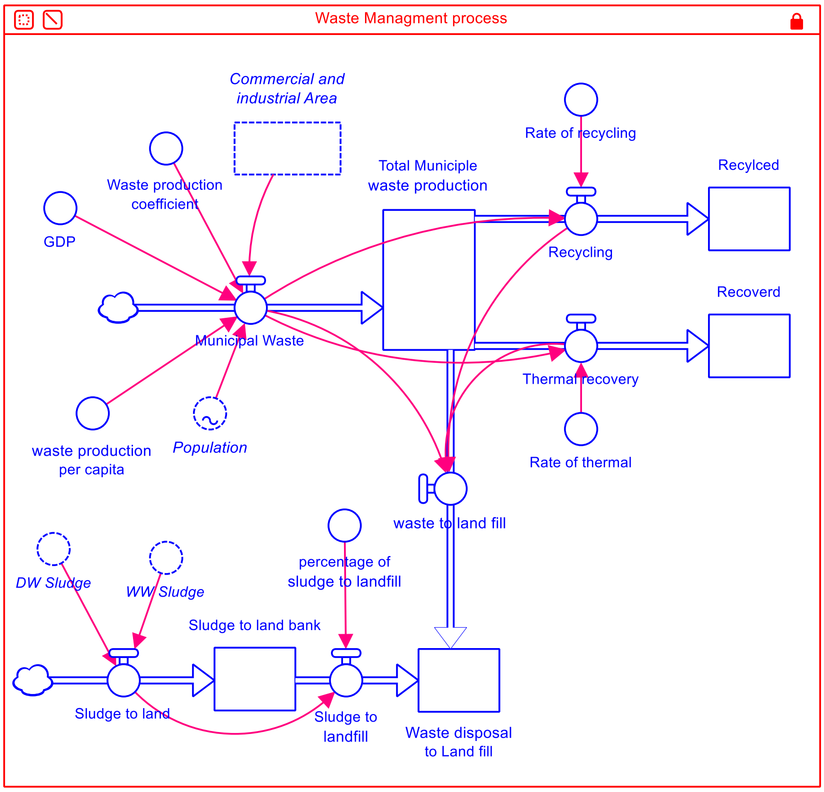


Figure 3.3.32: Waste management process

3.3.3.4 Food Sector Submodel

The south-west region is a net importer of general foodstuffs, and an exporter of dairy and meat products. As such the SDM focuses on these aspects examining the production of raw foodstuffs, i.e. the cultivation of crops or cattle, and the processing of those raw foodstuffs into marketable food products. Most raw food production is not fully processed locally but it is exported in raw form. Meat and dairy are the exceptions and the majority of these are processed within the region. The SDM relies heavily on data from CAPRI and uses the same approach to that described in the *Agricultural utilisation process,* for integrating data.

The food sector model is subdivided into arable, livestock modules, Dairy and Meat processing modules.

Arable module

Crop production process

Description: The *Crop production process* uses the area of land under each agricultural activity as calculated by the *Agricultural utilisation process*, a yield coefficient is applied based on data from CAPRI to provide total production in each category.

Inputs – Arable crop areas by type (km^2) / arable crop yield coefficients by type (dimensionless)

Prior processes interactions: Primary land resource process / Agricultural utilisation process

Outputs – Arable crop production volumes by type (tonne)

Subsequent process interactions: agriculture demands for water end energy

Policy decision variables: none

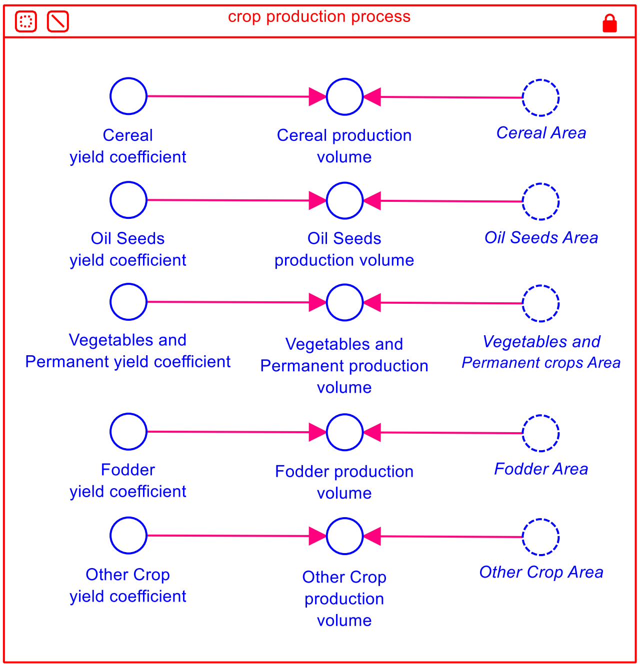


Figure 3.3.33: Crop production process

Crop production demands process

Description: All arable crops in the south-west are "rain-fed" so there are no irrigation demands, whereas demands for chemicals and energy are based on total production using coefficients from UK government statistics.

Inputs – arable crops production volume by type (tonnes) / CAPRI derived chemical demand coefficients (kg/hds)/ energy demand coefficients (kWh/hds)

Prior processes interactions: Primary land resource process / Agricultural utilisation process

Outputs –chemical (tonnes) and energy demands (kWh)

Subsequent process interactions: GHG / energy demand process

Policy decision variables: none

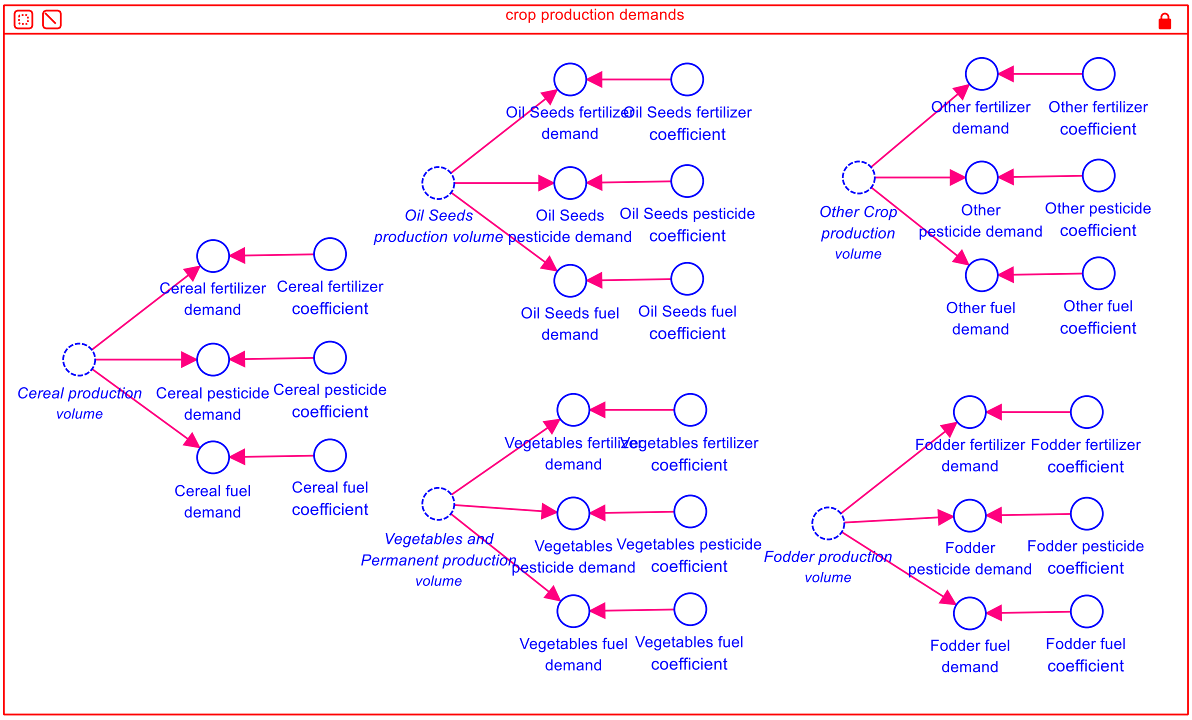


Figure 3.3.34: Crop production demands process

Livestock module

Raw animal produce process

Description: The production of raw animal products is based on the Pasture Area calculated in the *Agricultural utilisation process* and a number of yield and density coefficients derived from the CAPRI data.

Inputs – pasture area (km^2) / heads of animals by type (hds) / CAPRI derived coefficients (dimensionless)

Prior processes interactions: Primary land resource process / Agricultural utilisation process

Outputs – animal produce by type (tonnes)

Subsequent process interactions: Abattoir processes / Dairy products process

Policy decision variables: none

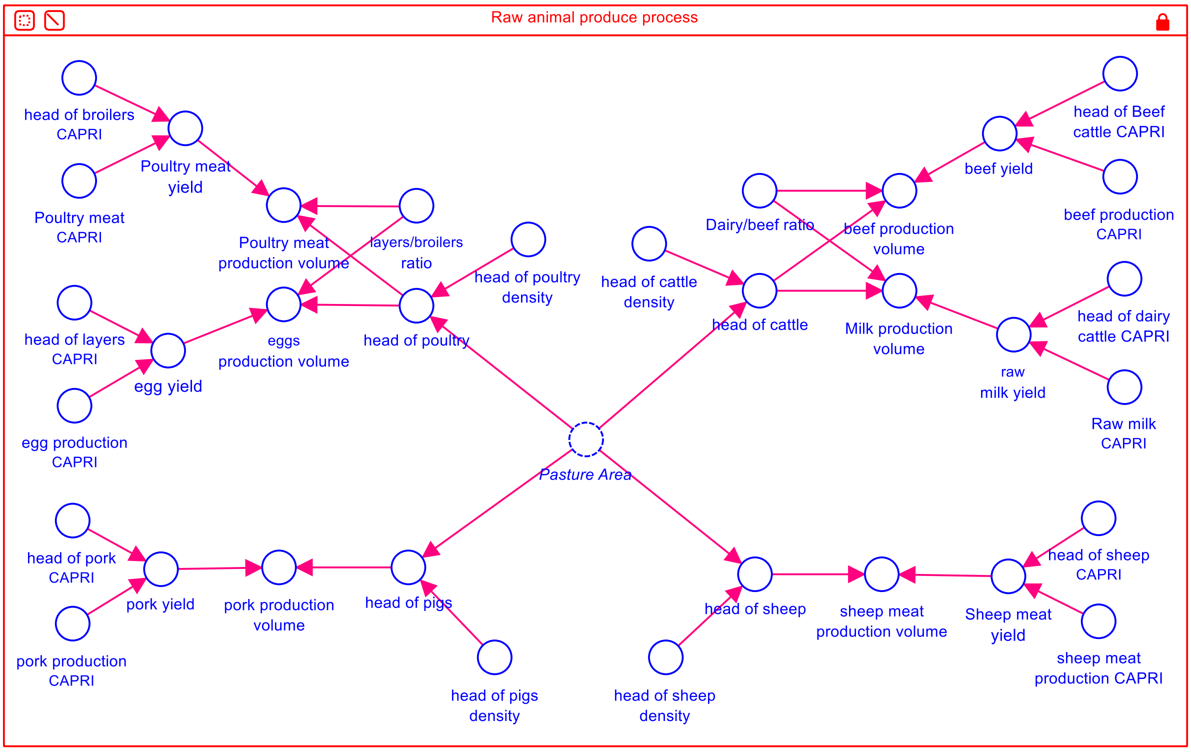


Figure 3.3.35: Raw animals produce process

Animal produce demands process

Description: Animal related demands for water, feed and fuel are calculated by the model based upon the head of each animal type and coefficients derived from the CAPRI model or UK government statistics.

Inputs – heads of animals by type (hds) / CAPRI derived coefficients (dimensionless)

Prior processes interactions: Primary land resource process / Agricultural utilisation process / Raw animal produce process

Outputs –Water (ML/d), Energy (kWh) and feed demand (Tonnes)

Subsequent process interactions: GHG / energy demand process

Policy decision variables: none

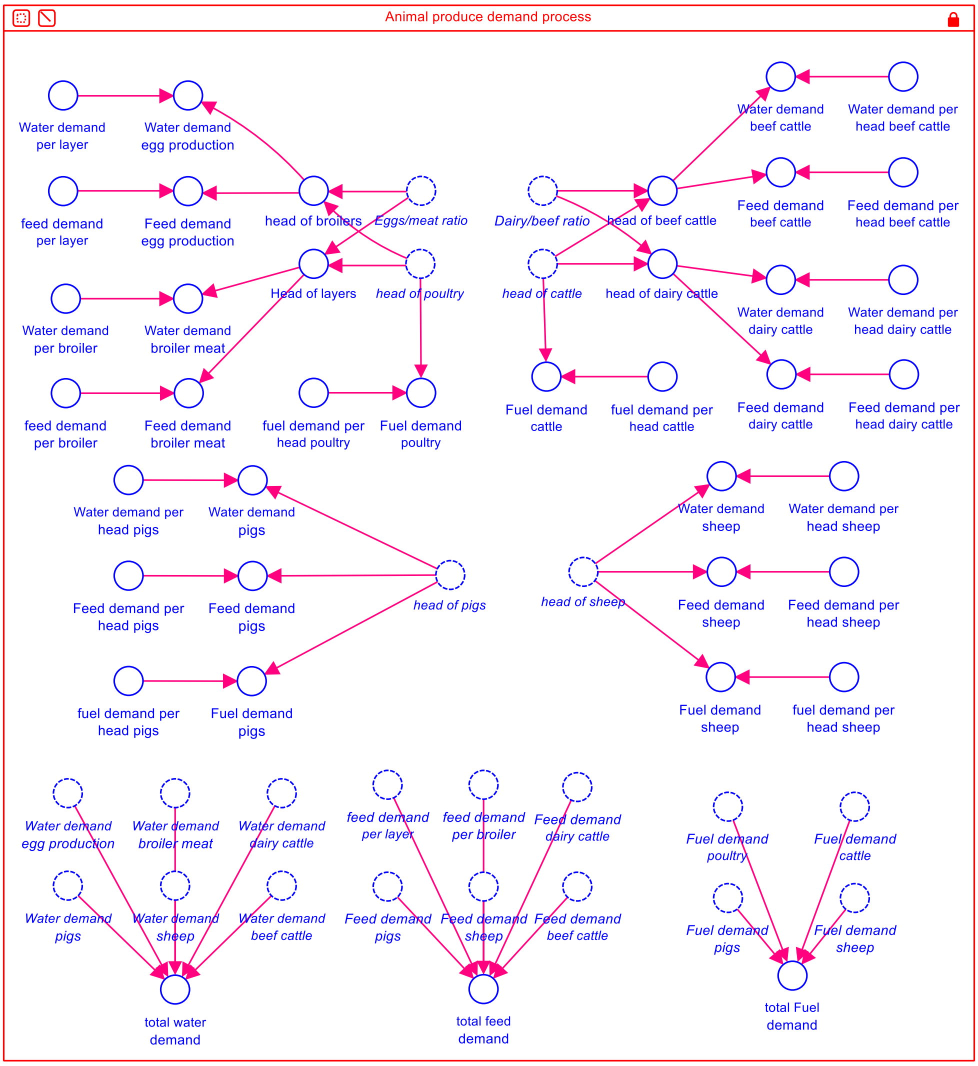


Figure 3.3.36: Animal produce demands process

Dairy module

The Dairy industry is a major contributor to the South West economy and provides nearly 25% of the dairy products consumed in the UK.

Dairy products process

Description: The *dairy products process* considers 8 dairy products produced from the available raw milk supply, these are: 1. Fresh milk products; 2. Cream; 3. Cheese; 4. Butter; 5. Concentrated milk; 6. Whole milk powder; 7. Skimmed milk powder *and* 8.Whey powder. At any point in time, the production ratio of these items is most significantly influenced by market forces, rather than the manufacturing capability or raw milk availability. The SDM, therefore, allows the economic interactions to be forecast by CAPRI in a similar approach to other aspects of food and land modelling. This is done in each time interval, where the production ratio is taken from CAPRI data and applied to the raw milk production volume calculated by the SDM. *Dairy products base* and *raw milk base* are taken directly from CAPRI data; these two values are used to calculate a *Dairy conversion efficiency*, which the SDM uses to determine how much of the produced Raw Milk is actually converted into useful products. The *Raw Milk*

available figure is then used to find that the actual volume of each product based on their respective percentage from CAPRI.
Inputs – raw milk volume (tonne) / dairy products ratios (dimensionless) / CAPRI dairy products volume (tonne) / CAPRI raw milk volume (tonnes)

Prior processes interactions: Raw animal produce process

Outputs – Dairy wastewater (ML/d) / Dairy waste slurry (tonne) / dairy products volume by type (tonne)

Subsequent process interactions: dairy demands process

Policy decision variables: none

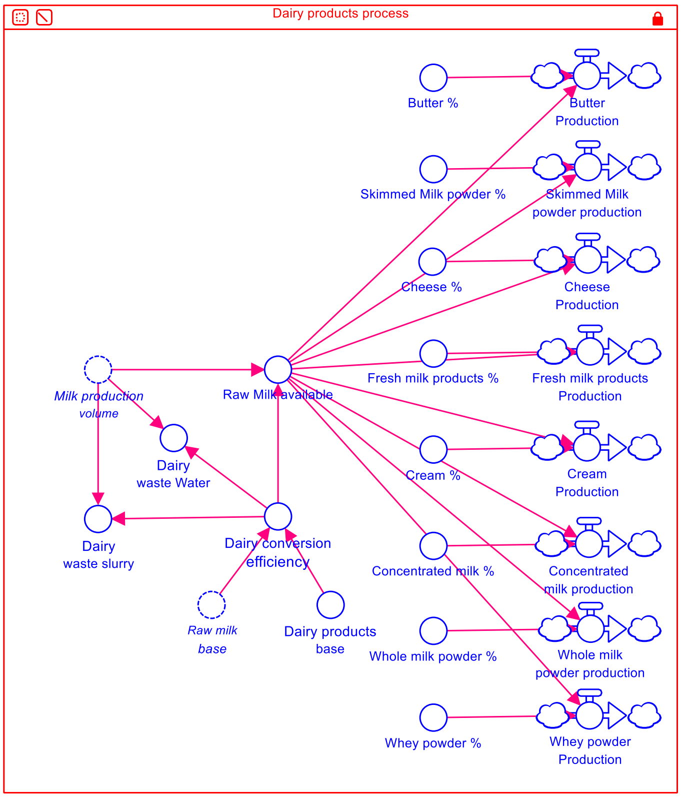


Figure 3.3.37: Dairy products process

Dairy products demand process

Description: The demands for water, electricity and gas, arising from the productions of dairy products is calculated in two processes. In *Dairy Demands process 1* demand coefficients for each product are applied to the total volume produced on a unit rate basis. Then in *Dairy Demands process 2* the individual demands are summed, to provide total; water, electricity and gas demands for all dairy production. Demand coefficients are taken from literature

Inputs – dairy products volume by type (tonne) / demand coefficients for water (ML/tonne) electricity (kWh/tonne) and heat (kWh/tonne) by product type

Prior processes interactions: Dairy products process (tonnes)

Outputs – total demands for water (ML/d) electricity (kWh) and heat (kWh)

Subsequent process interactions: Energy demands processes / water demands process

Policy decision variables: none

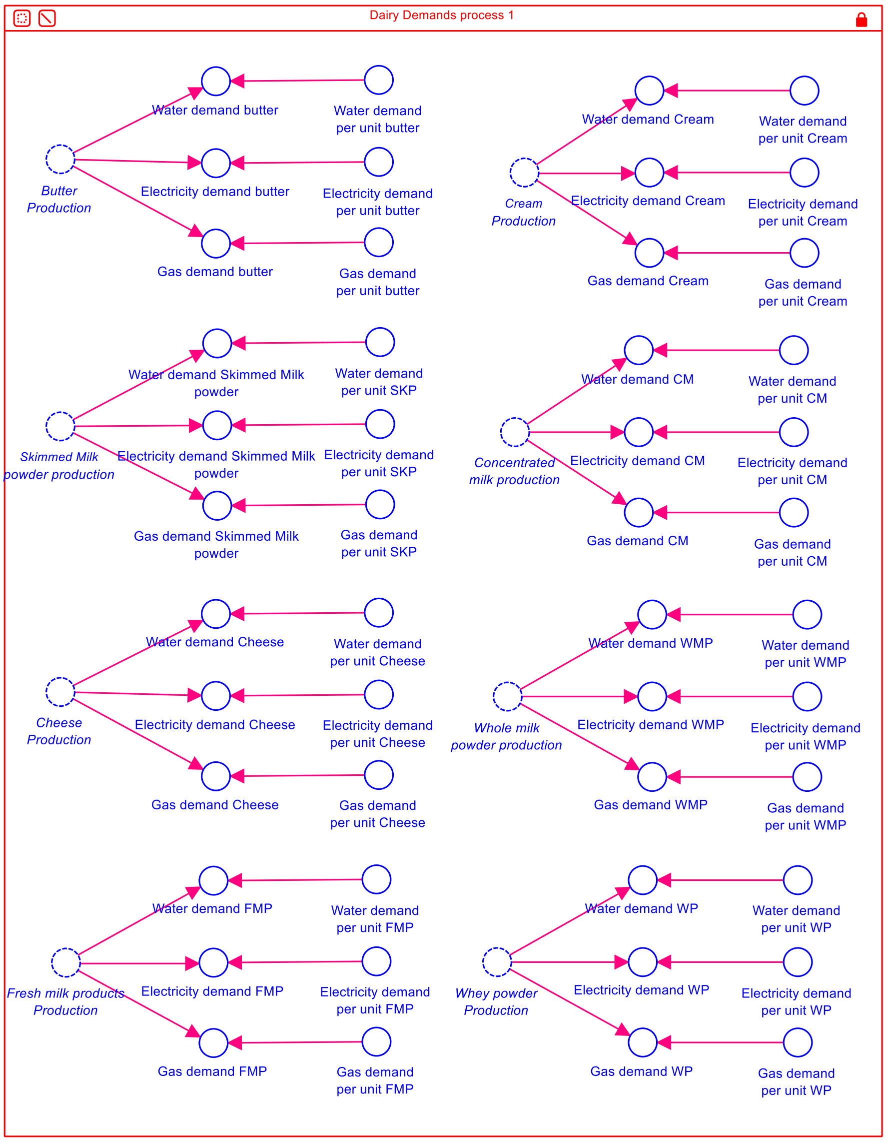


Figure 3.3.38: Dairy demands process 1

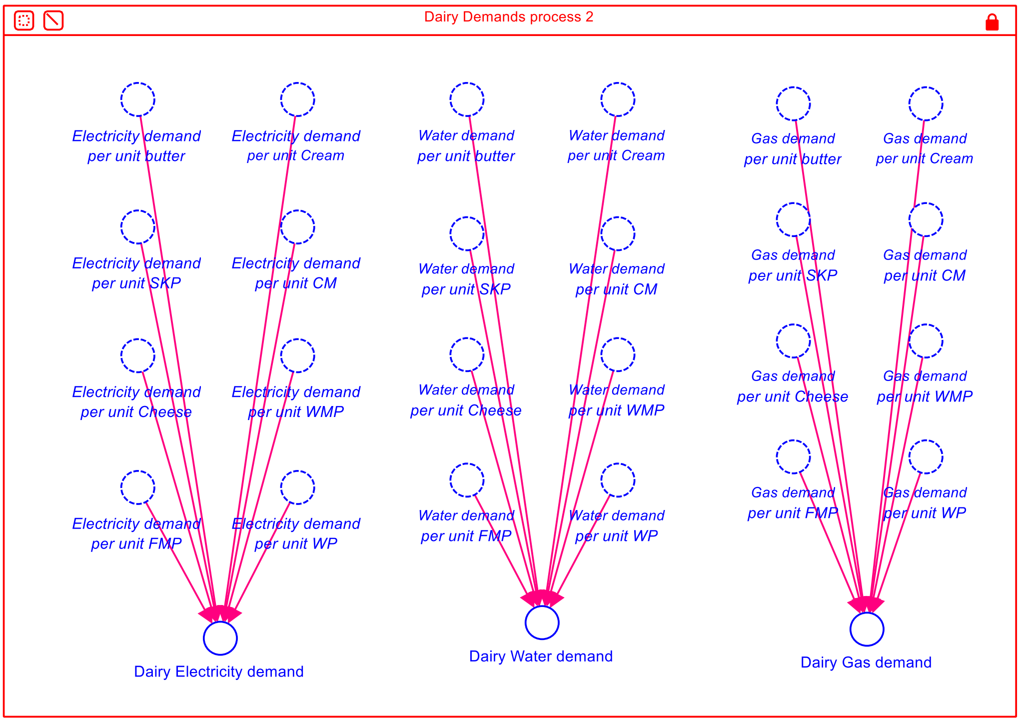


Figure 3.3.39: Dairy Demands process 2

Meat processing module

After dairy products, the next largest contributor to the food processing industry in the south-west is the processing of primary meat products. The SDM initially handles this in the *Raw animal produce process* where the production volume is calculated for each meat type based on herd size, and coefficients derive from CAPRI. The major impacts on the model from this activity are seen in terms of resource demands and waste products. Therefore the subsequent stages utilise the processed meat volumes to focus on these areas specifically.

Abattoir demands process

Description: Data from literature and government statistics is used to derive demand coefficients for water, electricity and gas for each meat type. These are then summated to provide total abattoir demands.

Inputs – meat production volume by type (tonne) / water (ML/tonne) electricity (kWh/tonne) and heat (kWh/tonne) by product type

Prior processes interactions: Raw animal produce process

Outputs – water (ML/d), electricity (kWh) and gas demands (kWh)

Subsequent process interactions: water and energy demand processes

Policy decision variables: none

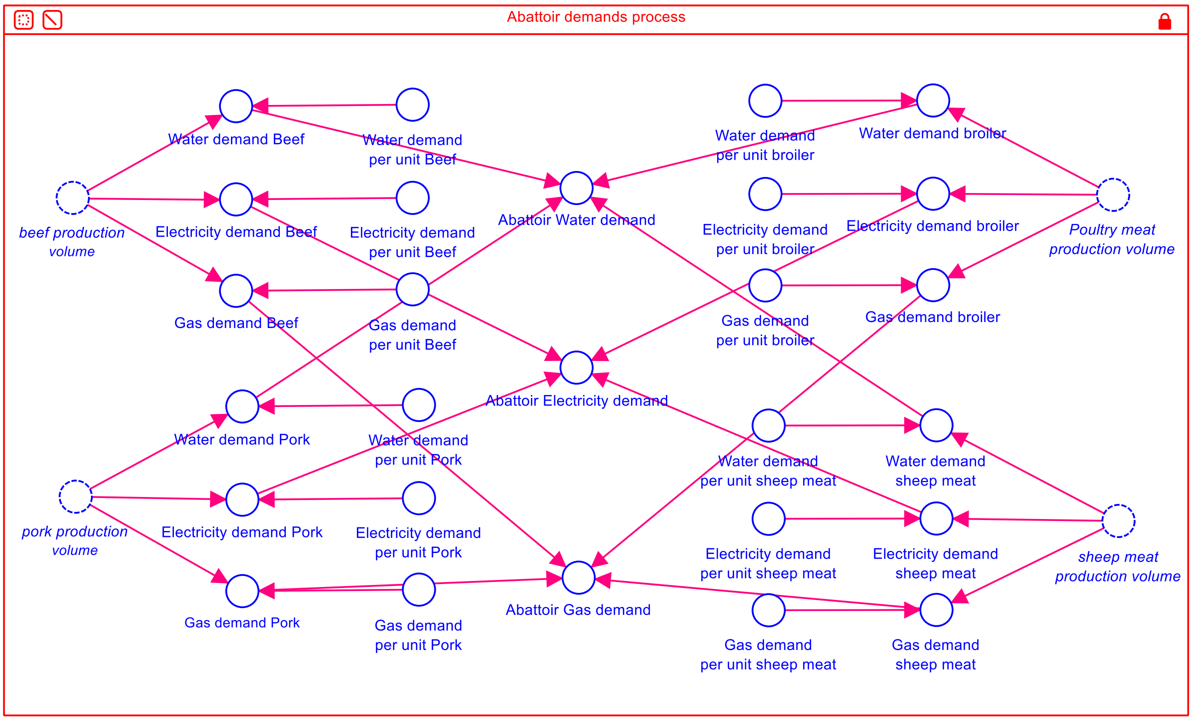


Figure 3.3.40: Abattoir demands process

Abattoir waste process

Description: Data from literature and government statistics are used to derive waste production coefficients for manure, wastewater, blood and heads-hooves-hides, which are the main waste streams from each meat type. These are then summated to provide total abattoir production volumes.

Inputs – waste production coefficients by type (tonne/tonne) (ML/tonne) / meat production volume by type (tonne)

Prior processes interactions: Raw animal produce process

Outputs – waste production volume (tonne) (ML/d)

Subsequent process interactions: wastewater treatment process / waste management process

Policy decision variables: none

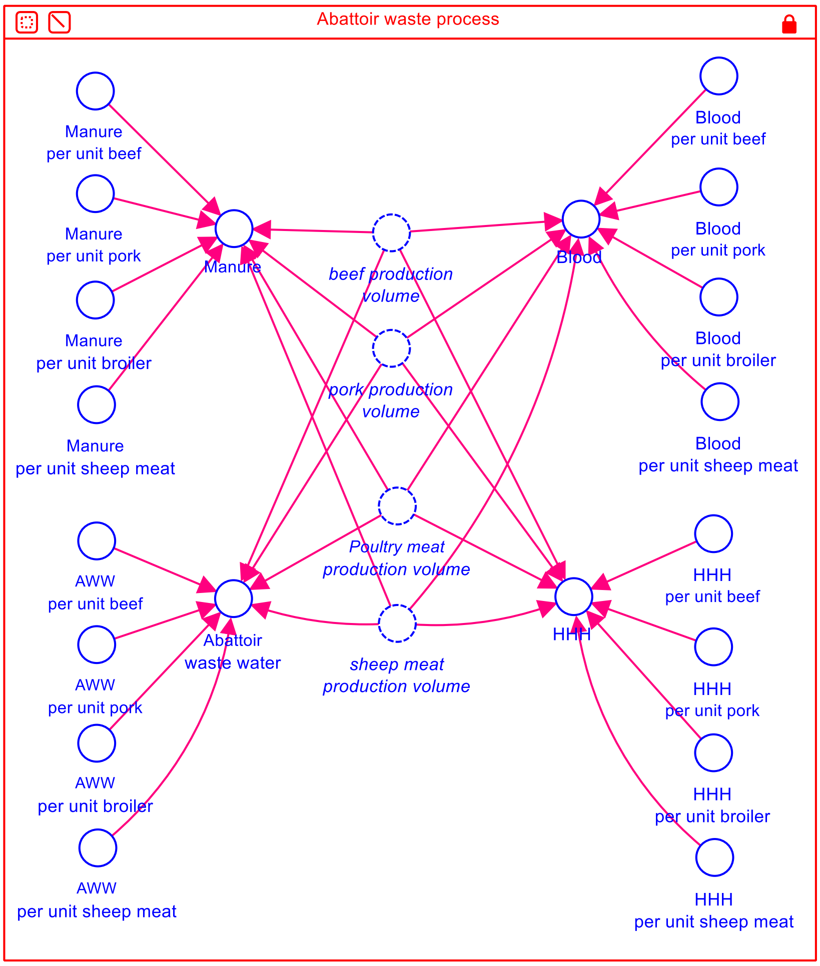
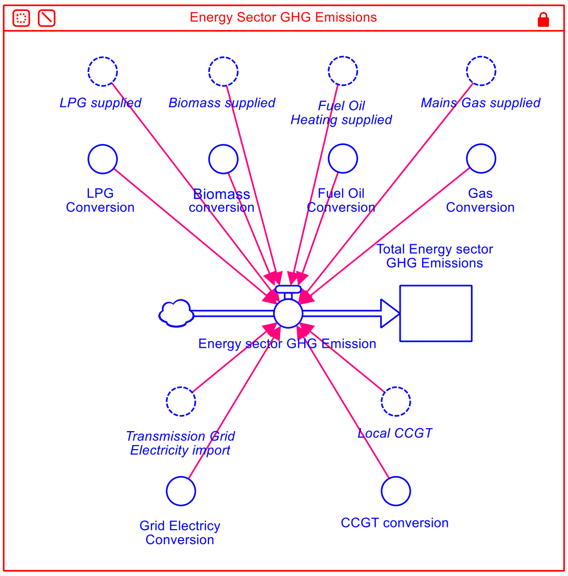


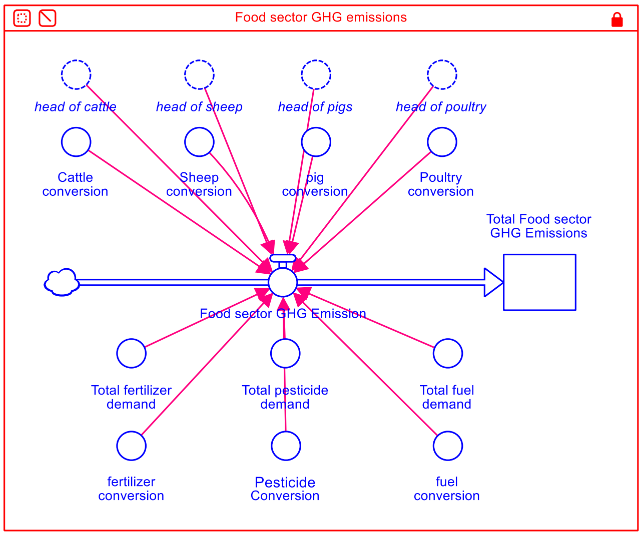
Figure 3.3.41: Abattoir waste process

3.3.3.5 Climate Submodel

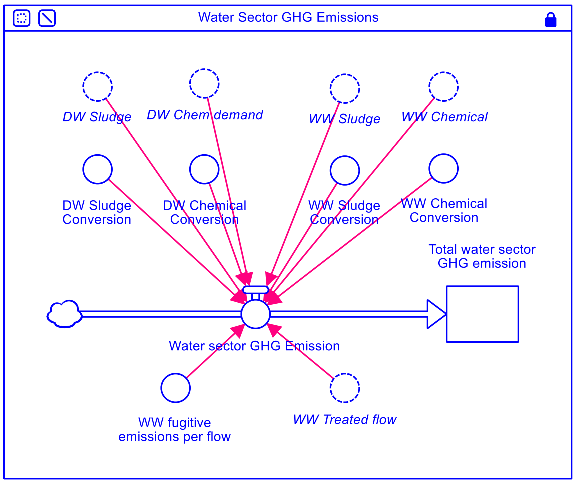
The Climate Model focuses solely on calculating total greenhouse emissions from the four nexus sectors and is split into four sub-models one for each sector. The method of calculation is the same in all modules, the source of emission is identified, and a conversion coefficient is applied. Conversion coefficients are provided by Department for Environment Food & Rural Affairs (DEFRA)



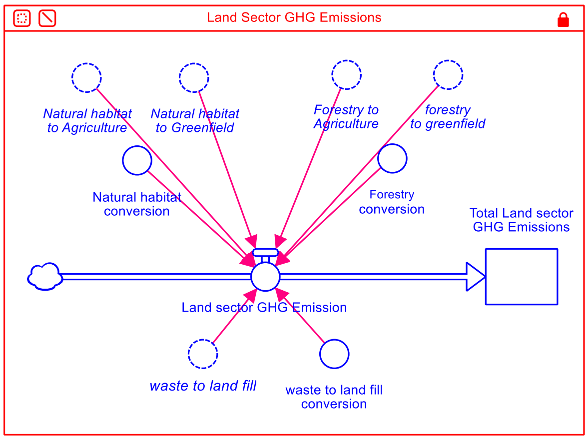
(a) Energy Sector GHG Emissions



(b) Food Sector GHG Emissions



(c) Water Sector GHG Emissions



(d) Land Sector GHG Emissions

Figure 3.3.42: GHG Emissions

All GHG emissions are normalised to tCO2e.

3.3.3.6 Policy implementation model

As noted previously, throughout the SDM are variables which have been embedded to enable the user to investigate the impact of polices identified in the case study. In every time step, the user can influence these variables to simulate policy interventions during a "model run".

To maintain consistency, all policy interactions are constrained within the same basic structure. The user is able to input a value between +2 and -2 describing their desired level of impact in terms of magnitude and polarity.

Where:

+2 = STRONG POSITIVE

+1 = MODERATE POSITIVE

0 = NEUTRAL

-1 = MODERATE NEGATIVE

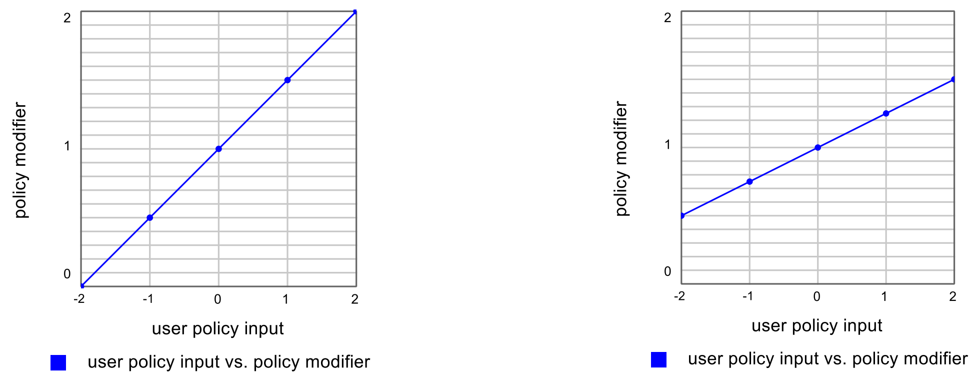
-2 = STRONG NEGATIVE

The value of the user input is translated into either a rate or capacity change following a linear relationship. To calibrate the range of influence available to the user, control variables are used to manipulate the relationship; these are *intercept* and *slope*.

Intercept: The model uses a default value of 1 for the intercept, ensuring that when a 0 (neutral) *user policy input* is selected the *policy modifier* equals 1 (Figure 3.3.43a).

Slope: The slope control is the most useful control variable and determines the magnitude and range of impact from the user input. The default value for slope is 1, which ensures that when a strong negative (-2) *user policy input* is selected the *policy modifier* equals 0, effectively switching off the policy. The linear calculation is structured so that the *slope* value represents the increase generated in the *policy modifier* when a strong positive (+2) *user policy input* is selected.

Therefore when user policy input = +2, policy modifier = 1 + slope, the results are shown in Figure 3.3.43(b).



(a) policy modifier vs policy input - default slope

(b) policy modifier vs policy input – modified slope

Figure 3.3.43: Policy modifier and slope. (a) Default intercept and slope, (b) modified intercept and slope

The *policy modifier* variable is a dimensionless quantity which is applied to the *policy base rate* as a coefficient. *Policy base rate* assumes the role of a target policy elsewhere in the model, and *policy output simple* becomes the output value. The *policy output simple* route works where a reference policy has been set which is used for the duration of the model run. In many cases, a slightly more complex approach is required because the impact of a policy is often not felt momentarily in the single time step but has a lasting effect which becomes cumulative over time. To account for cumulative effects in some situations the *policy modifier* value of the previous time step replaces the *policy base rate* in the current time step, to generate a cumulative effect, where *policy output cumulative* becomes the output value. This is achieved via the *rate counter* variable which acts a temporary record of the previous time step value.

Policy output simple and *policy output cumulative* are analogous to simple and compound interest respectively. The basic policy process model flowchart is shown in Figure 3.3.44.

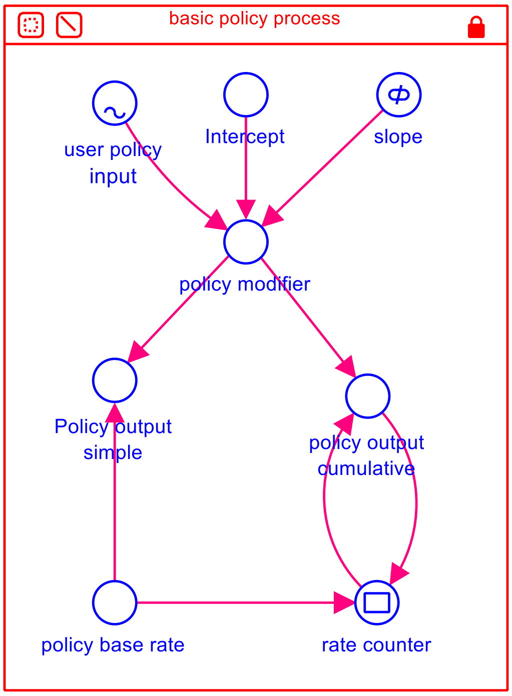


Figure 3.3.44: Basic policy process: Flowchart and model

This inclusion of policy implementation algorithms in the SDM is a unique feature appearing only in the SDM for the UK Case Study, investigating beyond the State-of-the-Art, ways to implement alternatives in the SDM, even without an SG. It was included here, because the main Case Study partner (South West Water) intends to use the model for actual strategic planning for the water utility.

3.4 Greece case study

3.4.1 Short description of the case study

Greece is located in the South-Eastern part of Europe (Southern part of the Balkan Peninsula) in the Mediterranean Sea. Its area is about 131,957 km^2 and its population has been estimated to 10.8M inhabitants. As projected by Eurostat, it is expected that by the year 2030 the Greek population will continuously decline (about 9,9M inhabitants) while by the year 2050 it is estimated to 8,9M inhabitants. Approximately 35% of the Greek population lives in the metropolitan area of Athens. Greece consists of nine geographic regions in the mainland and four insular regions/complexes. The Aegean Sea lies to the East of the mainland, the Ionian Sea to the West and the Mediterranean Sea to the South. Greece has the longest coastline in the Mediterranean Basin, approximately 16,300 km in length, and more than 5,000 islands (227 inhabited).

The major economic sectors supporting national income are agriculture and tourism. The Gross Domestic Product (GDP) per capita (main GDP aggregate per capita), measured in euro per capita, for the year 2015 was 16,200 euro, 23.22% lower than the one of 2007 due to the fiscal crisis that Greece faces the last seven years. Unemployment is one of the major socioeconomic issues in the country as it has experienced an extreme increase between 2007 and 2016.

The natural environment of Greece is of exceptional importance as its biodiversity – flora and fauna- is very rich. More than 25% of its total area is registered as 'NATURE 2000 area'.

The nexus components investigated in the Greek case study are: water, energy, climate, food and land as well as the sectors of agriculture and tourism. It should be noted that both sectors under study are prevailing economic sectors that put extra pressures to the nexus components in order to properly accommodate their needs.

Among the main issues explored are the sustainable management of water resources (surface water and groundwater), the management and regulation of land uses, the sustainable development of agricultural sector (including: certification of agricultural products, food quality and food safety), the management of conventional and renewable energy resources, the existing climate change adaptation and mitigation strategies, the sustainable development of the tourist sector, etc.

The available water resources have been classified in 14 hydrological districts while 765 streams (45 perennial, 4 transboundary) and 60 lakes (3 transboundary) are also recorded. Concerning groundwater, the total potential is about 10.3hm^3/y. Islands in the Aegean Sea are mainly supplied by groundwater resources while some small islands are supplied with water transferred by tankers. About 85% of the available freshwater resources are used in the agricultural sector, 3% in industry and 12% in the domestic sector (Agricultural University of Athens, 2017).

As for the energy sector, the total energy consumption was about 16M TOE in 2012. Public Power Corporation (PPC) supplied 77.3% of electricity demand while 61% of Greece's energy needs are covered by imports, mainly petroleum products (44%) and natural gas (13%). The remaining 39% is covered by lignite (77%) and Renewable Energy Sources (RES) mainly photovoltaics, wind parks, small hydro-power plants and biomass (22%). In 2015, the share of wind power for electricity production was about 9%. The highest percentage of electricity produced in Greece comes from lignite exploited within the Greek territory. RES follow with a total share of 29%, percentage that is constantly developing in the Greek energy market. The energy sector follows the general principles having been determined by the European Union and it has been totally reconciled with the respective European policy priorities. The national goals set for the year 2020 in combination with the 20-20-20 European Energy Policy are (Ministry of Environment and Energy):

- 20% reduction of GHG emissions in relation to the respective 1990 emissions levels
- 20% penetration of RES in the gross final energy consumption

- 20% saving of primary energy

The food sector is strongly related to the agricultural production. Extensive agricultural plains, producing large amounts of agricultural products and food, are primarily located in the regions of Thessaly, Central Macedonia and Thrace. These regions constitute key economic regions as they are among the few arable regions in the country. The agricultural sector contributes about 3.8% in the national GDP. The most representative Greek agricultural products are grapes, olives and olive oil. The agricultural sector continues to occupy a prevailing position in the Greek economy while its future development is strongly related to the priorities defined by the Common Agricultural Policy (CAP).

Climate change has already affected and it will further affect regions of Greece in the future. National policy priorities for climate change adaptation and mitigation strategies are under structure. The Ministry of Environment and Energy has published a National Strategic Plan for Climate Change adaptation concerning the adaptation of Greek society and economic sectors to the new climatic conditions. In addition, regional plans (NUTS 2 level) are about to be prepared exploring the specific impacts of climate change for each Greek NUTS 2 region and the corresponding necessary adaptation measures. In 2011, the Bank of Greece (2011) published an analytical study concerning climate change impacts in Greece until the year 2100. The total annual rainfall will be declined while heavy and short-term storms will be increased as well as the flood risk.

Finally, agriculture and tourism are prevailing economic activities in Greece, affected by climate change, and decision makers place special emphasis on their future adaptation to climate change.

3.4.2 Evolution and description of the conceptual diagram

In the Greek Case Study, the interlinkages among the five critical nexus components (water, energy, land, climate and food) were first identified and then graphically represented in a conceptual model (Figure 3.4.1). Agricultural and tourist sectors were also considered in the analysis as the dominant economic sectors in Greece that put extra pressures on the nexus components. Among the key issues explored and investigated in the Greek conceptual model are: water resources management; penetration of RES to the national energy mix; land use allocation; impacts of water, energy and land policies on food and energy production patterns, and; agricultural and tourist development under climate change conditions.

It should be mentioned that the structure of the Greek conceptual model was based on a scientific inventory concerning the key characteristics of the nexus components as well as the interactions existing among them (Laspidou et al., 2017). Moreover, the conceptual model was validated and enriched by the stakeholders involved in the Greek Case Study during the 1st stakeholders' workshop, at an early stage of the project, where all of them expressed their opinions and preferences as to its structure and content.

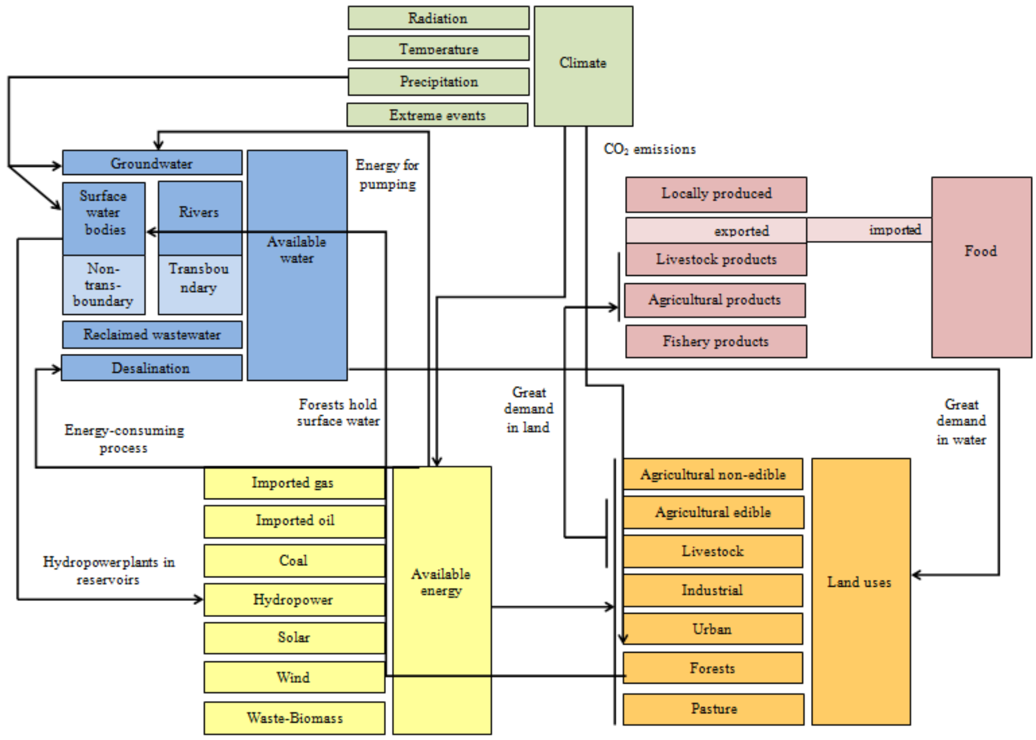


Figure 3.4.1: The Greek CS conceptual model (Papadopoulou et al., 2019)

During the conceptual model design process, each nexus component was "decomposed" into more detailed sub-components. Such decomposition contributed to an in-depth exploration of the nexus interlinkages and a more realistic assessment of the pressures put by each nexus component to the rest. An indicative list of the related sub-components per each nexus element is:

Water

- Groundwater
- Surface water bodies
- Rivers
- Reclaimed wastewater
- Desalination

Energy

- Imported gas
- Imported oil
- Coal
- Hydropower
- Solar
- Wind
- Waste-biomass

Climate

- Radiation
- Temperature
- Precipitation
- Extreme events

Land uses

– Agricultural non-edible
– Agricultural edible
– Livestock
– Industrial
– Urban
– Forests
– Pasture

Food

– Locally produced
– Livestock products
– Agricultural products
– Fishery products

Indicative interlinkages among the nexus components were identified and incorporated into the conceptual model. Such interlinkages concern: a) energy demand for pumping, b) CO_2 emissions, c) water demand related to land use, d) demand of land for food production, e) quantity of surface water hold by forest land, f) energy demand for desalination purposes and g) water demand for energy production in hydropower plants. For each component of the nexus, conceptual "sub-models" were built for the Greek CS in order to better explore the relative interlinkages.

The main interlinkages investigated in the Greek CS conceptual sub-model for the energy sector (Figure 3.4.2) are: a) the water volumes needed for electricity production by hydropower plants (energy-water), b) GHG emissions derived from energy consumption and affect climate (energy-climate), c) exploitation of agricultural and forest biomass for energy production (energy-land) and d) energy needed by the agricultural sector for food production (energy-food).

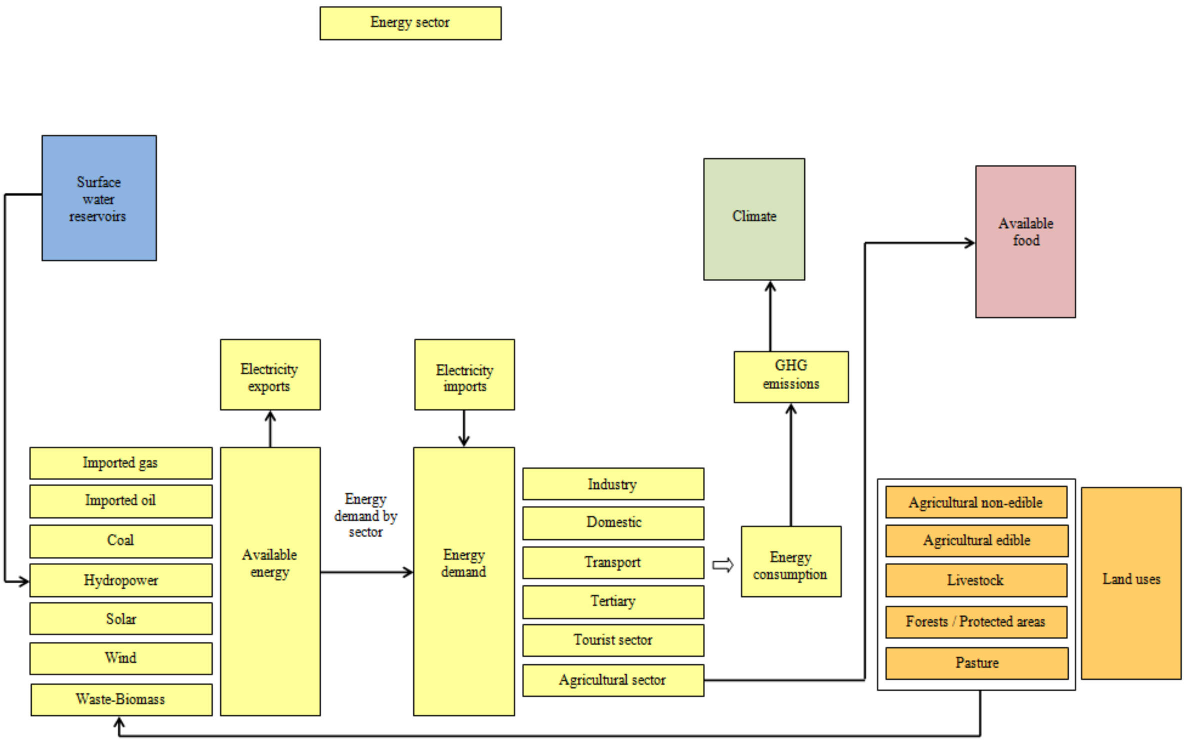


Figure 3.4.2: Greek CS Conceptual sub-model for energy

A substantive number of interlinkages is built among land use and: energy, water, food and climate (Figure 3.4.3). Such interactions refer to: a) water volumes needed by various land uses such as agriculture, livestock, industry, urban land, forest land and pastures, b) water demand for irrigated land, c) the effects of various land uses on water quality and d) estimation of surface runoff in forest land (land-water). The available land for agricultural and livestock activities affects food production (land-food) while, land use-energy interlinkages are also crucial. Indicatively: a) the demand of energy for urban, industrial, agricultural and livestock use and b) the exploitation of agricultural and forest biomass for energy production are considered. Finally, the various land uses contribute to the production of GHG emissions that affect climate while radiation, precipitation and temperature affect agricultural land, forests and pastures (land-climate).

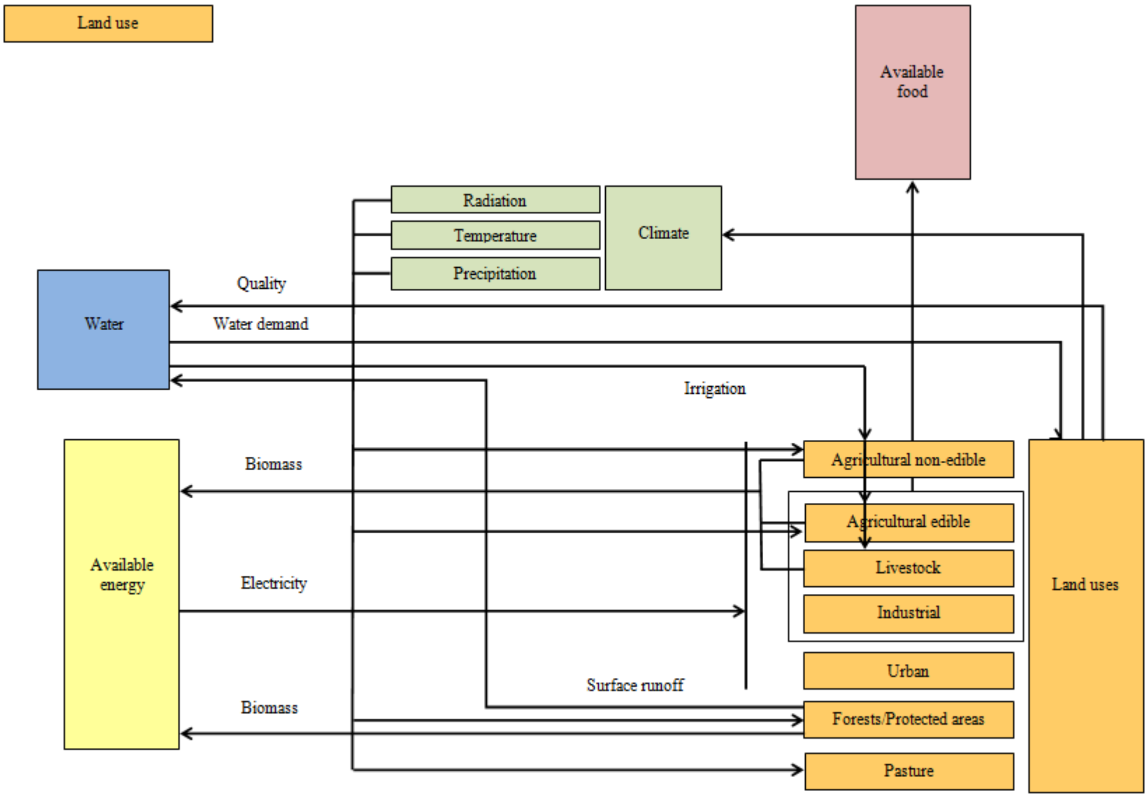


Figure 3.4.3: Greek CS Conceptual sub-model for land-use

Regarding water (Figure 3.4.4), its interlinkages with the rest of the nexus components mainly concern: a) the effects of evapotranspiration and precipitation on the available surface and subsurface water resources (water-climate), b) the GHG emissions derived from water reclamation and desalination processes (water-climate), c) water demand for food production (water-food), d) water demand for electricity production in hydropower plants (water-energy), e) energy demand for pumping (water-energy) and f) surface and groundwater volumes used to cover demand in several land uses (water-land use).

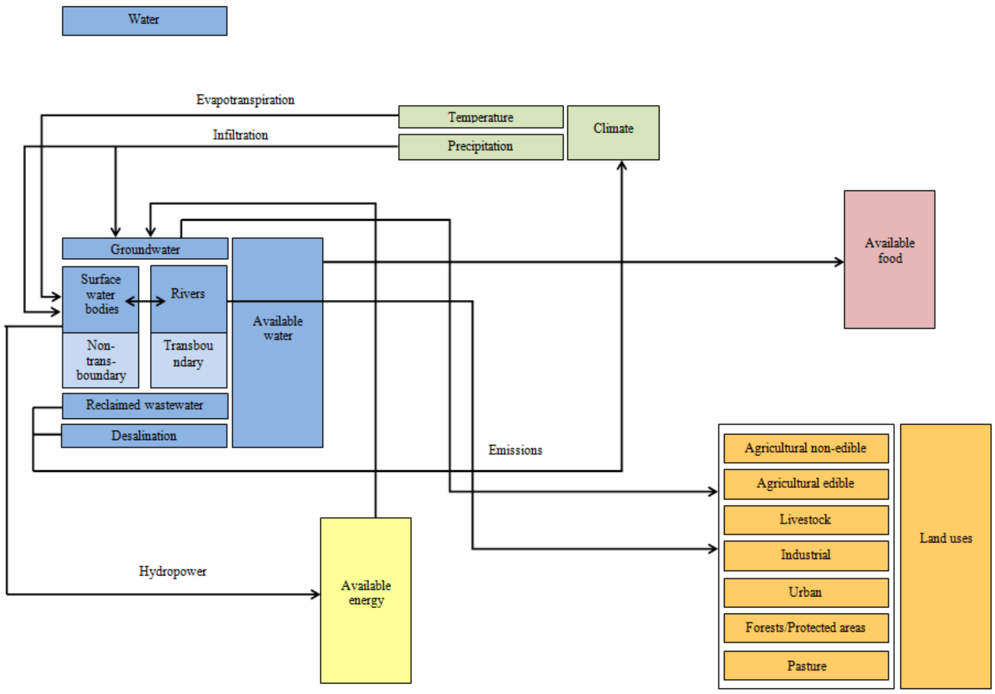


Figure 3.4.4: Greek CS Conceptual sub-model for water

Finally, with respect to the food sector, its interlinkages with the other nexus components include: a) water demand for food production (food-water), b) GHG emissions produced by transportation sector serving the allocation of food (food-climate), c) energy demand for food production (agri-food products, livestock products, fishery products, food processing) (food-energy) and d) availability and exploitation of land for the development of agricultural and livestock activities in order to produce agri-food and livestock products (food-land).

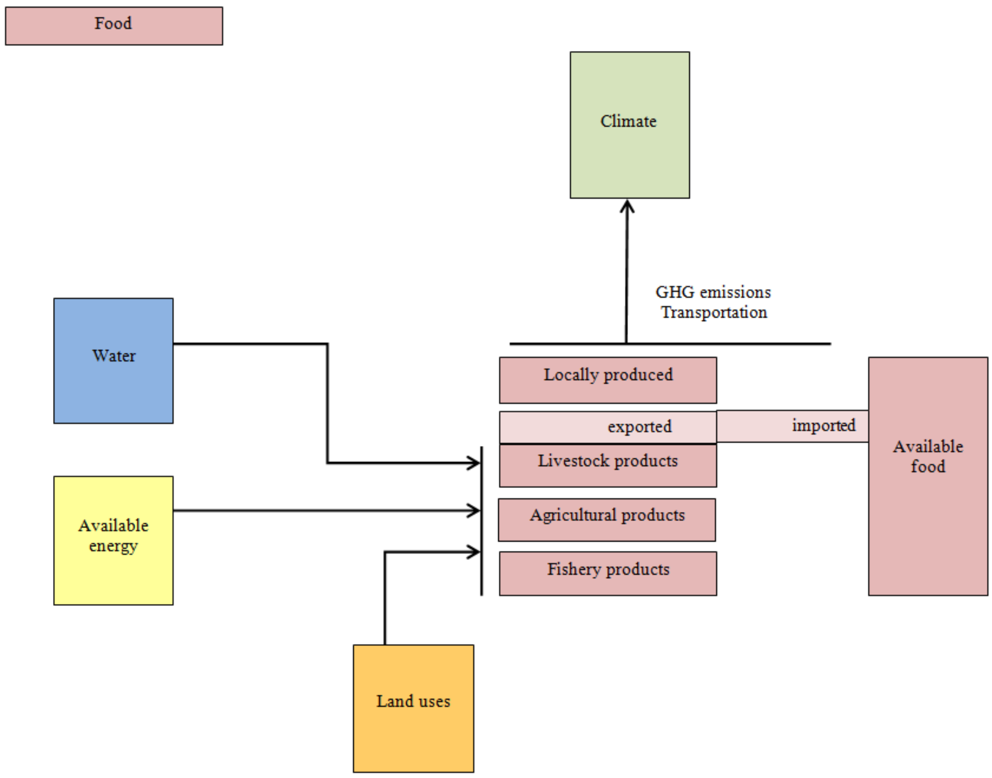


Figure 3.4.5: Greek CS conceptual sub-model for food

3.4.3 Description of the developed system dynamics model

The developed System Dynamics Model (SDM) for the Greek case study relies upon a detailed framework concerning the mapping and quantification of the interrelations of the five Nexus dimensions along with the detailed analysis behind each component (Figure 3.4.6). It is developed in the system simulation software STELLA (https://www.iseesystems.com/). The analysis is characterized by a high spatio-temporal resolution, justified by the expansion of the relevant information from national scale to River Basin District (RBD) level and by elongating the time scale on a monthly basis. Greece is a Mediterranean country with high spatial variability in terms of climate conditions, resources' availability, and demographic dynamics; thus, the disaggregation of national data to RBD level—14 RBDs—is deemed necessary to conduct a thorough and sufficiently precise Nexus analysis (Figure 3.4.7).

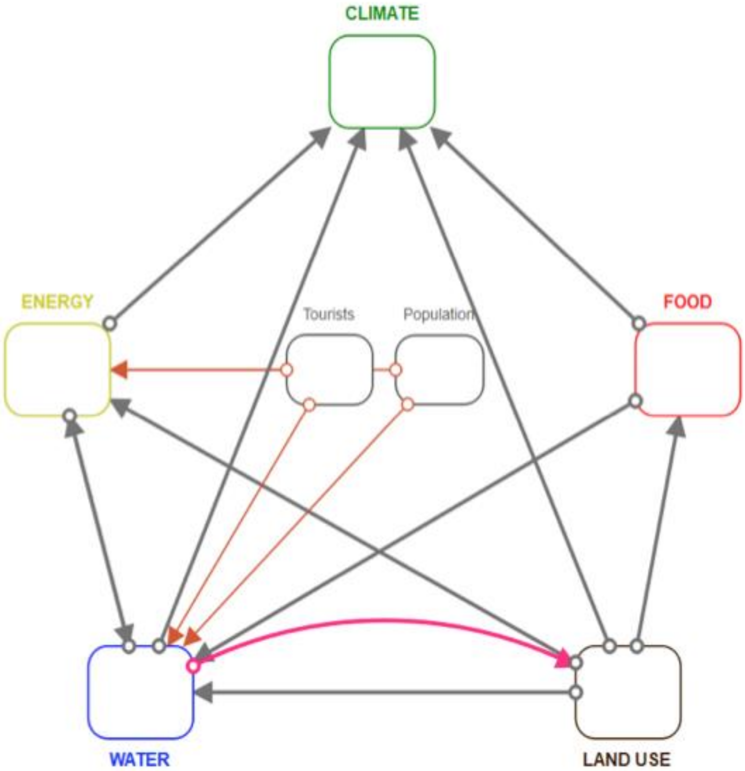


Figure 3.4.6: The five Nexus components and their interrelations as designed in the Greek SDM.

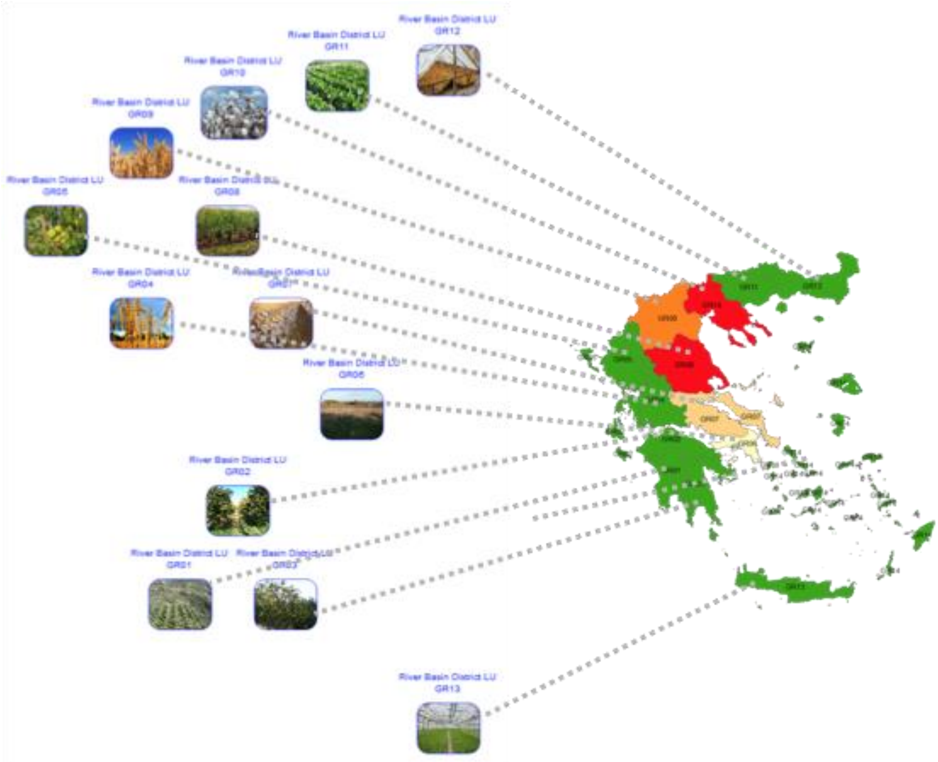


Figure 3.4.7: The 14 sub-models included in the Greek SDM corresponding to each one of the 14 RBDs in Greece. Each sub-model contains the same level of detail, modeling all-five Nexus components, essentially delivering 14 complete SDMs.

In the SDM, Land Use comprises the basic Nexus dimension in the SDM, containing the areas occupied by natural resources—forests, wetlands, grasslands—and by human-related activities such as cropland, livestock, and artificial areas (Figure 3.4.8). Cropland areas are connected to water, food, energy, and climate components through irrigation water demand, food production, energy demand, and Greenhouse Gas Emissions (GHGs), respectively. On the other hand, forests, wetlands, and grasslands operate as relievers to climate GHGs increasing carbon sequestration. ELSTAT, the Greek Statistical Authority, provided all the relative information concerning crop areas, crop types, irrigated crops or not, livestock areas, animal types, and animal heads in each RBD. Forest, wetland and grassland areas were provided by the European Land Cover Corine database, provided by the Copernicus system (https://land.copernicus.eu/). The SDM provides the ability to apply changes to land use and consequently it returns the impact on other dimensions through the aforementioned interlinkages; thus, one can realize the multi-dimension effects of adopting different land use policies.

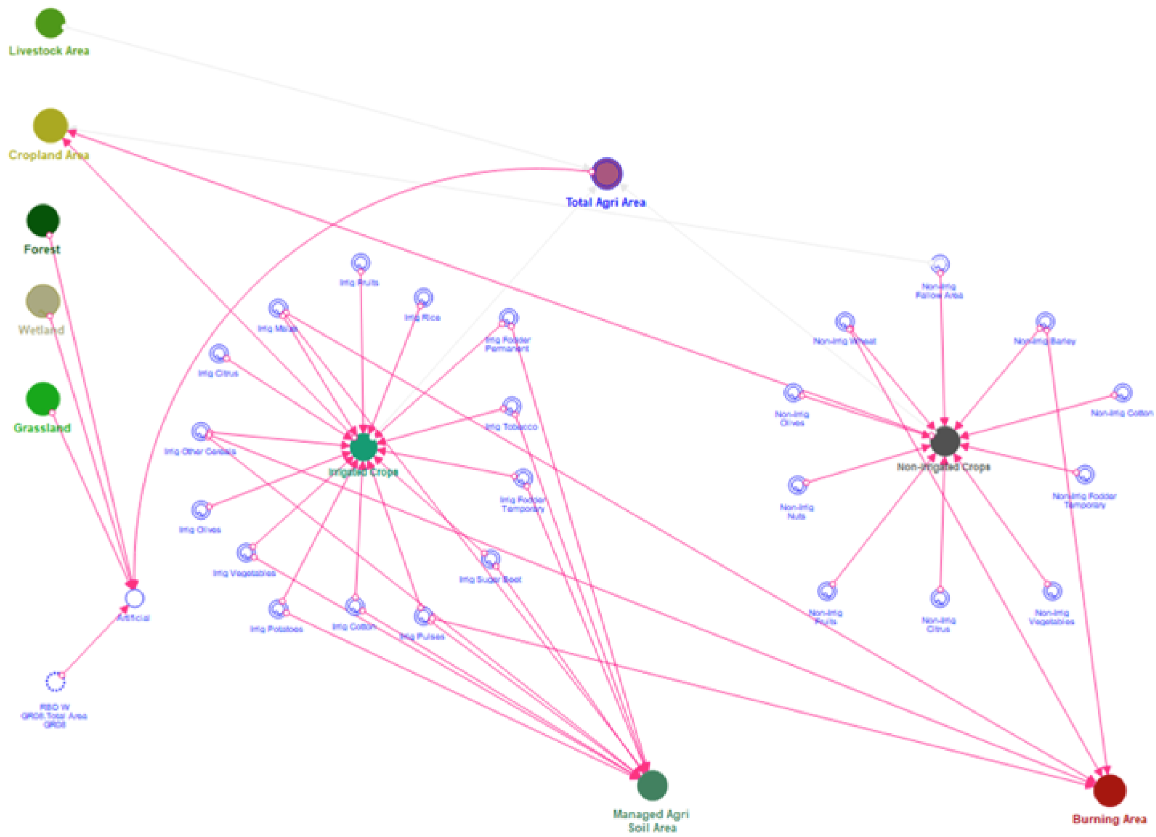


Figure 3.4.8: The Land Use dimension in the Greek SDM.

Figure 3.4.9 shows how the SDM works in terms of establishing and quantifying interlinkages. It is possible to introduce changes in Land Use categories that include Cropland areas (with a variety of Irrigated and Non-Irrigated crops comprising fourteen crop categories). Such changes would include changing the area of a crop type to another (from olives to cotton, for example), or switching from an irrigated to a non-irrigated crop. It is also possible to introduce changes in livestock areas, wetland, grassland and forest areas. As a result, changes in any of these variables in the Land Use module, would cause changes (i) in the Climate sector (agricultural emissions depend on crop types and livestock use); (ii) in the Food sector due to different Crop/Livestock production; (iii) in the Water sector due to different irrigation needs and (iv) in the Energy sector, since agricultural energy demand depends on irrigated cropland area. Wetlands, Grasslands and Forests would have implications in the Climate sector, since emissions from these types of Land Uses have either positive or negative greenhouse gas (GHG) emissions.

<table>
<tr><td rowspan="6">A Change in Land Use includes changes in...</td><td rowspan="2">Cropland Area</td><td>Irrigated Crops: Fruits, rice, fodder temporary & permanent, tobacco, pulses, cotton, potatoes, vegetables, olives, other cereals, citrus, maize, sugar beet</td><td rowspan="3">Agricultural Area</td><td rowspan="3">And brings about changes in...
➢ Climate (Agricultural Soil Emissions)
➢ Food (Crop/Livestock production)
➢ Water (Irrigation)
➢ Energy (Agricultural Energy Demand)</td></tr>
<tr><td>Non –Irrigated Crops: Barley, cotton, fodder temp., vegetables, citrus, fruits, nuts, olives, wheat</td></tr>
<tr><td colspan="2">Livestock Area</td></tr>
<tr><td colspan="3">Wetland Area</td><td>➢ Climate (LULUCF Emissions)</td></tr>
<tr><td colspan="3">Grassland Area</td><td>➢ Climate (LULUCF Emissions)</td></tr>
<tr><td colspan="3">Forest Area</td><td>➢ Climate (LULUCF Emissions)</td></tr>
</table>

Figure 3.4.9: Land Use categories included in the model and Nexus components they affect (LULUCF stands for Land Use Land Use Change and Forestry)

The water dimension of the SDM involves surface and groundwater dynamic availability as a result of the balance between precipitation, water losses though evapotranspiration, runoff to the sea and several anthropogenic water stressing activities (agriculture, industry, household/commercial, power generation, and livestock) (Figure 3.4.10). Surface water and ground water are modelled separately in the SDM, providing a powerful tool that keeps track of water demands specific to each water body. Figure 3.4.11 shows a schematic of how the water cycle is modelled in the SDM. Precipitation and actual evapotranspiration estimates and forecasts for future decades for different RCPs are provided by Potsdam Institute for Climate Impact research.

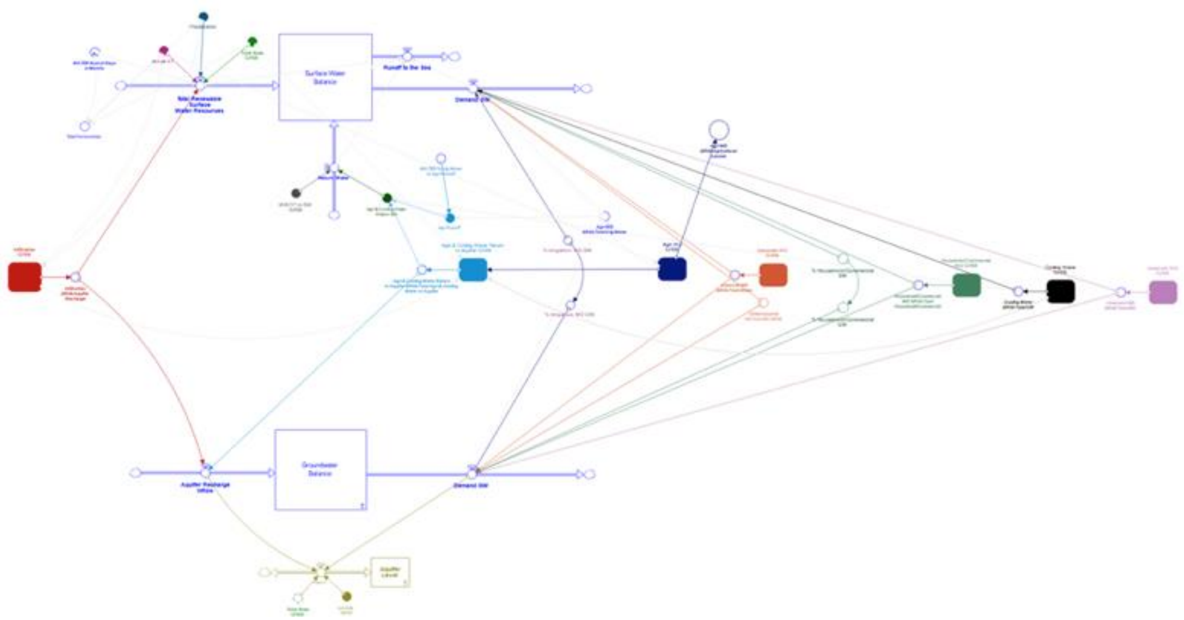


Figure 3.4.10: The water dimension in the Greek SDM.

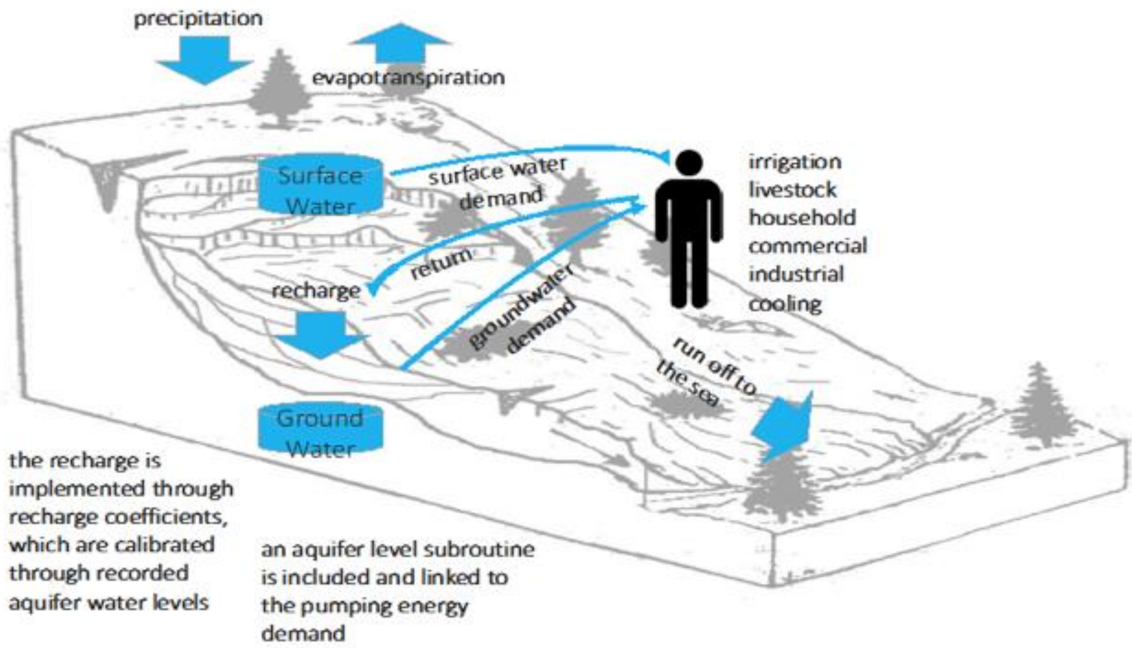


Figure 3.4.11: The water cycle as modelled in the SDM.

Especially for irrigation water, which consists the highest water consumer in Greece, matching crop types with precise seasonal irrigation needs and water losses with irrigation technologies renders it feasible to dynamically map irrigation demand. Population and tourism distribution on RBDs determine the household/commercial water demand, while industrial, power generation and livestock water demand are distinguished according to each RBD's potential in each subsector. Water is interlinked to energy and to climate dimensions of the Nexus through several cause and effect pathways. Irrigation technologies used in the agricultural sector are mapped in the SDM, providing the ability to estimate the real irrigation needs while switching between the technologies results in different water demands. Pumping water is directly connected to energy demand and consequently to GHG emissions. Additionally, wastewater resulting from wastewater treatment plants and industry, contributes to GHG emissions. Population and tourism dynamics pose the main regulator of wastewater, meaning that a possible change can induce different GHG emissions regimes. Eurostat, through the European open data portal, provided all the relevant datasets of the water subsectors in the SDM. Figure 3.4.12 provides a list of the quantities that can be altered in the Water module and the corresponding changes they will bring about in other modules.

Changes in Water can be implemented through changes in...	Population	And bring about changes in...
	Tourism	➢ Climate (wastewater emissions) ➢ Energy (Water pumping)
	Irrigation Efficiency	
	Per capita water use (different for tourists or householders)	

Figure 3.4.12: Water categories included in the model and Nexus components they affect.

Food is treated as the product of crops and livestock activities mapped in the land dimension of the SDM (Figure 3.4.13). According to the crop type and the area it occupies in each RBD, food, feed, and industrial products arise as a function of surface unit multiplied by a crop type-oriented yield coefficient.

Livestock products—meat, milk, eggs, and honey—arise as a function of animal heads multiplied by a yield coefficient customized according to the product type. In this way, agricultural products are quantified and distributed in each RBD, constituting an inventory map of agricultural products downscaled from national to RBD level.

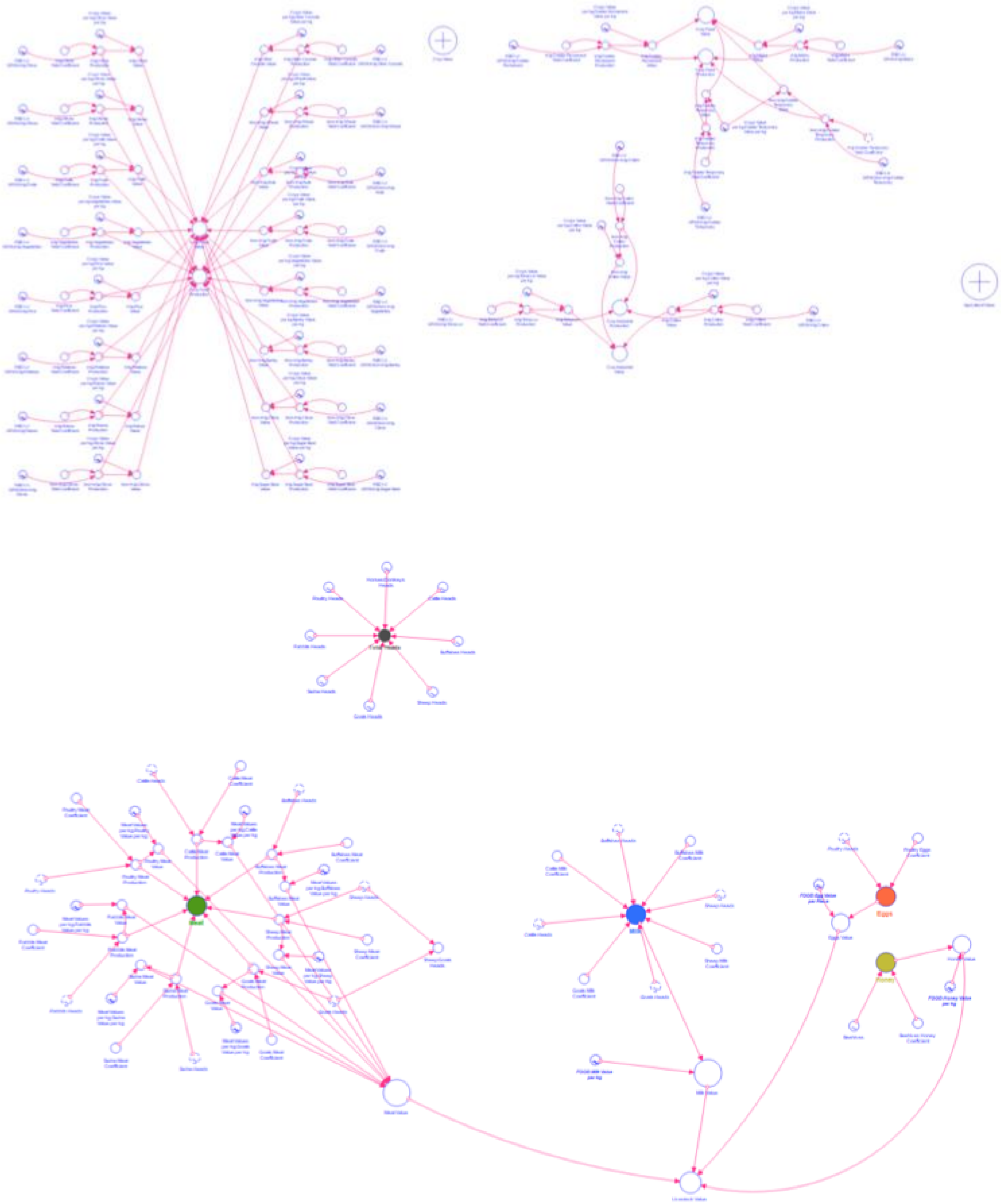


Figure 3.4.13: The food dimension in the Greek SDM.

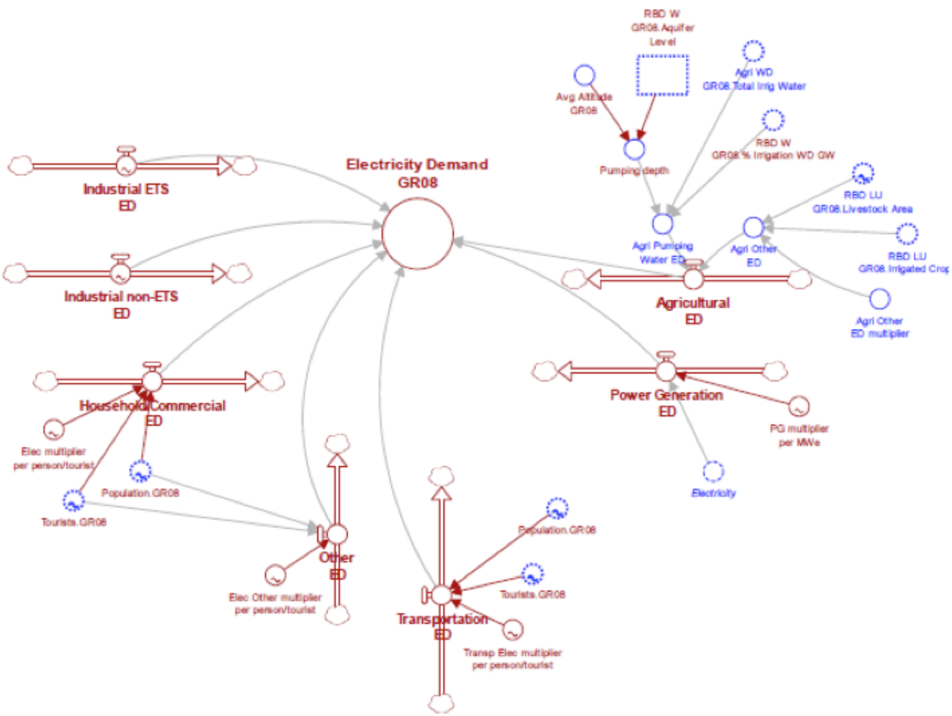
The food dimension, apart from the quantities produced, contains the value of crop and livestock products as a function of production units multiplied by customized value coefficients, respectively. Both production quantities and corresponding value data are provided by ELSTAT. Possible changes in food production are linked to different GHG emissions and different water demand regimes, which lead to alterations in energy consumption. Figure 3.4.12 provides a list of the quantities that can be altered in the Water module and the corresponding changes they will bring about in other modules, as Figure 3.4.14 presents the same for the food sector.

A change in Food can be implemented through changes in...	Crop yields Animal productivity Livestock (number of animal heads)	And brings about changes in...
	Crop yields	➢ Climate (Livestock Emissions) ➢ Water (Irrigation and Livestock water demand)
	Animal productivity	
	Livestock (number of animal heads)	

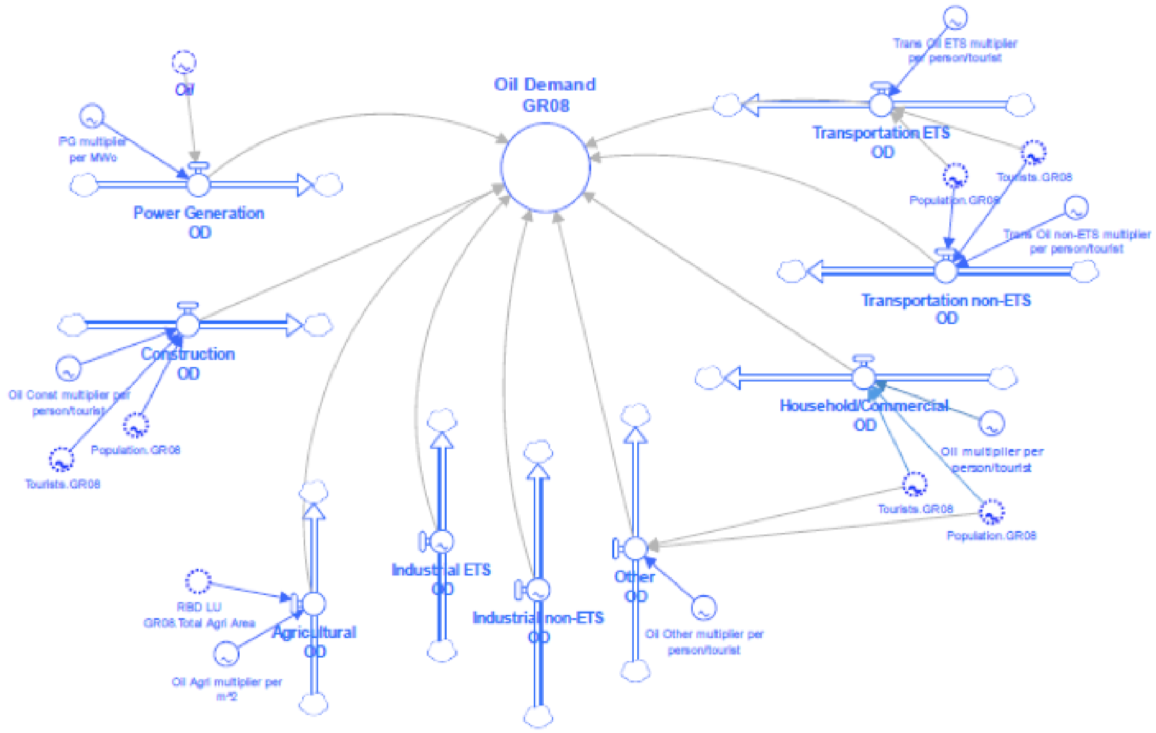
Figure 3.4.14: Food categories included in the model and Nexus components they affect.

The energy sector is modelled in the SDM both from the perspective of demand and generation (Figure 3.4.15). Oil, gas, coal, heat, biomass and electricity demands are quantified and mapped in all RBDs. These energy demand categories are divided in several subsectors such as the industrial, the household/commercial, the transportation, the agricultural, the power generation and other. Regarding power generation, all the electricity-producing plants according to the fuel type they use (oil, coal, gas, biomass, renewables: solar, wind, hydropower) are mapped in each RBD. E3ME, a global, macro-economic model designed to address major economic and economy-environment policy challenges, provided all the relative data used in the SDM.

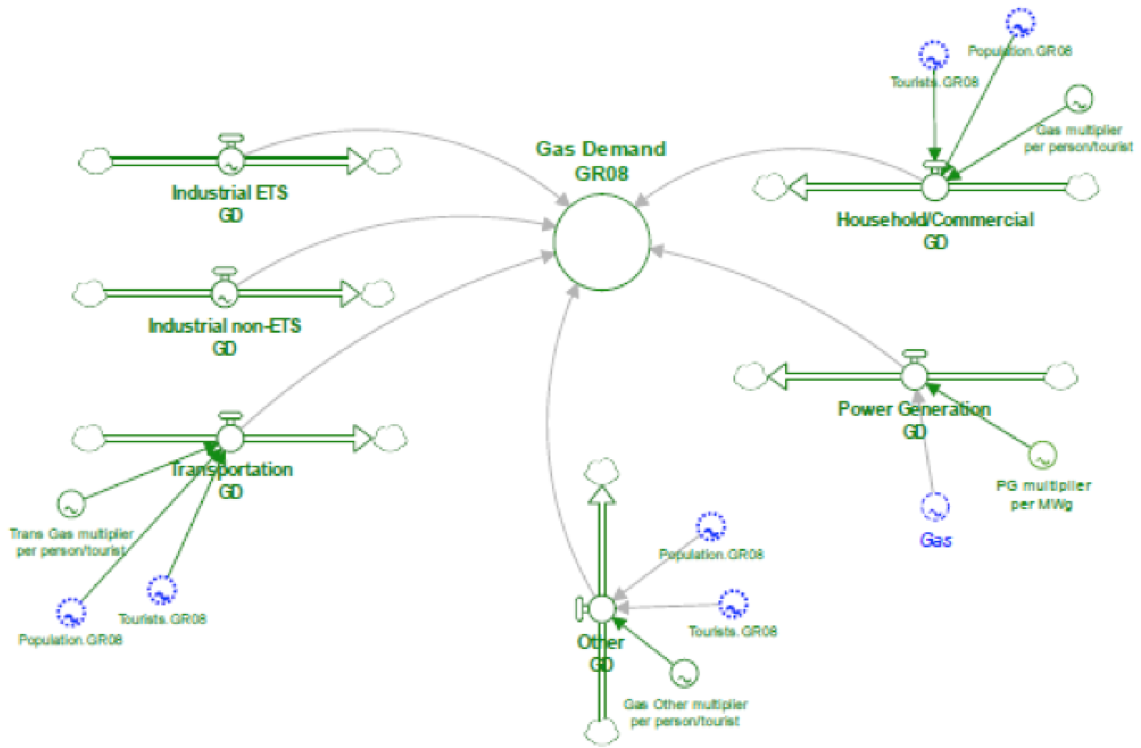
(a)



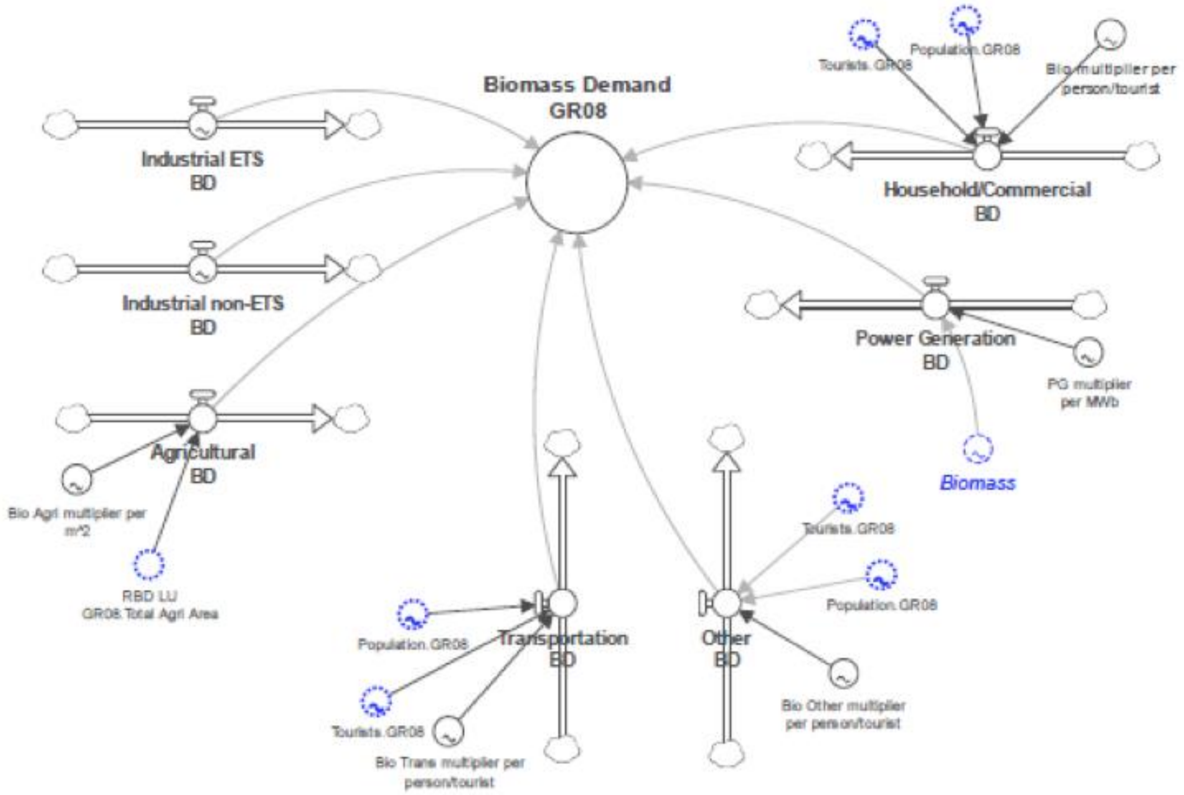
(b)


Oil Demand
GR08
Oil
PG multiplier
per MWe
Power Generation
OD
Trans Oil ETS multiplier
per person/tourist
Transportation ETS
OD
Tourists.GR08
Population.GR08
Trans Oil non-ETS multiplier
per person/tourist
Transportation non-ETS
OD
Construction
OD
Oil Const multiplier per
person/tourist
Population.GR08
Tourists.GR08
Household/Commercial
OD
Oil multiplier per
person/tourist
Tourists.GR08
Population.GR08
Industrial ETS
OD
Industrial non-ETS
OD
Other
OD
Oil Other multiplier per
person/tourist
RBD LU
GR08.Total Agri Area
Agricultural
OD
Oil Agri multiplier per
m^2

(c)

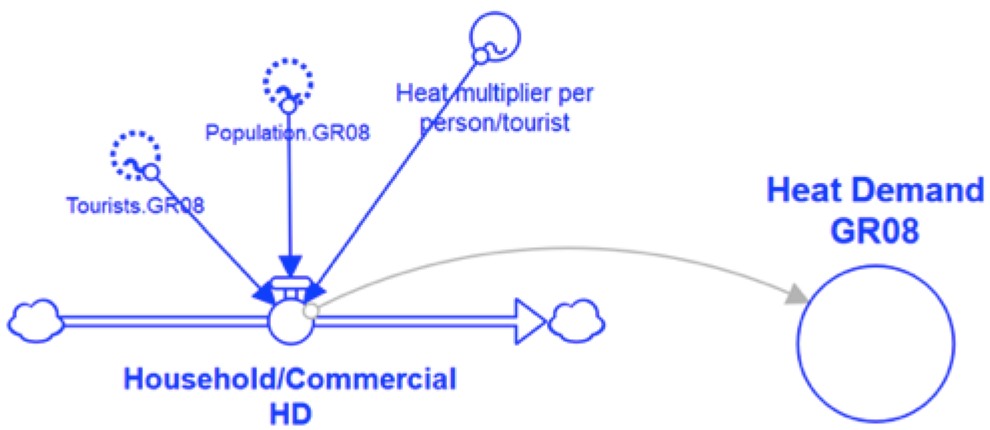

Gas Demand
GR08
Industrial ETS
GD
Industrial non-ETS
GD
Transportation
GD
Trans Gas multiplier
per person/tourist
Population.GR08
Tourists.GR08
Household/Commercial
GD
Tourists.GR08
Population.GR08
Gas multiplier
per person/tourist
Power Generation
GD
PG multiplier
per MWg
Gas
Other
GD
Population.GR08
Tourists.GR08
Gas Other multiplier
per person/tourist

(d)



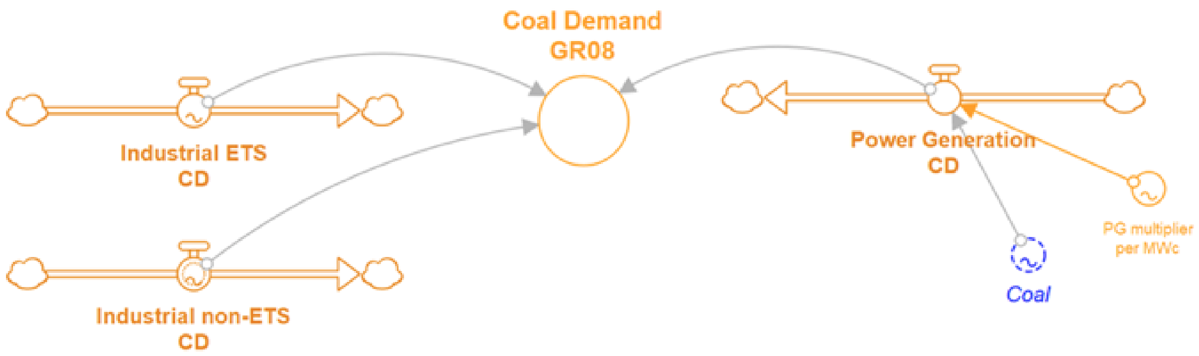
Biomass Demand
GR08
Tourists.GR08
Population.GR08
Bio multiplier per
person/tourist
Industrial ETS
BD
Household/Commercial
BD
Industrial non-ETS
BD
Power Generation
BD
PG multiplier
per MWh
Agricultural
BD
Biomass
Bio Agri multiplier per
m^2
RBD LU
GR08.Total Agri Area
Tourists.GR08
Population.GR08
Population.GR08
Transportation
BD
Other
BD
Tourists.GR08
Bio Trans multiplier per
person/tourist
Bio Other multiplier
per person/tourist

(e)



Heat multiplier per
person/tourist
Population.GR08
Tourists.GR08
Heat Demand
GR08
Household/Commercial
HD

(f)



(g)

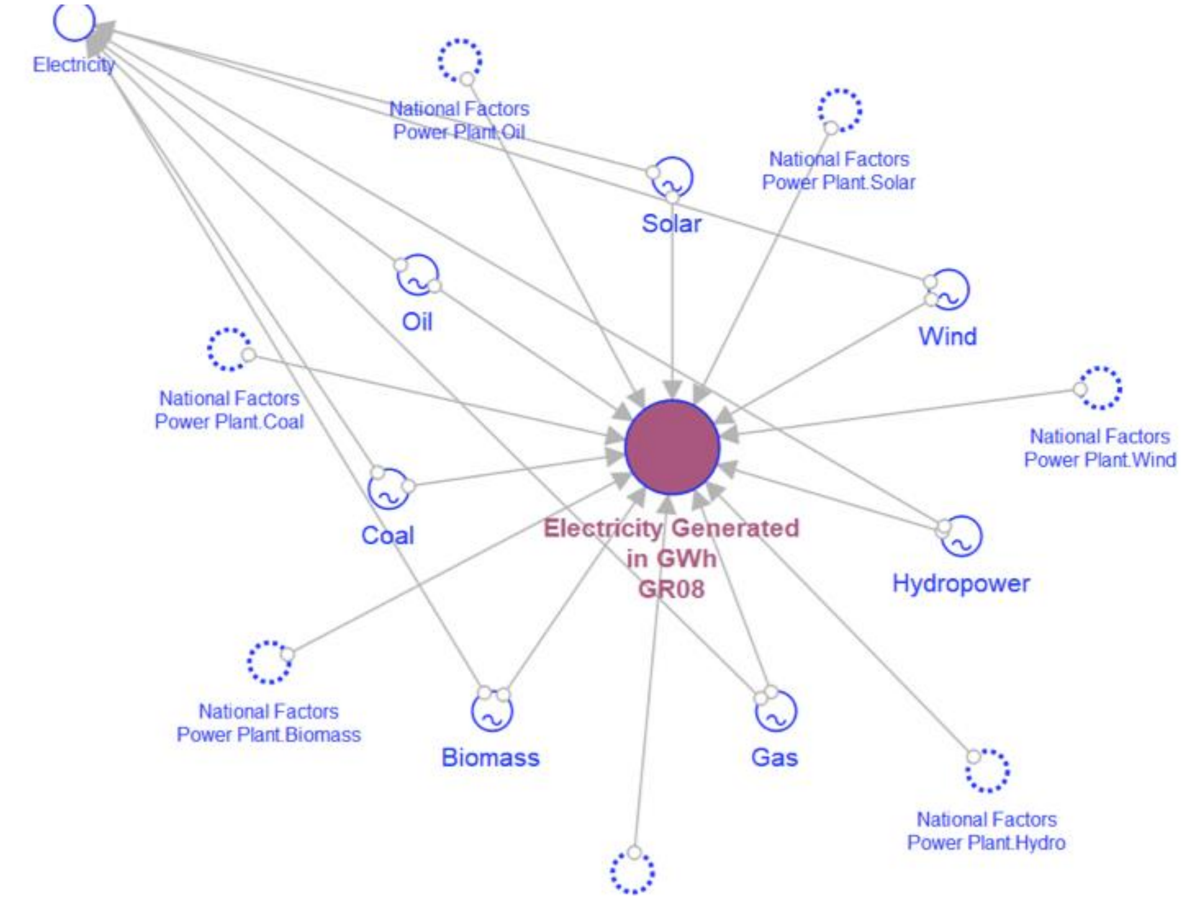


Figure 3.4.15: The energy dimension in the SDM. Figures (a)-(f) depict the energy demand while (g) depicts the energy generation sub-module.

Possible changes in energy demand are connected to climate through interlinkages with the GHG emissions, while other energy-related sectors, such as water and food, play a decisive role both in energy demand and in GHG emissions. Figure 3.4.16 provides a list of the quantities that can be altered in the Energy module and the corresponding changes they will bring about in other modules.

A change in Energy can be implemented through changes in...	Population	And bring about changes in...
	Tourism	*Climate* (Emissions)
	Installation of a new power plant	*Water* (Cooling water, hydropower)

Figure 3.4.16: Energy categories included in the model and Nexus components they affect.

Climate is a sector which is dealt as Greenhouse Gas Emissions (GHGs) coming mainly from fuel emissions and secondly from agriculture, livestock, LULUCF, and wastewater treatment (Figure 3.4.17). EUROSTAT provided all the relevant GHG information on a national level forming the basis on which disaggregation to RBD level relied. The SDM relates GHG emissions to every aforementioned source through several pathways that are mapped and quantified. Since climate can be affected by all other dimensions in the SDM, possible policy interventions on current land use, water, food, and energy components will affect GHG emissions.

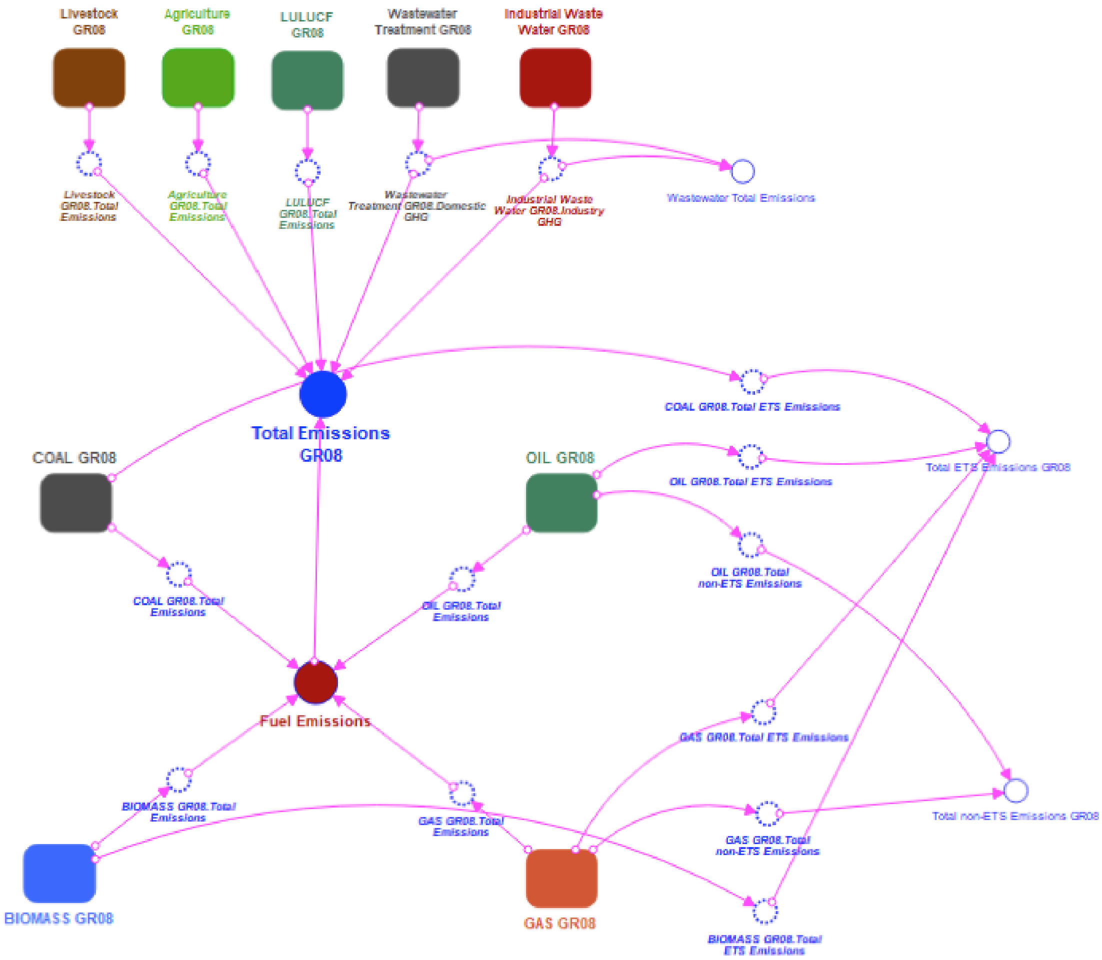


Figure 3.4.17: The climate dimension of the Greek SDM.

The whole Nexus concept is underpinned by the interaction of the five components as well as the scale of information detail in each one, highlighting the SDM potential and effectiveness in depicting and evaluating the flows among the Nexus dimensions. The outcome of the SDM indicates which e components strongly affect others and which interlinkages are comparatively and relatively weak. Concluding, the SDM is a powerful tool that can be used to model complex systems. The resource Nexus for Water-Energy-Food-Land Use-Climate has been modelled for the national case study of Greece and the interlinkages among all Nexus dimensions are quantified in a user-friendly environment that is intended for use by policy-makers and stakeholders in a participatory process.

3.5 Latvia Case study

3.5.1 Short description of the case study

Latvia is located in north-eastern Europe, bordering Estonia, Lithuania, Russia, Belarus, and the Baltic Sea (Figure 3.5.1). It has a total land area of 64 573 km2, and a population of about 2 million inhabitants. Forests cover 48% of the land, with agricultural land occupying 38% of the land surface. Wholesale, retail and transport are important economic sectors, while timber, wood and forestry are important industrial sectors. Indeed, 78% of forestry products are exported.

Low-carbon development is the key focus of the Latvia case study (Figure 3.5.1). According to the goals and priorities set by national policy, Latvia is seeking for possibilities to reduce energy dependency from imported fuels, increase sustainable use of renewable energy sources and ensure economic development while reducing greenhouse gas emissions. For selection of the appropriate direction of the case study, key stakeholders from ministries (Environment, Agriculture), scientific institutes, regional and local authorities were approached. Several small meetings, followed by a thematic event on energy & waste and a stakeholder workshop on 15 November 2017, involving stakeholders from various institutions, were organised. Key case study issues were identified as (as and such will be addressed in the conceptual model and the SDM): (i) is it possible to enlarge energy self-supply, by widening the use of renewable energy sources in the country; (ii) which trade-offs would be acceptable and what are the possible solutions towards low carbon economy.

Latvia has a high potential for renewable energy (e.g., hydro, biomass), but remains largely dependent on imported fossil fuels and electricity. Thus, energy security is a key concern and ensuring the energy supply, competitiveness, energy efficiency and the use of renewable energy. At the same time along with significant reduction of total GHG emissions since 1995, the current level of GHG emissions in Latvia remains high and is between the highest values in the European Union. As a result, much effort must be paid to reduce emissions and reach mandatory CO_2 reduction targets set for 2030. Increasing use of bio-resources and renewable energy sources (RES) can be considered an option. At the same time, such options raise several questions about the trade-offs of renewable energy production such as: harvesting of biomass puts a pressure on forestry and growing energy plants compete with crops and food production. Growing energy plants also require a large amount of fertilizer, resulting in detrimental impacts on water quality and causing eutrophication of water bodies thus posing a risk to climate change adaptation. Climate change has an impact on water resources e.g., increasing autumn and winter precipitation generates higher flood risks. During these periods soils, in Latvia suffer from excessive moisture. On the other hand, periods of droughts in summer have an impact on use of hydropower, particularly for small scale applications, as well as on agriculture. Thus, preparedness to resist climate change and reduce adverse effects is becoming of high importance for national economy and the society in general.

Figure 3.5.1: Map showing the SIM4NEXUS Latvian case study.

In Latvia, low carbon development is getting an increasing attention on various policy levels along with elaboration of the "National strategy on low-carbon development 2050" (due for the end of 2017). Low carbon development calls for reduction of greenhouse gas (particularly CO_2) emissions as well as maintaining or increasing CO_2 sequestration, having positive environmental, economic, and social impacts. Potential directions of low-carbon development in Latvia comprise sustainable energy, increasing energy efficiency; resource efficient and environmentally friendly transport; sustainable land management, consumption, and production; research and innovation on low carbon technologies.
Acknowledging the need to increase the use of natural resources, a draft national strategy "Bio-economy strategy 2030" has been elaborated and submitted to Cabinet of Ministers on 3 August 2017. According to the strategy, the priority directions comprise promotion and maintenance of employment level in the branches of bioeconomy (e.g., agriculture, forestry, fishery, food production), increasing the added value of products of bioeconomy, increasing the export value of products of bioeconomy branches. Substitution of fossil fuels with bio-resources is one of the main goals of the strategy.

3.5.2 Evolution and description of the conceptual diagram

As with all the case studies described here, the Latvian conceptual diagram started at a very early stage in the project. It started relatively simply, gradually increasing in complexity and detail until a final satisfactory version was arrived at. This process (in all SIM4NEXUS case studies) was led by the case study leads, and guided by stakeholder workshops and close cooperation with IHE Delft modellers. This section compares the first and final versions of the conceptual models to illustrate the vast developments made during this process.

The first version of the Latvian conceptual model is shown in Figure 3.5.2. As shown in this figure, the model represents a 'high-level' overview of the main nexus connections in the Latvian case. Agriculture and energy feature prominently, consistent with the overall focus of the case study described above, namely a transition to a lot carbon economy, potentially with a shift to the use of biocrops for energy, with possible impacts on the agricultural and forestry sectors in Latvia. The emphasis on water is weaker on this version, and the link to climate and climate change is represented, but is not at the forefront.

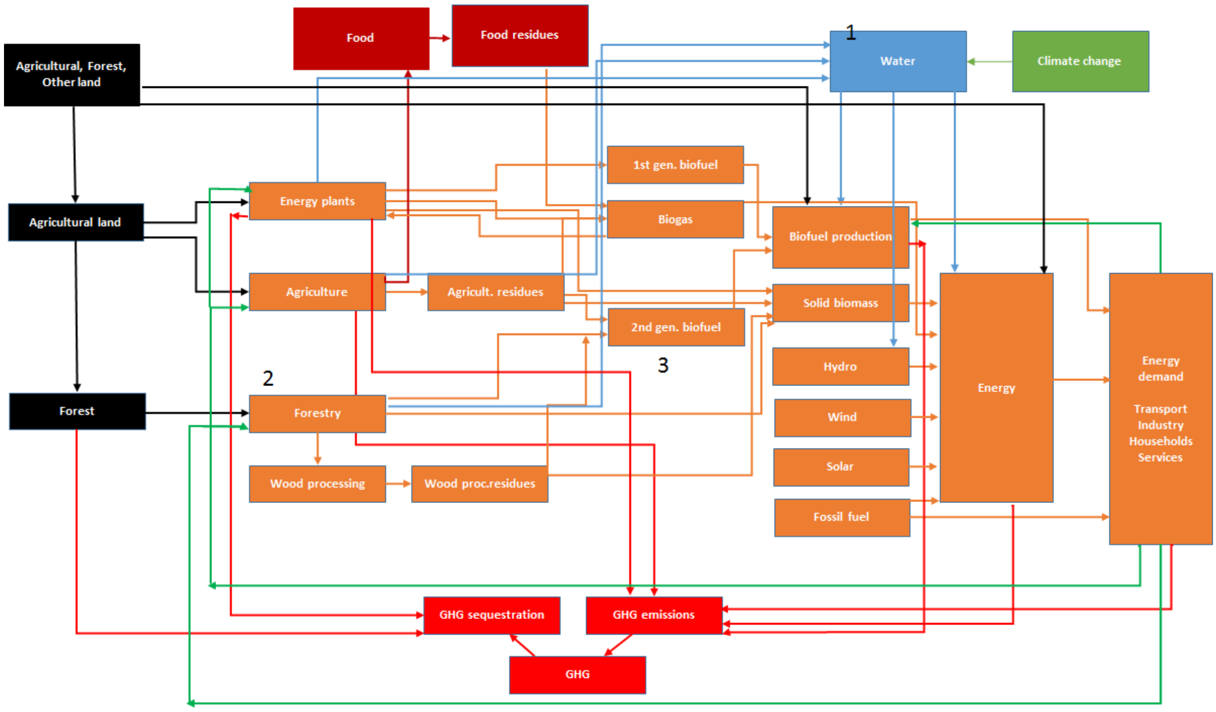
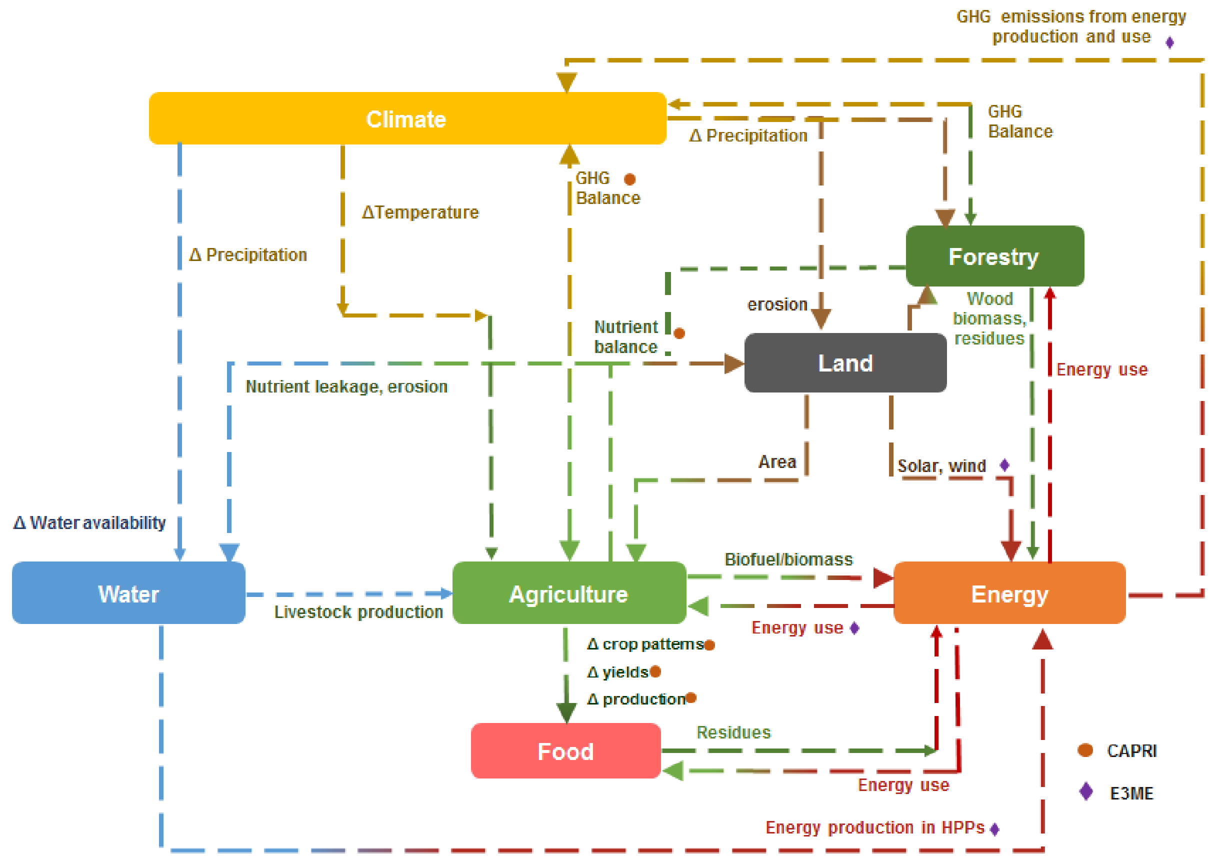


Figure 3.5.2: Initial version of the Latvian conceptual model.

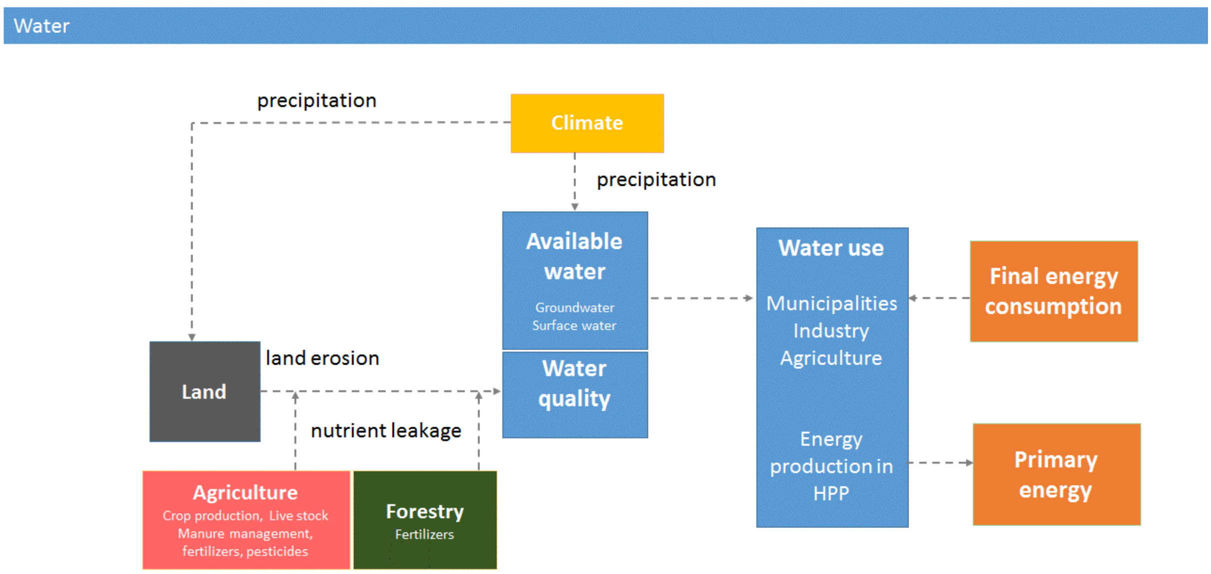
Future iterations gradually refined that in Figure 3.5.2, adding complexity and detail. Ultimately, the final developed conceptual model consists of a high-level overview (Figure 3.5.3a), followed by a detailed conceptual for each nexus sector, with the links to other sectors made explicit (Figure 3.5.3b-f). As with Figure 3.5.2, the emphasis is still clearly on the agricultural, energy, land an forestry sectors (Figure 3.5.3a), but now the links to other nexus sectors are more clearly highlighted, including some of the processes that define these interactions. In Figure 3.5.3a, all the main sectors (e.g. 'water', 'energy'), were subsequently developed in more detail. The subsequent SDM model accounts for all these interactions, offering consistent nexus-wide analysis. These sub-sector conceptual diagrams are illustrated in Figure 3.5.3b-f.

Figure 3.5.3b deals with the water sector, which is not of key concern in the Latvian case. The main aspects of consideration here are having a broad overview of water supply and water use in different water-demanding sectors. Water quality is also brought out as being important here. The links from water to the land (via erosion), agricultural, forestry (both via nutrient leakage), energy (via energy demands in the water sector) and climate sectors are highlighted. Figure 3.5.3c shows the details for the land sector. The focus here is on agricultural lands, forestry and 'other', which includes land used for renewable energy production. The links to water (via nutrient runoff), food, and energy (via energy crops and wood biomass) are made clear. Figure 3.5.3d shows the food sector. Agriculture only considers rain-fed crops as there is no irrigation in Latvia. The rest of the sector considers the balance between food produced (both on Latvian territory and imported) and food consumed by the local population. The links to other sectors are made via runoff (to water), energy crops, residues and biogas (energy) and direct emissions to the atmosphere (climate). In turn, precipitation, temperature and greenhouse gas (GHG) emissions feedback to influence crop production.

(a)

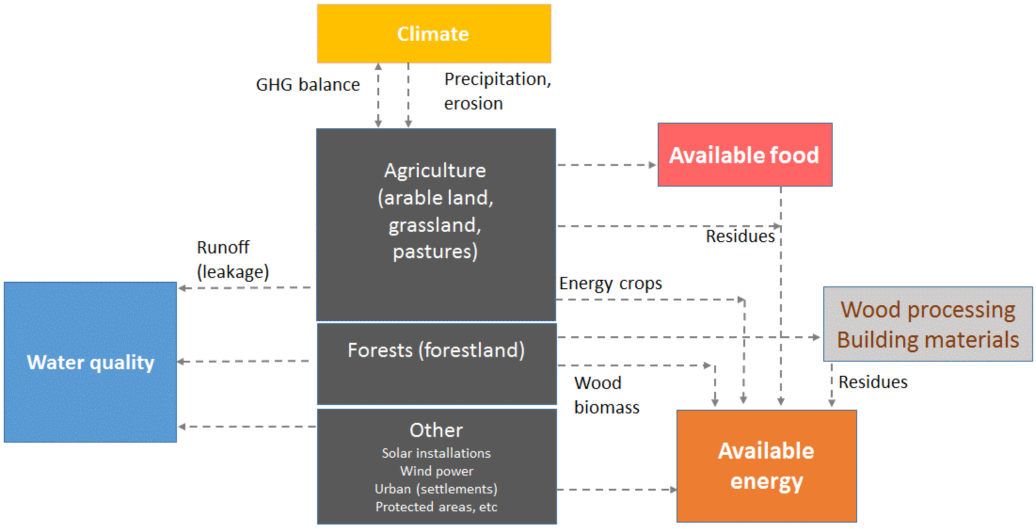

GHG emissions from energy production and use
Climate
Δ Precipitation
GHG Balance
ΔTemperature
Δ Precipitation
GHG Balance
Forestry
erosion
Nutrient balance
Land
Wood biomass, residues
Nutrient leakage, erosion
Energy use
Area
Solar, wind
Δ Water availability
Water
Livestock production
Agriculture
Biofuel/biomass
Energy
Energy use
Δ crop patterns
Δ yields
Δ production
Food
Residues
Energy use
CAPRI
E3ME
Energy production in HPPs

(b)


Water
precipitation
Climate
precipitation
Available water
Groundwater
Surface water
Water use
Municipalities
Industry
Agriculture
Energy production in HPP
Final energy consumption
Primary energy
Water quality
Land
land erosion
nutrient leakage
Agriculture
Crop production, Live stock
Manure management, fertilizers, pesticides
Forestry
Fertilizers

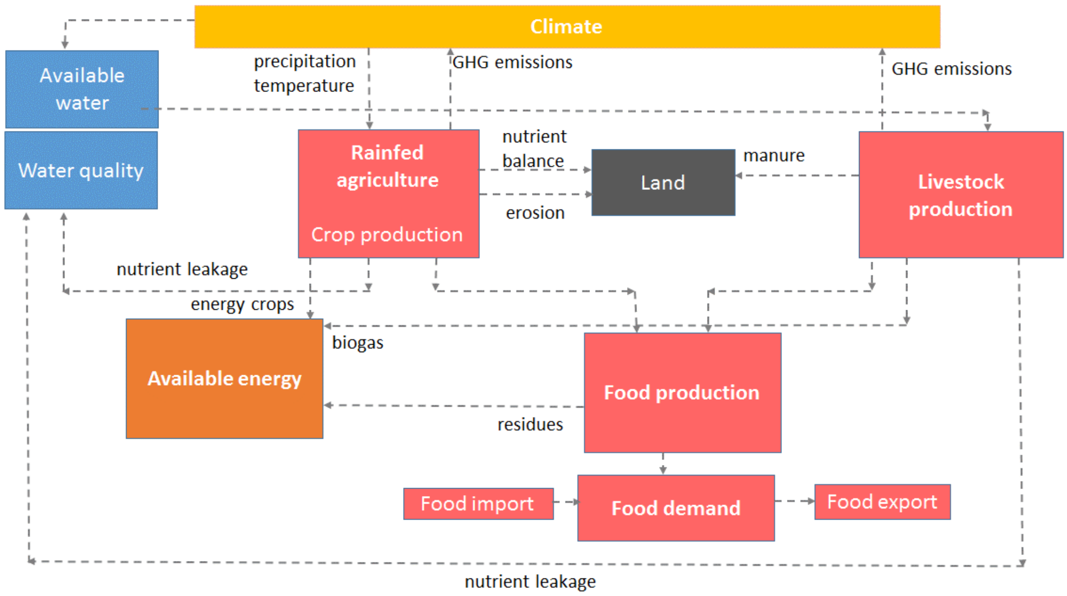
(c)

Land

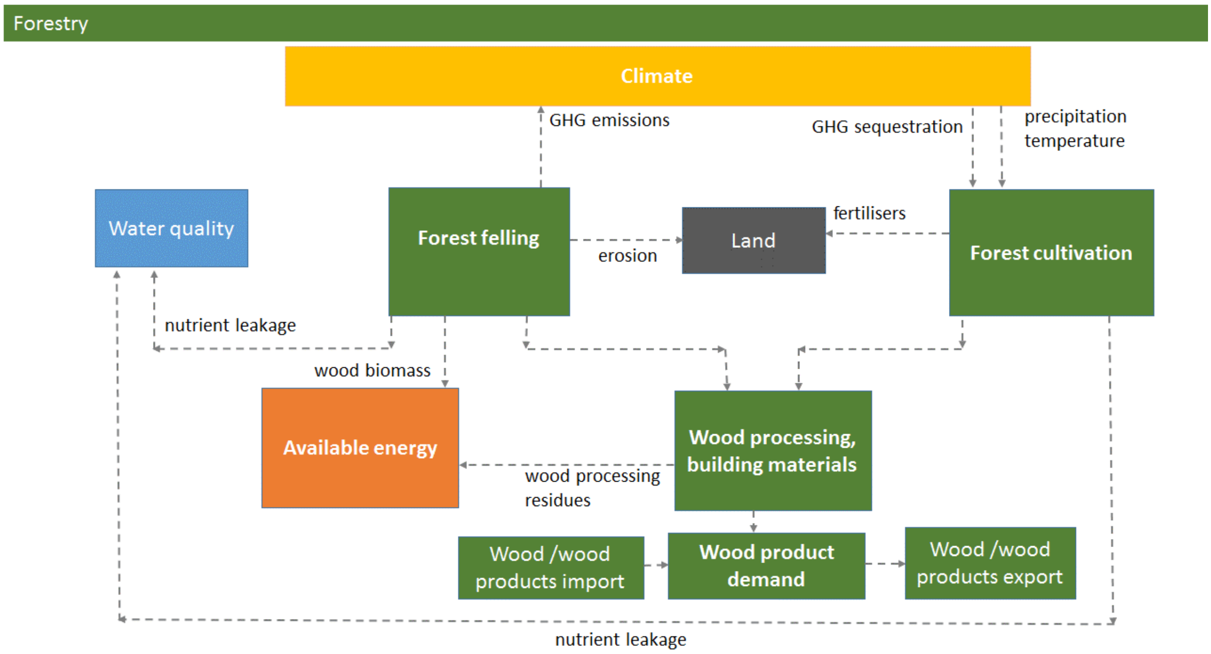

Climate
GHG balance
Precipitation, erosion
Agriculture (arable land, grassland, pastures)
Available food
Residues
Runoff (leakage)
Energy crops
Water quality
Wood processing Building materials
Forests (forestland)
Wood biomass
Residues
Other
Solar installations
Wind power
Urban (settlements)
Protected areas, etc
Available energy

(d)

Food


Climate
Available water
precipitation temperature
GHG emissions
GHG emissions
Water quality
Rainfed agriculture
Crop production
nutrient balance
erosion
Land
manure
Livestock production
nutrient leakage
energy crops
biogas
Available energy
Food production
residues
Food import
Food demand
Food export
nutrient leakage

(e)



(f)

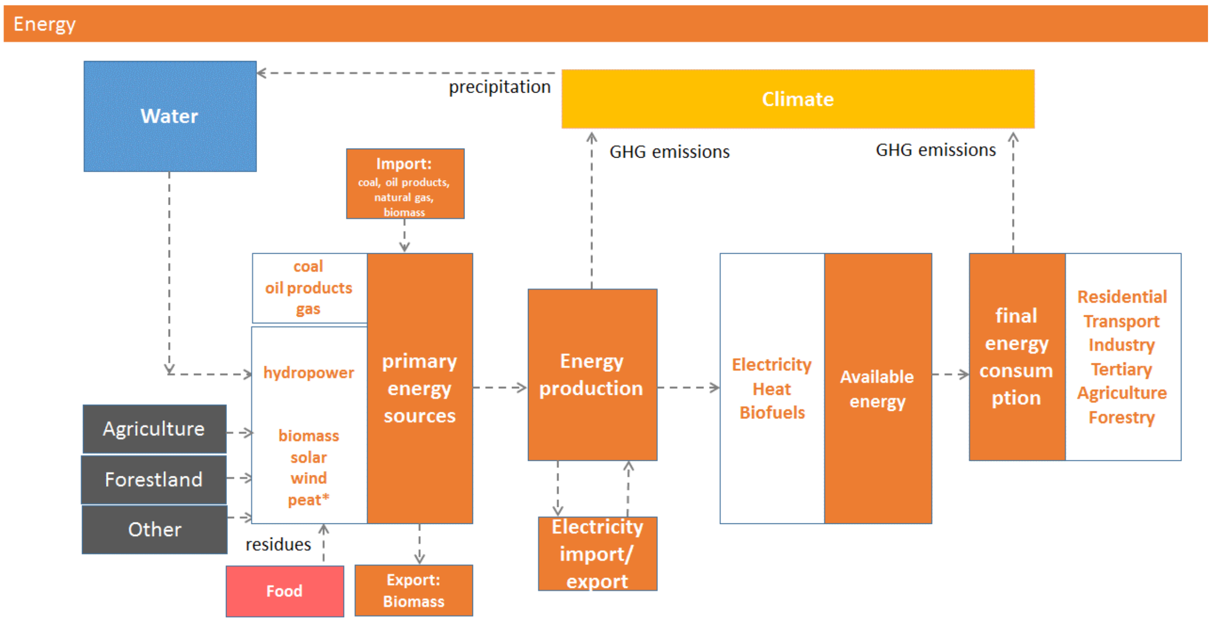


Figure 3.5.3: The final conceptual model for the Latvian case showing (a) the top level schematic indicating the links between all nexus components and then details for (b) the water sector, (c) the land sector, (d) the food sector, (e) the forestry sector, and (f) the energy sector.

Figure 3.5.3e shows the details for the forestry sector, an important feature unique to the Latvian and Swedish case studies. Important here is the emphasis on tree felling and cultivation, and the relationship to wood processing, building materials and of course to the energy sector via the production of wood biomass and residual products. Also to highlight in this section is the link to the climate sector, which influences forest growth via precipitation and temperature, and which itself is influenced by GHG emissions and particularly sequestration by the growth of forests. Finally, Figure 3.5.3f details the energy sector, which models processes from primary energy sources and composition from many different means, to energy production (electricity, heat) and through to final energy consumption by numerous sectors. In this way, the climate impact of both energy generation and consumption can be attributed, and the changes in emissions as a result of a switch to renewables can be assessed. More than this however, the impacts for example to local food production can also be assessed by comparing how much agricultural land may be lost as a result of conversion to energy crops, offering a true nexus analysis for Latvian low carbon energy policies.

3.5.3 Description of the developed system dynamics model

Figure 3.5.4 shows the top-level SDM for the Latvia case. This corresponds to Figure 3.5.3a, and shows the high-level connections between all the five main nexus sectors. Within each rounded box in Figure 3.5.4, the nexus sectors have been developed in considerable detail, and is described below.

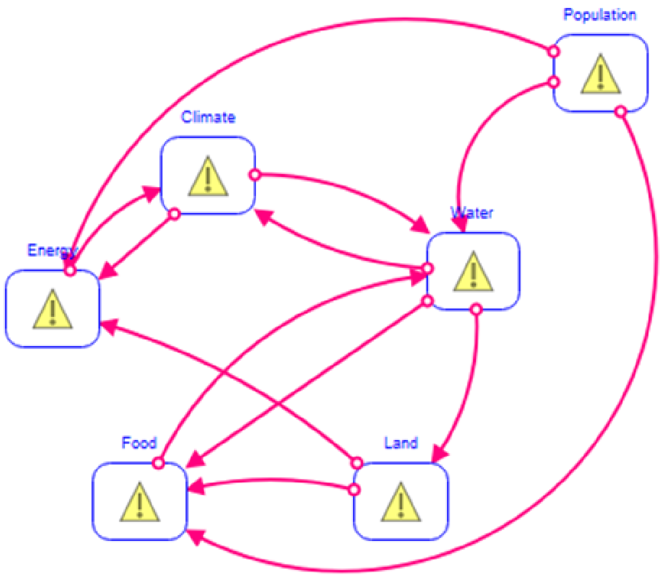


Figure 3.5.4: Top-level of the Latvian SDM, showing the high-level nexus connections.

In all subsequent sub-model descriptions, the model structure is identical for all the six regions in Latvia, though the data vary in each. The population sub-model simply contains a variable tracking population change over time. The water sector (Figure 3.5.5) is relatively simple, reflecting the less importance of water in this case study.

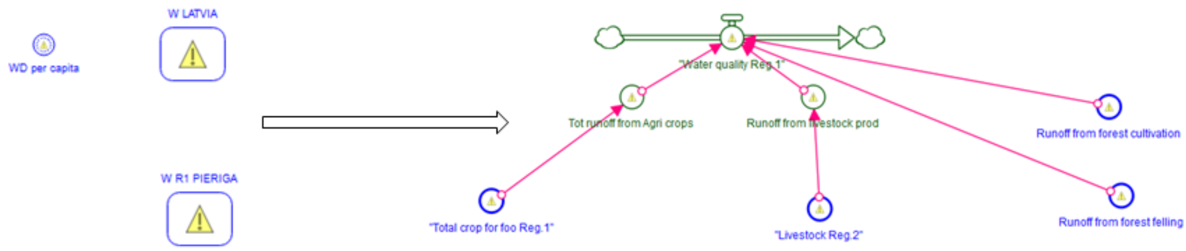
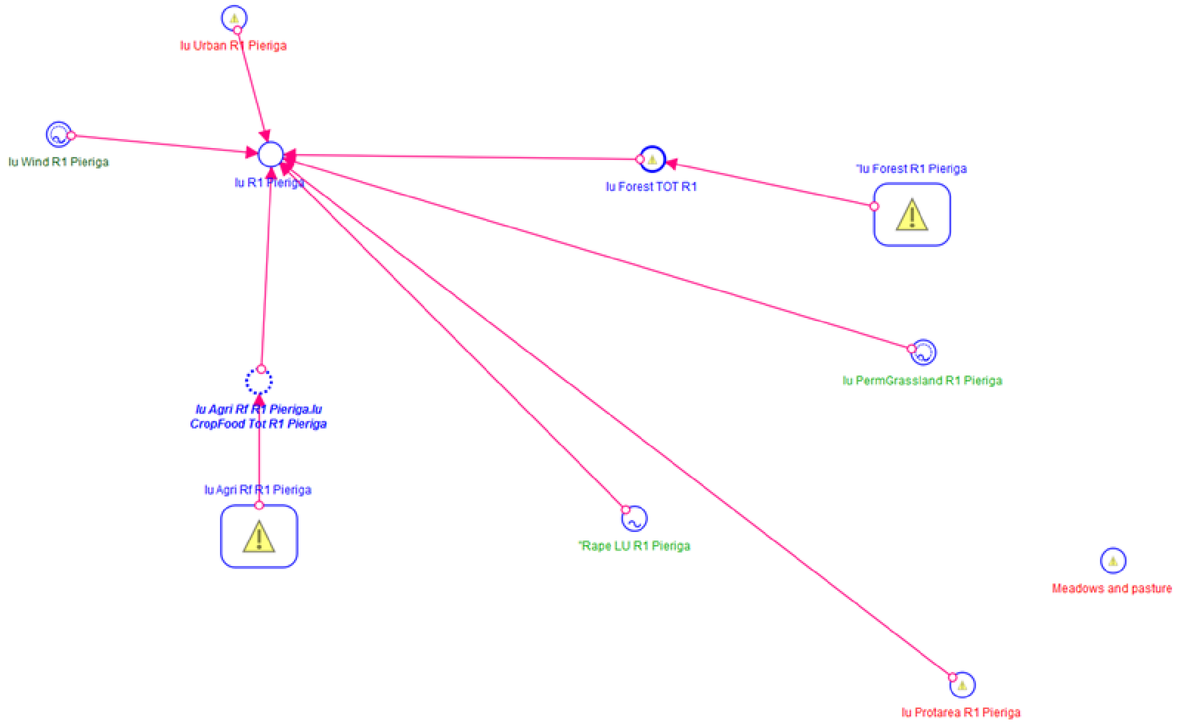


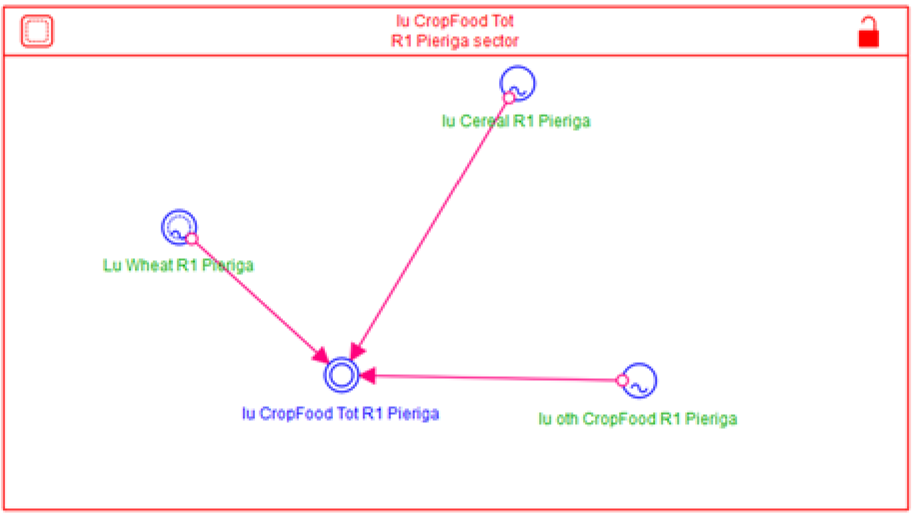
Figure 3.5.5: Details of the water sub-model of the Latvia case study.

Indeed, in water only water quality parameters are tracked, with runoff from livestock, crops and forests affecting water quality. In terms of land, this sector is defined in much more detail (Figure 3.5.6).

(a)


lu Urban R1 Pieriga
lu Wind R1 Pieriga
lu R1 Pieriga
lu Forest TOT R1
'lu Forest R1 Pieriga
lu PermGrassland R1 Pieriga
lu Agri Rf R1 Pieriga.lu CropFood Tot R1 Pieriga
lu Agri Rf R1 Pieriga
'Rape LU R1 Pieriga
Meadows and pasture
lu Protarea R1 Pieriga

(b)


lu CropFood Tot R1 Pieriga sector
lu Cereal R1 Pieriga
Lu Wheat R1 Pieriga
lu CropFood Tot R1 Pieriga
lu oth CropFood R1 Pieriga

(c)

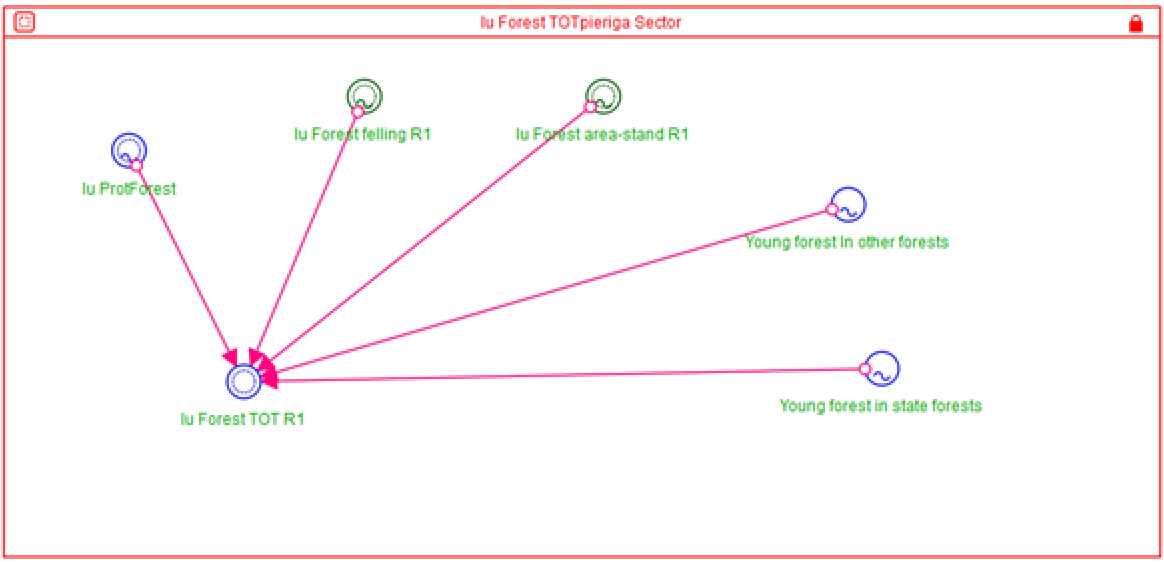
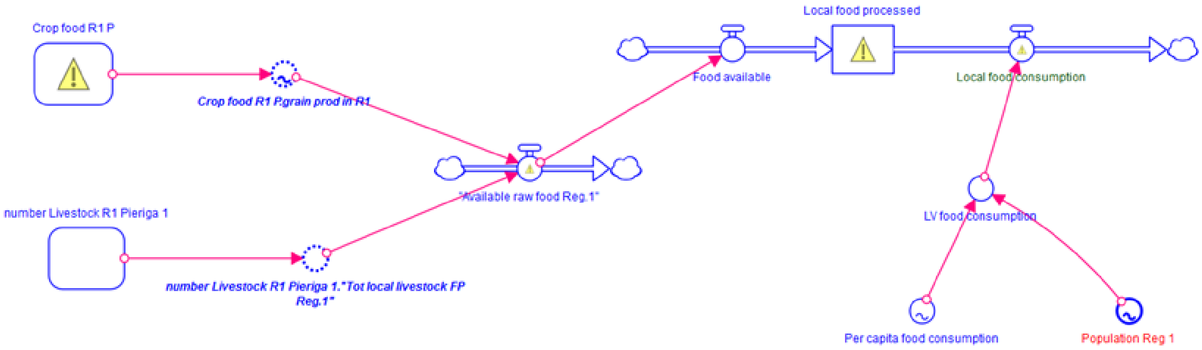


Figure 3.5.6: (a) the top level in the land sub-model; (b) the crop food specific model and; (c) the forestry sector specific model. See text for details.

Figure 3.5.6a shows the main land sector sub-model. Urban land use, wind power installations, grassland, protected areas and the area planted with rape crops are specifically included. Food crops and forest areas have their own separate sub-models, shown as rounded boxes in Figure 3.5.6a, and shown in detail in Figure 3.5.6b and c respectively. For food crops (Figure 3.5.6b), wheat, cereal and other crop areas are included, whereas in the forestry model (Figure 3.5.6c) the areas of protected forest, forests actively being felled, standing forests (outside protected areas), and young forests (due for cultivation and felling) are all defined. Figure 3.5.7 details the food sector sub model.

(a)



(b)

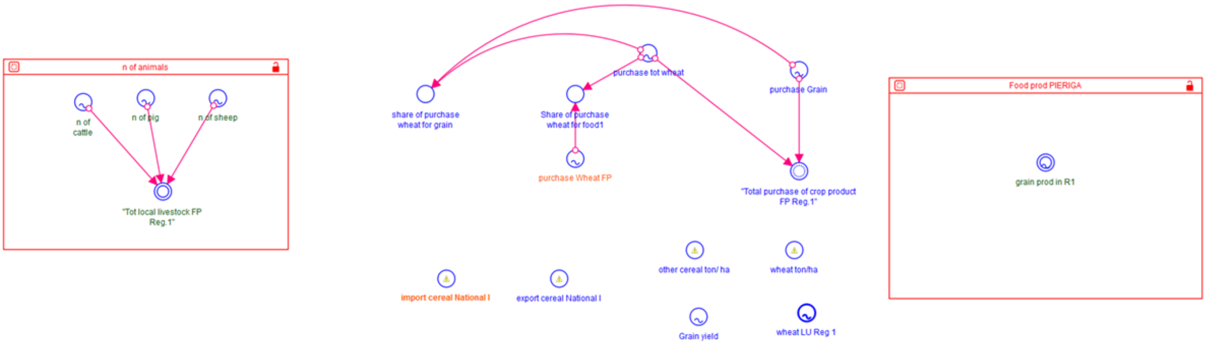
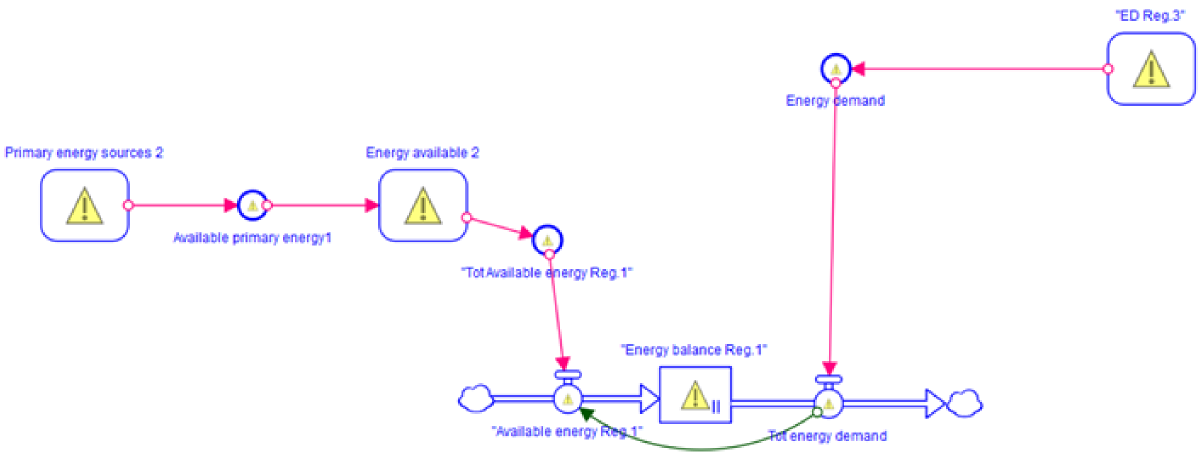


Figure 3.5.7: showing (a) the top level food sub-model and (b) the livestock and crop production models.

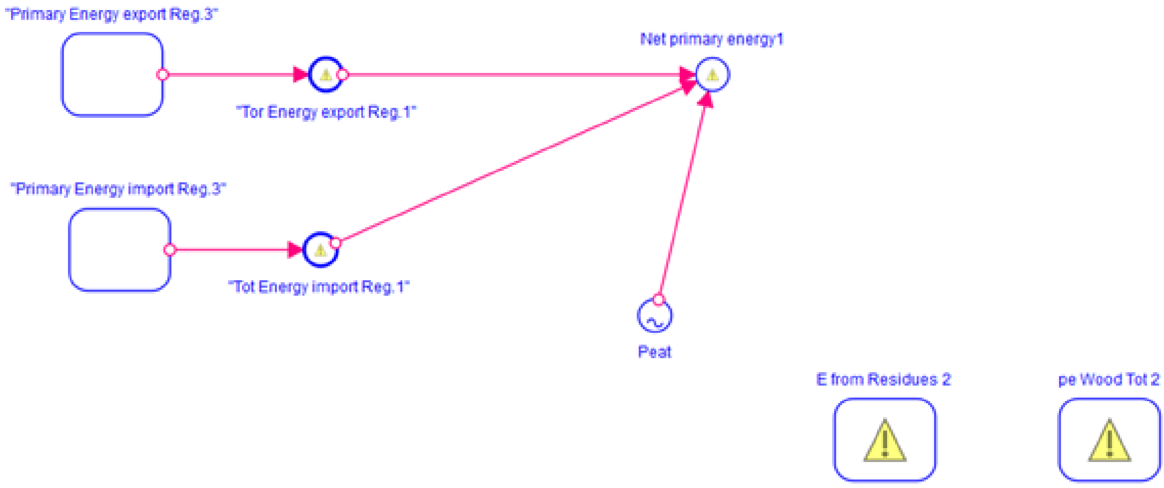
The top-level of the food sub-model (Figure 3.5.7a) shows that production is divided into crops and livestock, each with their own sub-model (Figure 3.5.7b). These sectors' production is summed to give total food production in each region in Latvia. Each region is subsequently summed to give Latvian food production. Food consumption is driven by the population and food consumption per capita. With the livestock model (Figure 3.5.7b), pigs, cattle and sheep are specified, while the crop production model is more detailed. For crop production, imports and exports are accounted for. The yields of wheat, grains and other crops are defined, and when multiplied by areas, give values of production (in kg). Certain proportions of wheat and grain are purchased for food, while the rest is purchased for non-food uses (e.g. for cattle feed). These proportions are captured in the model, with data coming from Latvian statistics. Therefore, in the top-level model (Figure 3.5.7a), the net food production (accounting for imports and exports, and also for the crops not used for food) is captured and fed forward to yield food availability within Latvia. The amount of crop production has impacts on water quality, as shown in Figure 3.5.5.

The Latvian energy sector sub model is comprehensively developed (Figure 3.5.8). The top level of the model (Figure 3.5.8a) shows primary energy and it's conversion into secondary (available) energy. There is also energy demand from many sectors. As in previous figures, rounded boxes indicate further sub-models, which are now described.

(a)

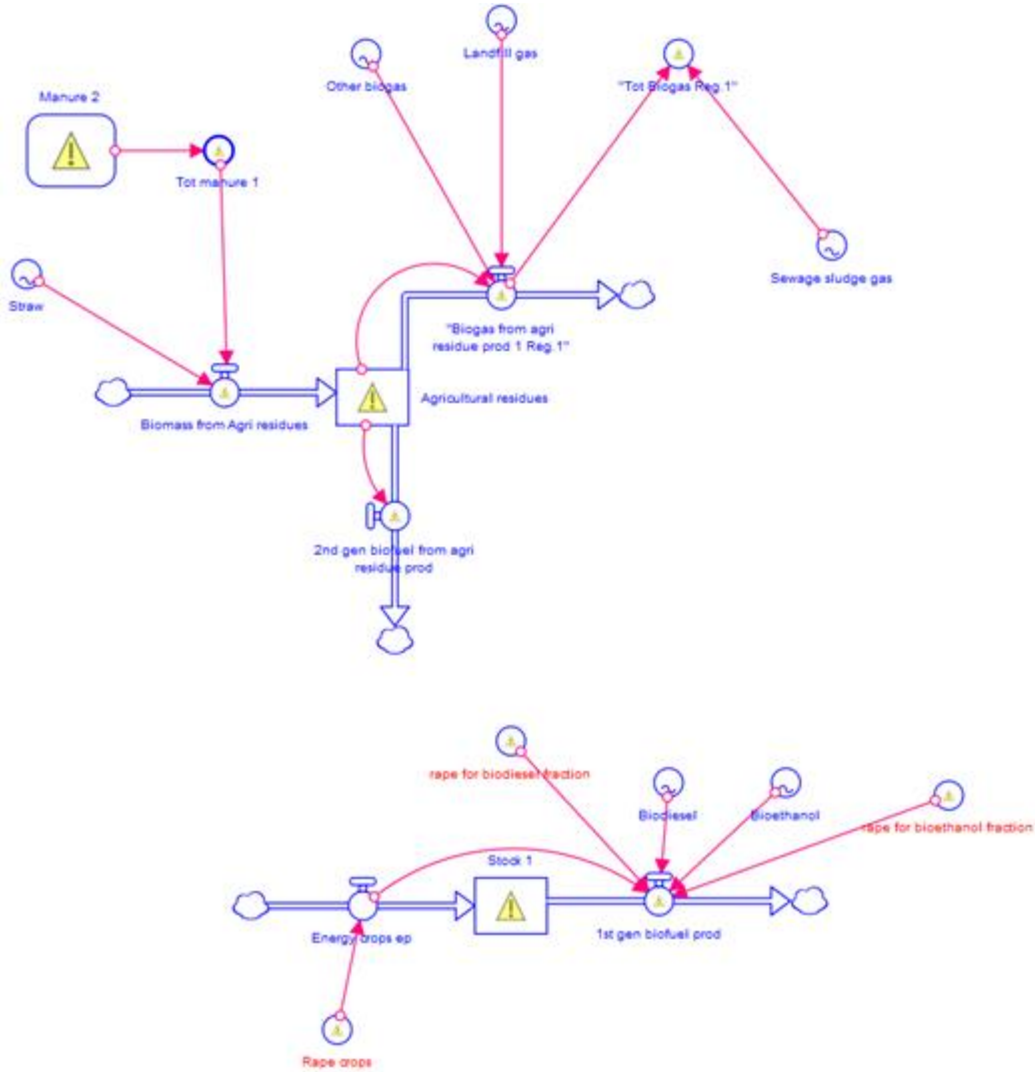


(b)



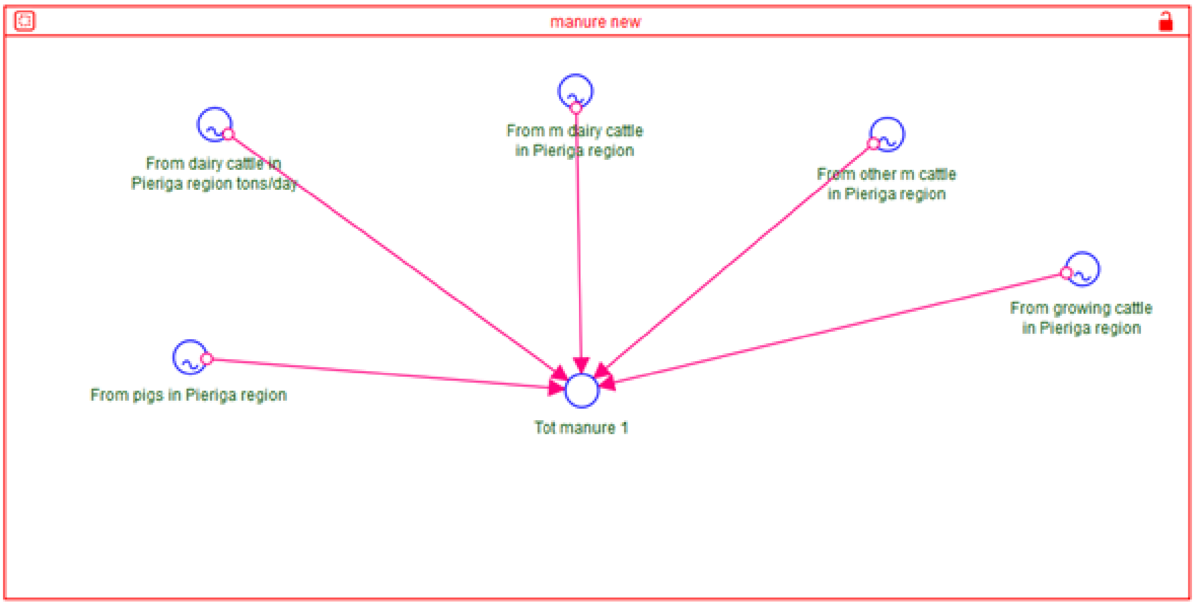
"Primary Energy export Reg.3"
"Tor Energy export Reg.1"
Net primary energy1
"Primary Energy import Reg.3"
"Tot Energy import Reg.1"
Peat
E from Residues 2
pe Wood Tot 2

(c)



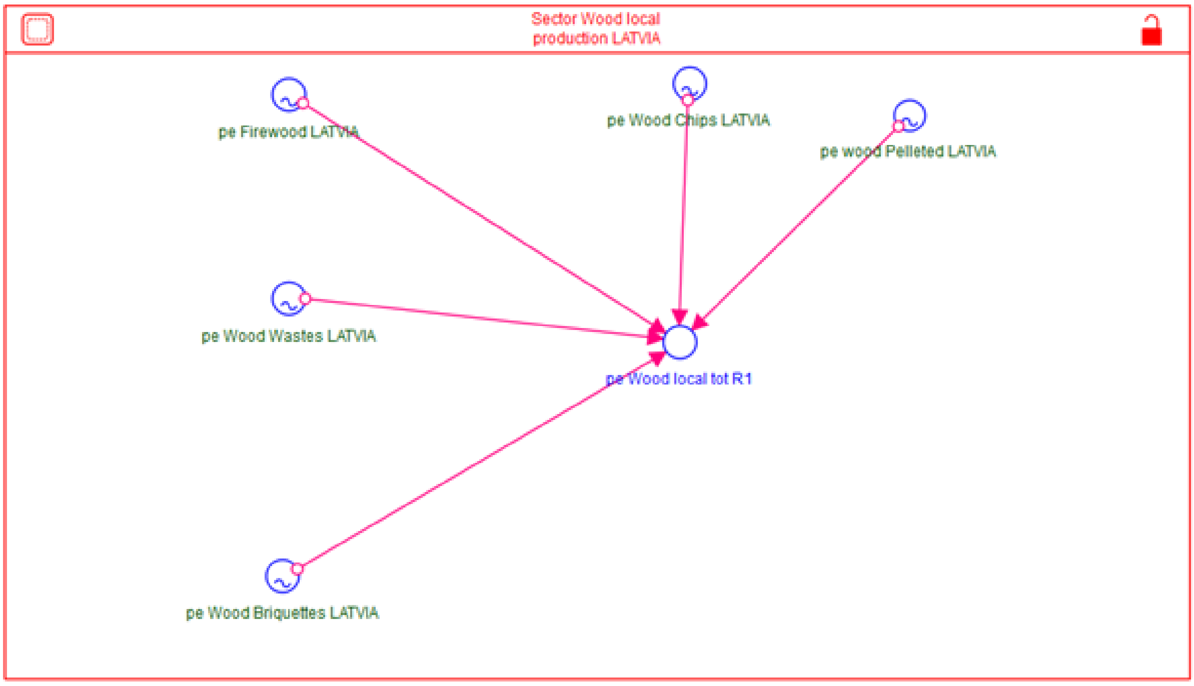
Manure 2
Tot manure 1
Other biogas
Landfill gas
"Tot Biogas Reg.1"
Sewage sludge gas
Straw
"Biogas from agri residue prod 1 Reg.1"
Agricultural residues
Biomass from Agri residues
2nd gen biofuel from agri residue prod
rape for biodiesel fraction
Biodiesel
Bioethanol
rape for bioethanol fraction
Stock 1
Energy crops ep
1st gen biofuel prod
Rape crops

(d)



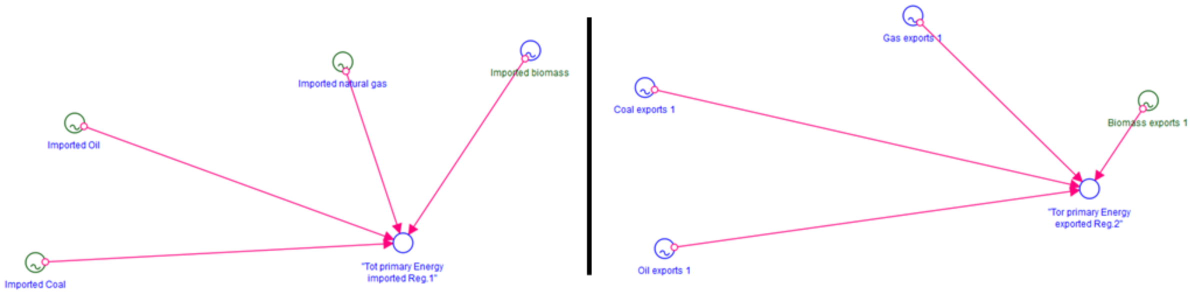
manure new
From dairy cattle in Pieriga region tons/day
From m dairy cattle in Pieriga region
From other m cattle in Pieriga region
From growing cattle in Pieriga region
From pigs in Pieriga region
Tot manure 1

(e)



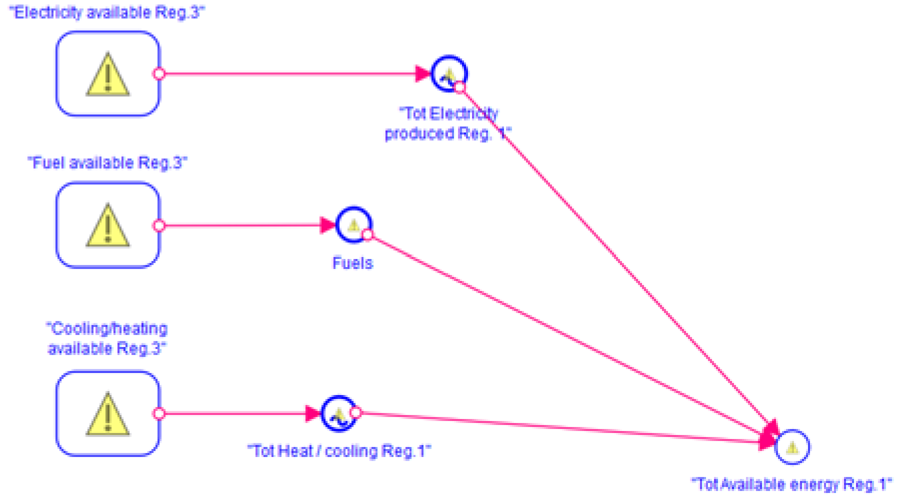
Sector Wood local production LATVIA
pe Firewood LATVIA
pe Wood Chips LATVIA
pe wood Pelleted LATVIA
pe Wood Wastes LATVIA
pe Wood local tot R1
pe Wood Briquettes LATVIA

(f)

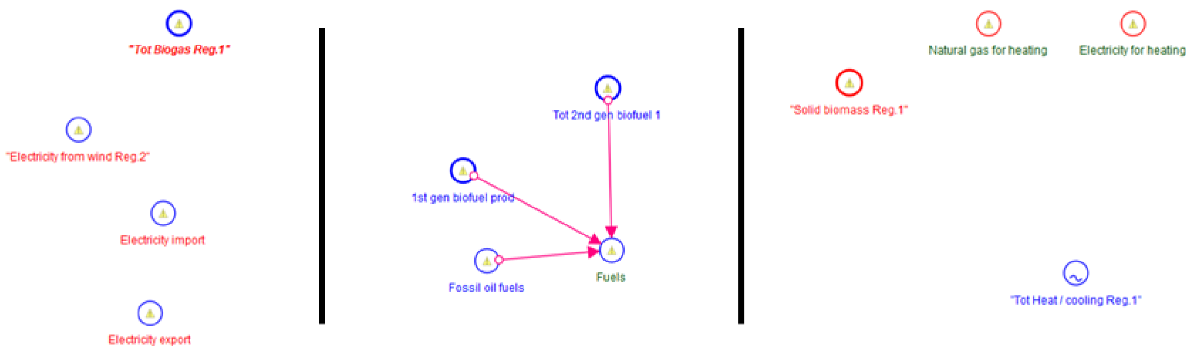


Imported natural gas
Imported biomass
Imported Oil
Imported Coal
"Tot primary Energy imported Reg.1"
Gas exports 1
Coal exports 1
Biomass exports 1
"Tor primary Energy exported Reg.2"
Oil exports 1

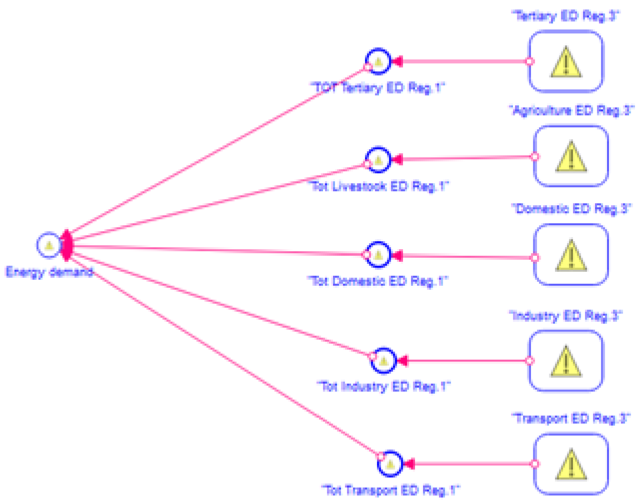
(g)


"Electricity available Reg.3"
"Tot Electricity produced Reg. 1"
"Fuel available Reg.3"
Fuels
"Cooling/heating available Reg.3"
"Tot Heat / cooling Reg.1"
"Tot Available energy Reg.1"

(h)


"Tot Biogas Reg.1"
"Electricity from wind Reg.2"
Electricity import
Electricity export
Tot 2nd gen biofuel 1
1st gen biofuel prod
Fossil oil fuels
Fuels
Natural gas for heating
Electricity for heating
"Solid biomass Reg.1"
"Tot Heat / cooling Reg.1"

(i)


"Tertiary ED Reg.3"
"TOT Tertiary ED Reg.1"
"Agriculture ED Reg.3"
"Tot Livestock ED Reg.1"
"Domestic ED Reg.3"
Energy demand
"Tot Domestic ED Reg.1"
"Industry ED Reg.3"
"Tot Industry ED Reg.1"
"Transport ED Reg.3"
"Tot Transport ED Reg.1"

(j)

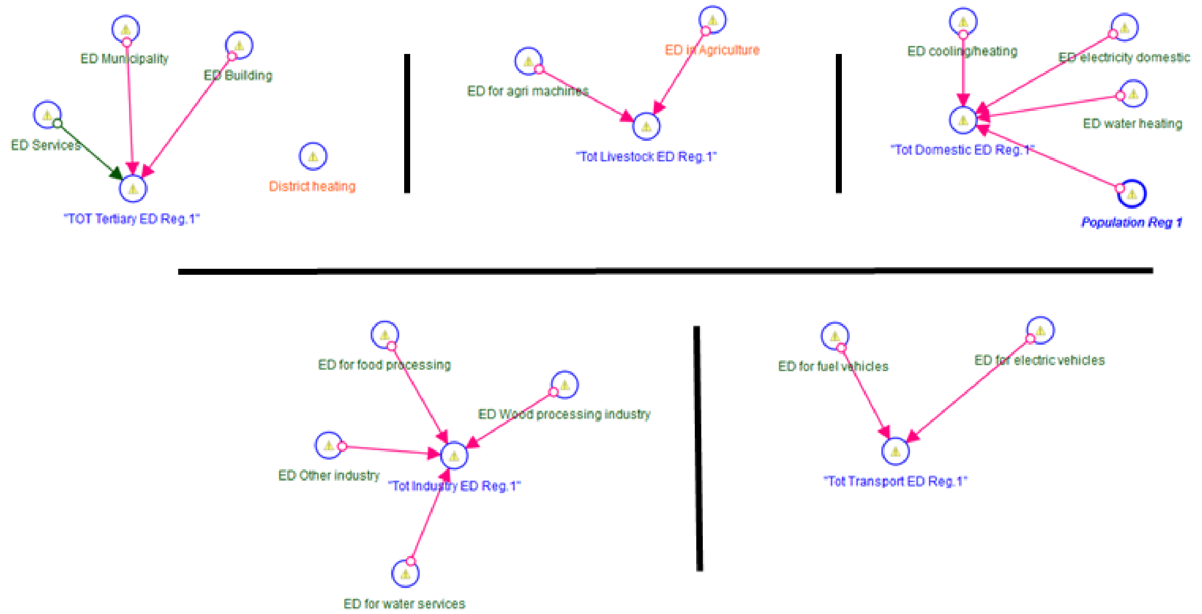
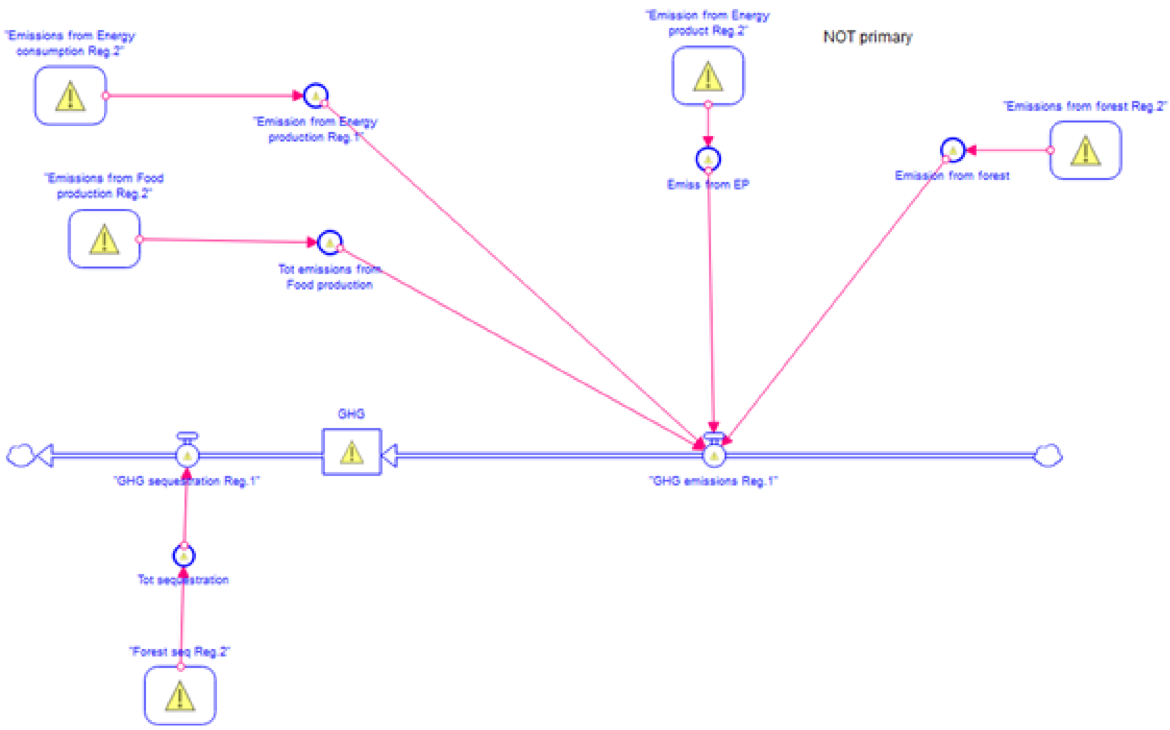


Figure 3.5.8: the energy sub-model for Latvia, showing: (a) the top-level of the energy model; (b) the primary energy source sub-model; (c) the primary energy from biomass residues sub-model and with that, (d) the manure primary energy source model; (e) the local wood production for primary energy sub-model; (f) the sub model for primary energy imports (left) and exports (right); (g) the available energy sub-model divided into electricity, fuels and thermal energy (h, left, middle and right, respectively); (i) the sub model quantifying final energy demand, split into the tertiary, livestock, domestic, industrial and transport sectors (j, top left, middle and right, bottom left and right, respectively).

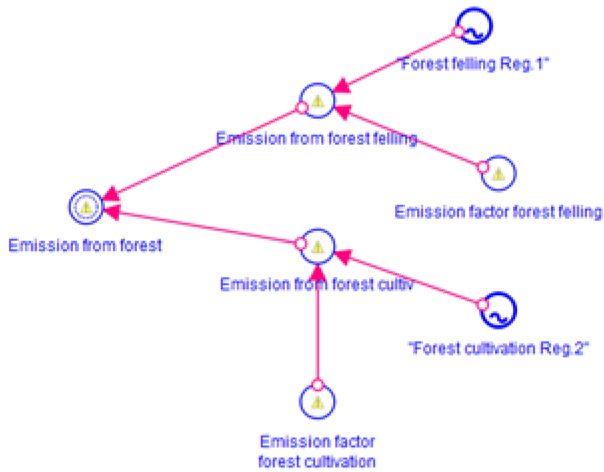
Primary energy sources (Figure 3.5.8b) are divided into agricultural residues, wood biomass, and imports and exports (Figures 3.5.8c – f). Agricultural residues (Figure 3.5.8c) specifies many sources including animal manure (with its own sub-model in Figure 3.5.8d, and detailed manure from pigs, dairy cattle and other cattle), straw, and rape. Products from these sources include: biogas (including from landfill and sewage sludge), first, and second generation biofuels. Woody primary energy sources (Figure 3.5.8e) include wood briquettes, firewood, wood chips and wood pellets, with data coming from national statistics. Imports and exports (Figure 3.5.8f left and right respectively) account for coal, oil, natural gas and biomass/gas. The primary energy sources are converted in secondary (available) energy for consumption (Figure 3.5.8g), which here is split in electricity, fuels and heating (Figure 3.5.8h, left, middle and right respectively). As the sources of each secondary type are attributed, the climate impact of energy production as a result of changes to the energy mix can be estimated. Finally, five energy demanding sectors are identified (Figure 3.5.8i),each of which has its own sub-model for calculation: tertiary sector, livestock, domestic demand, industrial demand and transport (Figure 3.5.8j, top left, middle right, bottom left, right, respectively). Therefore, energy demand in Latvia per-sector, when coupled to the energy type consumed, can have a climate impact attributed to it, and the changes thereof as energy mixes change.

The final sector in the Latvian model is the climate sector (Figure 3.5.9). The top-level model for the climate sector (Figure 3.5.9a) shows a greenhouse gas (GHG) balance, with emissions from a number of sectors and sequestration from forested lands. Each of the sectors has a separately developed sub-model.

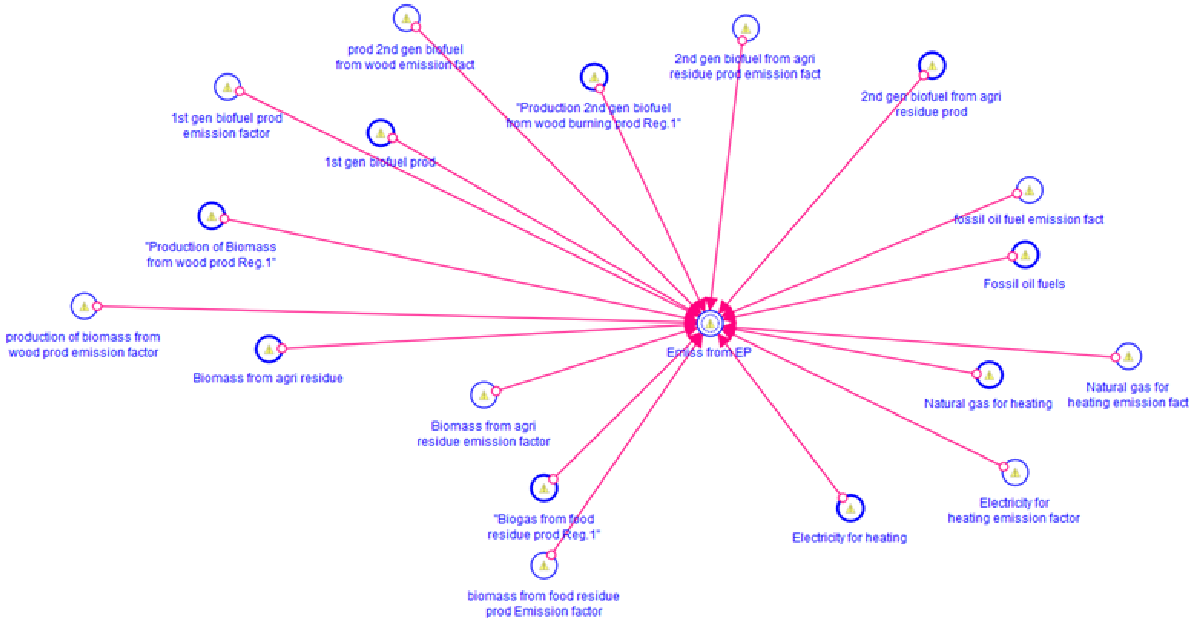
(a)


"Emissions from Energy consumption Reg.2"
"Emission from Energy production Reg.1"
"Emissions from Food production Reg.2"
Tot emissions from Food production
"Emission from Energy product Reg.2"
Emiss from EP
NOT primary
"Emissions from forest Reg.2"
Emission from forest
GHG
"GHG sequestration Reg.1"
"GHG emissions Reg.1"
Tot sequestration
"Forest seq Reg.2"

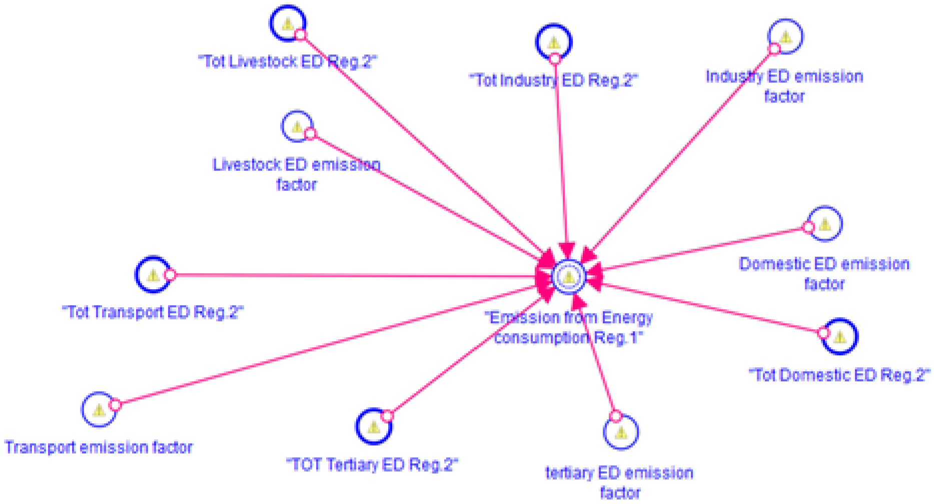
(b)


"Forest fellling Reg.1"
Emission from forest felling
Emission factor forest felling
Emission from forest
Emission from forest cultiv
"Forest cultivation Reg.2"
Emission factor
forest cultivation

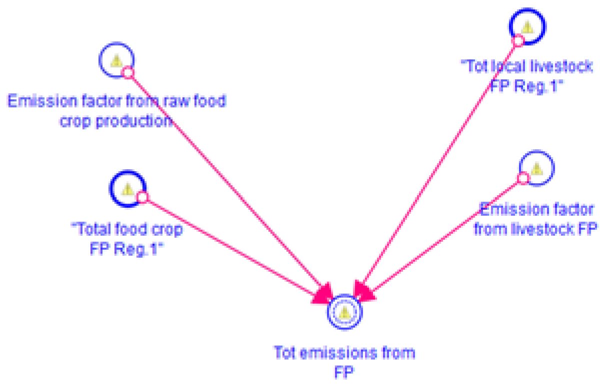
(c)


prod 2nd gen biofuel from wood emission fact
2nd gen biofuel from agri residue prod emission fact
"Production 2nd gen biofuel from wood burning prod Reg.1"
2nd gen biofuel from agri residue prod
1st gen biofuel prod emission factor
1st gen biofuel prod
"Production of Biomass from wood prod Reg.1"
fossil oil fuel emission fact
Fossil oil fuels
production of biomass from wood prod emission factor
Biomass from agri residue
Emiss from EP
Natural gas for heating
Natural gas for heating emission fact
Biomass from agri residue emission factor
"Biogas from food residue prod Reg.1"
biomass from food residue prod Emission factor
Electricity for heating
Electricity for heating emission factor

(d)


"Tot Livestock ED Reg.2"
"Tot Industry ED Reg.2"
Industry ED emission factor
Livestock ED emission factor
"Tot Transport ED Reg.2"
Domestic ED emission factor
"Emission from Energy consumption Reg.1"
"Tot Domestic ED Reg.2"
Transport emission factor
"TOT Tertiary ED Reg.2"
tertiary ED emission factor

(e)


Emission factor from raw food crop production
"Tot local livestock FP Reg.1"
"Total food crop FP Reg.1"
Emission factor from livestock FP
Tot emissions from FP

(f)

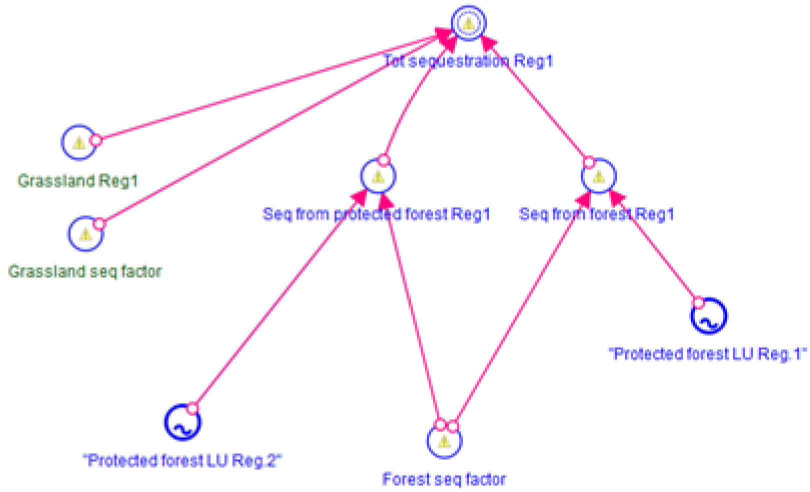


Figure 3.5.9: the climate sector sub model for the Latvia case study showing: (a) the top-level of the sub-model, showing emissions (and the main sources) and sequestration) and further sub-models for; (b) emissions from forest felling; (c) emissions from energy production; (d) emissions from energy consumption; (e) emissions from food production and; (f) sequestration of GHGs.

Figure 3.5.9b shows the sub-model for emissions from the forestry sector. Such emissions come from felling and cultivation activities. In the energy production sector (Figure 3.5.9c), emissions derive from: biomass from food and agricultural residues, biomass from wood products, the production of 1st and 2nd generation biofuels, fossil oils, natural gas and electricity production (the composition of which, and therefore the climate change potential, will change as the electricity energy source mix changes). Emissions from energy consumption (Figure 3.5.9d) emanate from the industrial, domestic, tertiary, livestock and transport sectors. Emissions here relate to final energy consumption. Emissions from crop and livestock production are also quantified (Figure 3.5.9e). Finally, the sequestration potential of forest lands (Figure 3.5.9f) is modelled, such that the impacts of land use change on net GHG emissions can be assessed.

3.6 Sweden case study

3.6.1 Short description of the case study

Sweden is a country in northern Europe (Figure 3.6.1) bordered by Norway in the west, the North Sea in the southwest, the Baltic Sea in the east and Finland in the northeast.

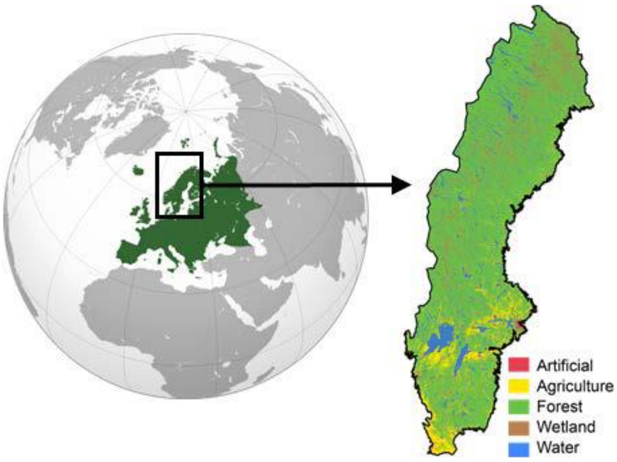


Figure 3.6.1: Map of the Sweden SIM4NEXUS case study

Sweden currently has two major initiatives of interest relating to these nexus sectors: (1) "The Generation Goal" and (2) "The Environmental Objectives" (Swedish Environmental Protection Agency, 2017). The generation goal – the overall goal of Swedish environmental policy – defines the direction of the changes in society that need to occur within one generation if the country's environmental quality objectives are to be achieved. One of its targets is to increase the share of renewable energy and use energy efficiently with minimal impact on the environment. This goal is already achieved (Swedish Environmental Protection Agency, 2017), because Sweden managed to reach its goal of a 50 per cent renewable energy share several years ahead of the Swedish government's 2020 schedule, in 2012. Swedish bioenergy use has grown from 40 TWh/year in 1970 to around 140 TWh in 2012 (Andersson, 2012). Bioenergy use was the leading factor in Sweden's 9% decrease in greenhouse gases between 1990 and 2010, while gross national product increased by 50 percent. According to Andersson (2012), bioenergy's success also rests on the long-standing tradition of using natural forest resources while also protecting and developing them. Sweden's total forest stock has increased each year despite the rapid expansion in biomass use for energy.

The sixteen environmental quality objectives describe the state of the Swedish environment which environmental action is to result in. These objectives are to be met within one generation, i.e. by 2020 (2050 in the case of the climate objective). Objectives related to the forest and water sectors include:

- Reduced Climate Impacts (to be met by 2050)
- Flourishing Lakes and Streams (to be met by 2020)
- Good-Quality Groundwater (to be met by 2020)
- Sustainable Forests (to be met by 2020)

According to present forecasts (Swedish Environmental Protection Agency, 2017), these environmental objectives will not be met in time. In fact, the objectives of reducing climate impacts even shows a negative trend in the state of the environment, because greenhouse gas emissions are still rising. This shows that the current environmental initiatives are not sufficient to achieve society's agreed environmental objectives for water and forests. For example, the growing demand for bioenergy has led to an intensification of the forest industry through extensions of managed forest land, introduction of fast-growing tree species, increasing use of fertilization and increasing felling rates. The effects of such new management strategies for increased biomass production on forest species, soil resources and water quality at landscape scales are, however, not well understood and not addressed adequately. These issues will be addressed by the Swedish national case study focusing on a time frame until 2050. Together with stakeholders, the question as to whether the goal of becoming a fossil-free nation interferes with some of the national environmental objectives will be discussed.

3.6.2 Evolution and description of the conceptual diagram

The Swedish conceptual diagram started at a very early stage in the project, and started relatively simply, gradually increasing in complexity and detail until a final satisfactory version was arrived at. The first version of the Swedish conceptual model is shown in Figure 3.6.2. As shown in Figure 3.6.2, the model represents a ‘high-level’ overview of the main nexus connections in the Swedish case.

Land and energy feature prominently, together with their respective links to the climate sector, consistent with the focus of the case study described above, namely achieving targets such as greenhouse gas emission reductions, and an increased reliance on energy produced from biomass originating from the forestry sector (forests are explicitly mentioned in the LAND box in Figure 3.6.2). Indeed, in the ENERGY box in Figure 3.6.2, biomass is listed as a primary energy source (and linked to the land sector), and biofuels are mentioned as energy carriers. The emphasis on water and food is weak in this version.

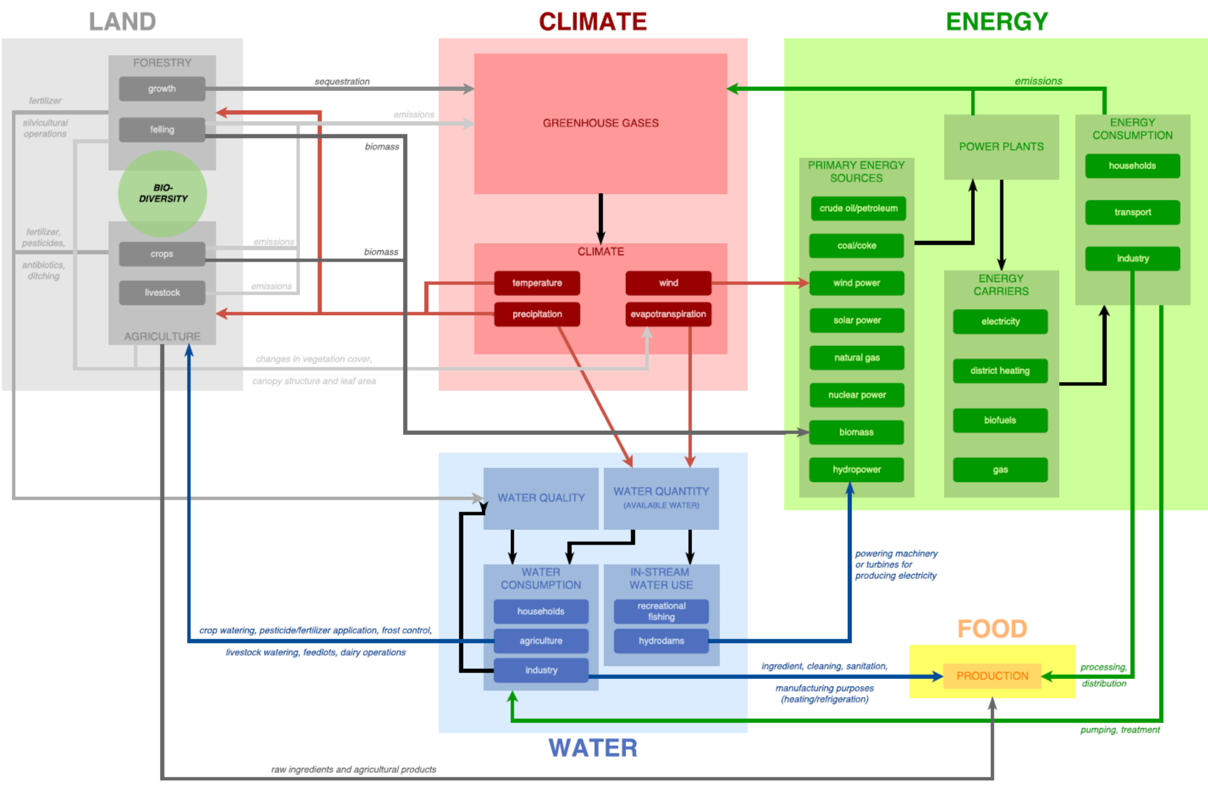


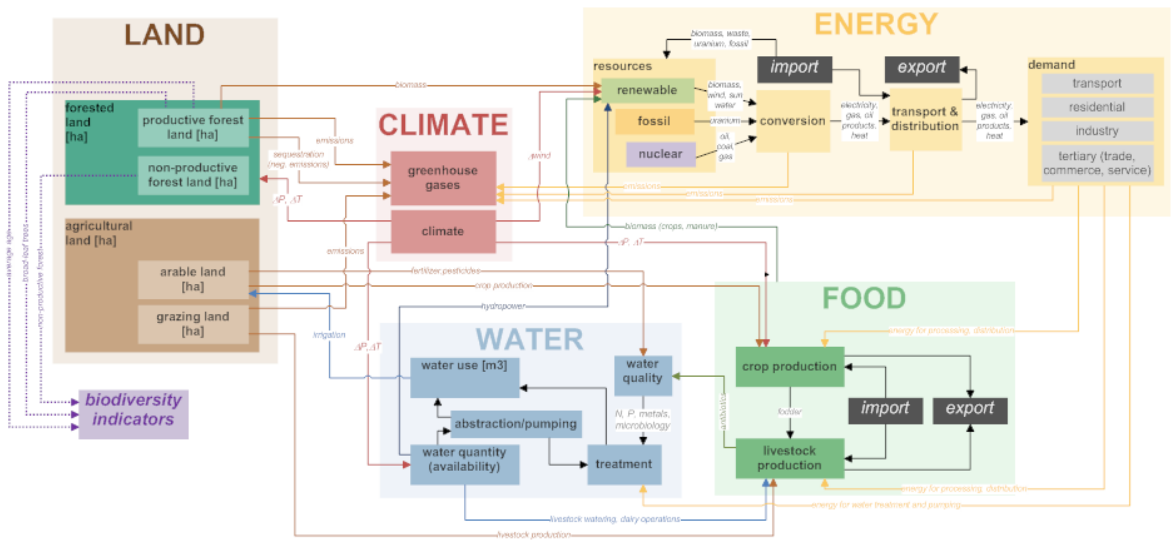
Figure 3.6.2: First version of the Swedish conceptual diagram.

Gradual iterations refined that in Figure 3.6.2, adding complexity and detail. Ultimately, the final developed conceptual model consists of a high-level overview (Figure 3.6.3.a), followed by a detailed conceptual for each nexus sector, with the links to other sectors made even more explicit (Figure 3.6.3b-f). As with Figure 3.6.2, the emphasis is still clearly on the land (agriculture and forestry) and energy sectors, with their link to climate (Figure 3.6.3a), but now the links to other nexus sectors are more clearly highlighted, including some of the processes that define these interactions. In Figure 3.6.3a, all the main sectors (e.g. 'water', 'energy'), were subsequently developed in more detail. The subsequent SDM model accounts for all these interactions, offering consistent nexus-wide analysis. The detailed sub-sector conceptual diagrams are illustrated in Figures 3.6.3b-f.

Figure 3.6.3b deals with the land sector, which is elaborated in some considerable detail, and especially important to note is the split by agriculture and forestry, which themselves have considerable detail. In forestry, different tree species are indicated in order to assess forest biodiversity (which is defined by having its own indictor definitions), while in agriculture, a wide variety of crop types are considered. The links to the other nexus sectors are also indicated, including their mechanisms (e.g. irrigation as a water demand, carbon sequestration as a positive climate impact, forest products for energy generation). Figure 3.6.3c shows the details for the food sector. The focus here is on crop and livestock production, which are both elaborated in some detail. Import and exports are noted. The link to the other nexus sectors are indicated (e.g. to energy from biomass input, water demand for livestock rearing, as a demand on land use). Figure 3.6.3d shows the climate sector, which is relatively simply represented. Emissions to the climate system come from the other four nexus sectors, while the land sector in particular contributes negative emissions via sequestration of GHGs.

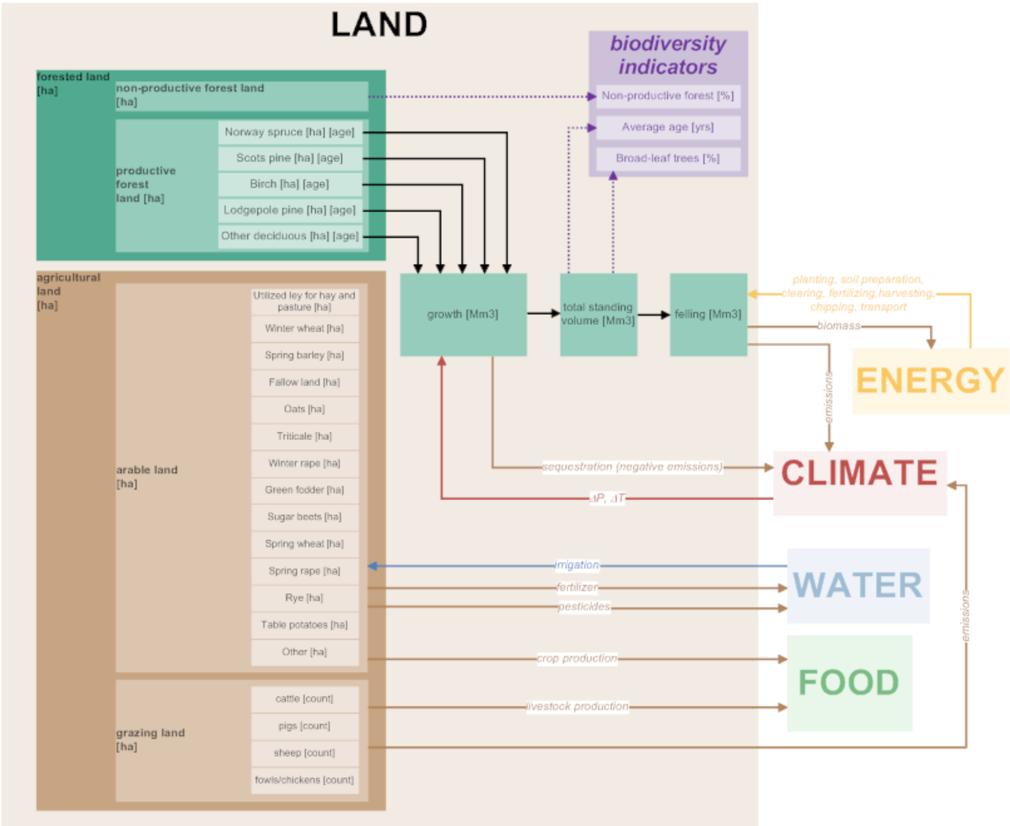
(a)

CONCEPTUAL FRAMEWORK



(b)

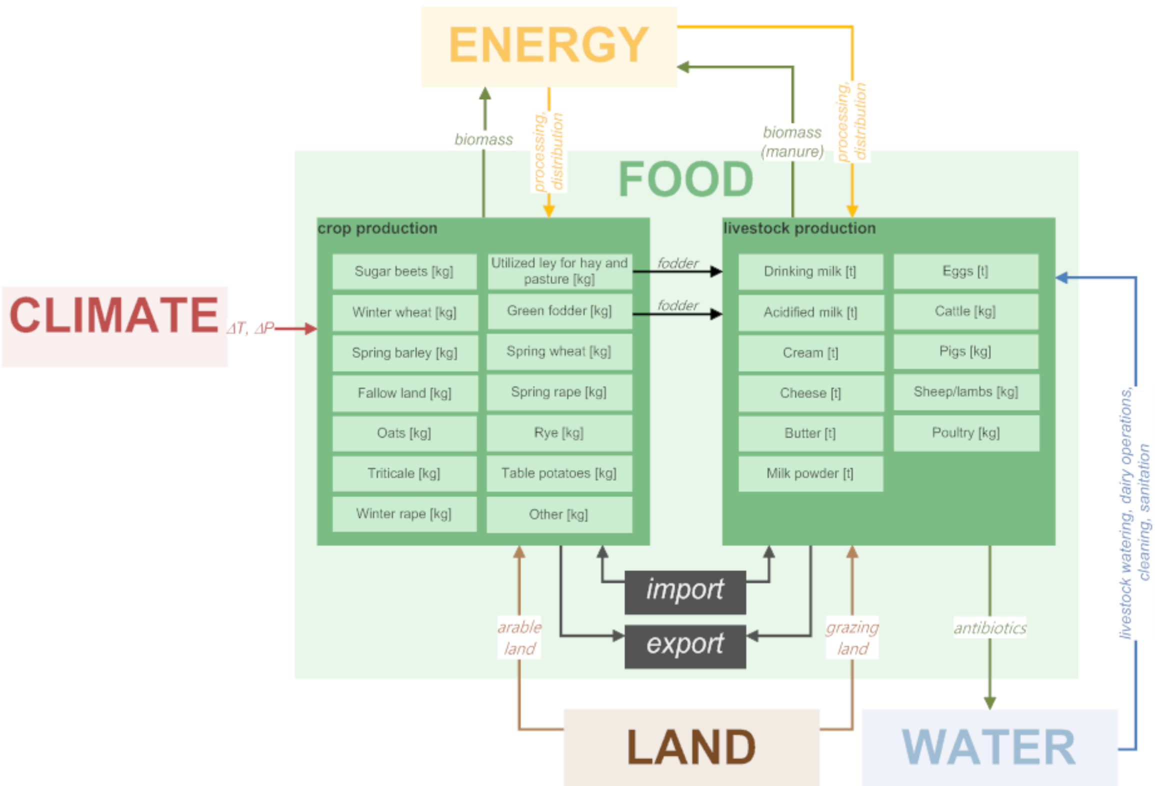
LAND



LAND
forested land [ha]
non-productive forest land [ha]
productive forest land [ha]
Norway spruce [ha] [age]
Scots pine [ha] [age]
Birch [ha] [age]
Lodgepole pine [ha] [age]
Other deciduous [ha] [age]
biodiversity indicators
Non-productive forest [%]
Average age [yrs]
Broad-leaf trees [%]
growth [Mm3]
total standing volume [Mm3]
felling [Mm3]
planting, soil preparation, clearing, fertilizing, harvesting, chipping, transport
biomass
ENERGY
emissions
sequestration (negative emissions)
ΔP, ΔT
CLIMATE
agricultural land [ha]
arable land [ha]
Utilized ley for hay and pasture [ha]
Winter wheat [ha]
Spring barley [ha]
Fallow land [ha]
Oats [ha]
Triticale [ha]
Winter rape [ha]
Green fodder [ha]
Sugar beets [ha]
Spring wheat [ha]
Spring rape [ha]
Rye [ha]
Table potatoes [ha]
Other [ha]
irrigation
fertilizer
pesticides
WATER
crop production
FOOD
grazing land [ha]
cattle [count]
pigs [count]
sheep [count]
fowls/chickens [count]
livestock production
emissions

(c)

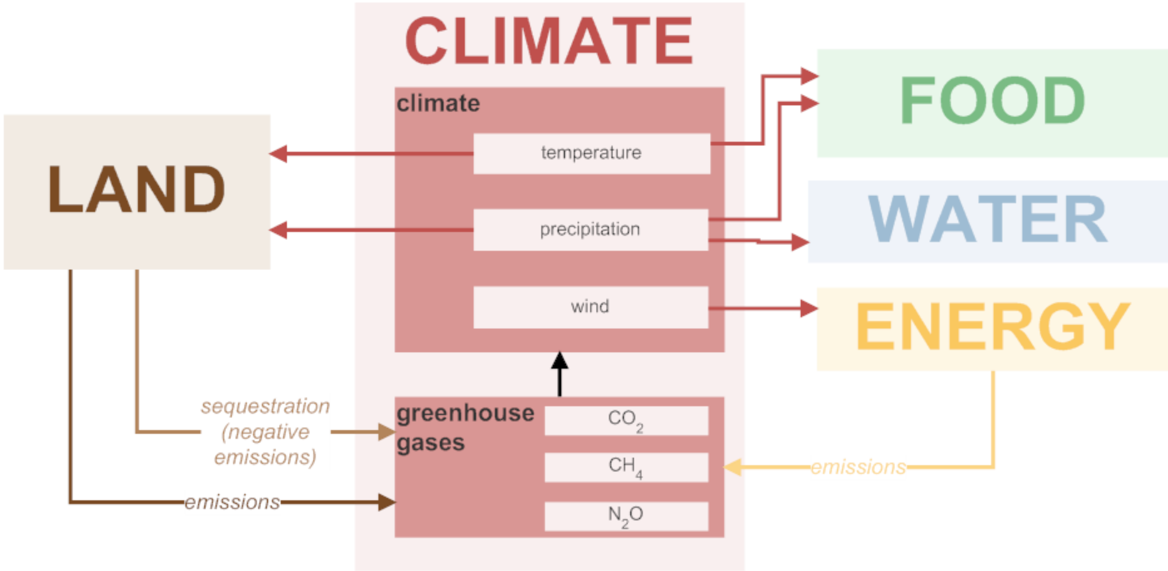
FOOD



ENERGY
biomass
processing, distribution
biomass (manure)
processing, distribution
FOOD
crop production
Sugar beets [kg]
Utilized ley for hay and pasture [kg]
Winter wheat [kg]
Green fodder [kg]
Spring barley [kg]
Spring wheat [kg]
Fallow land [kg]
Spring rape [kg]
Oats [kg]
Rye [kg]
Triticale [kg]
Table potatoes [kg]
Winter rape [kg]
Other [kg]
fodder
fodder
livestock production
Drinking milk [t]
Eggs [t]
Acidified milk [t]
Cattle [kg]
Cream [t]
Pigs [kg]
Cheese [t]
Sheep/lambs [kg]
Butter [t]
Poultry [kg]
Milk powder [t]
CLIMATE
ΔT, ΔP
import
export
arable land
grazing land
antibiotics
livestock watering, dairy operations, cleaning, sanitation
LAND
WATER

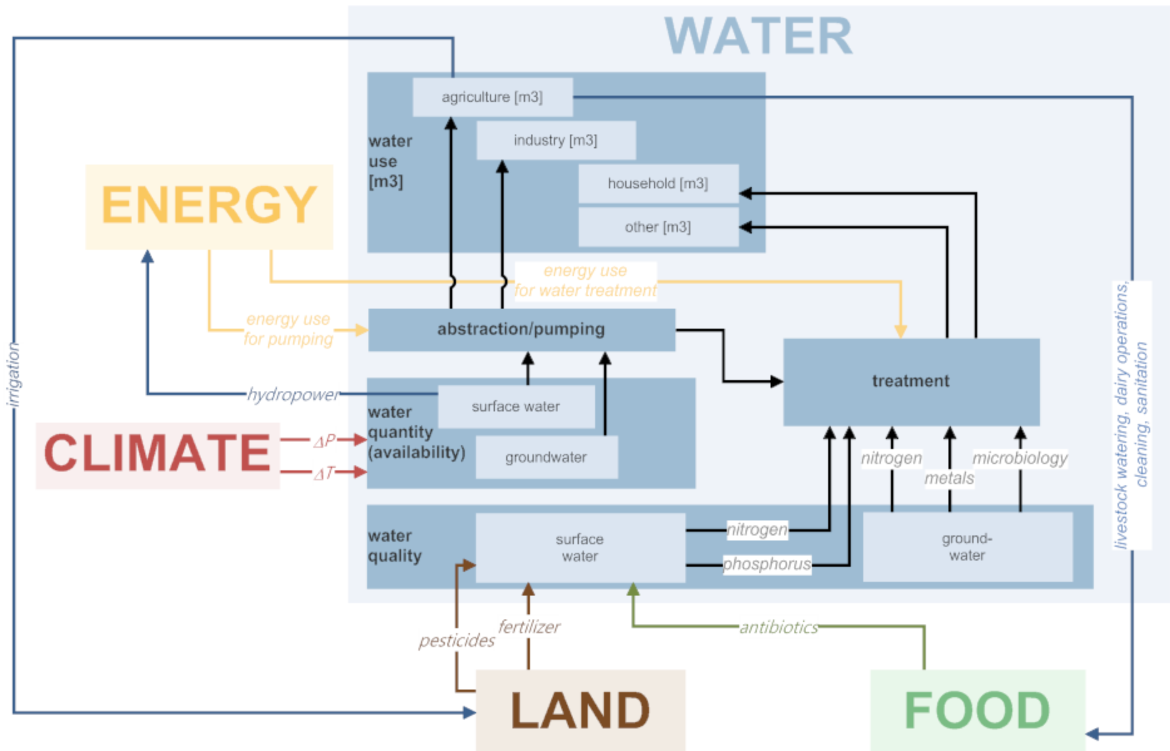
(d)

CLIMATE



(e)

WATER



(f)

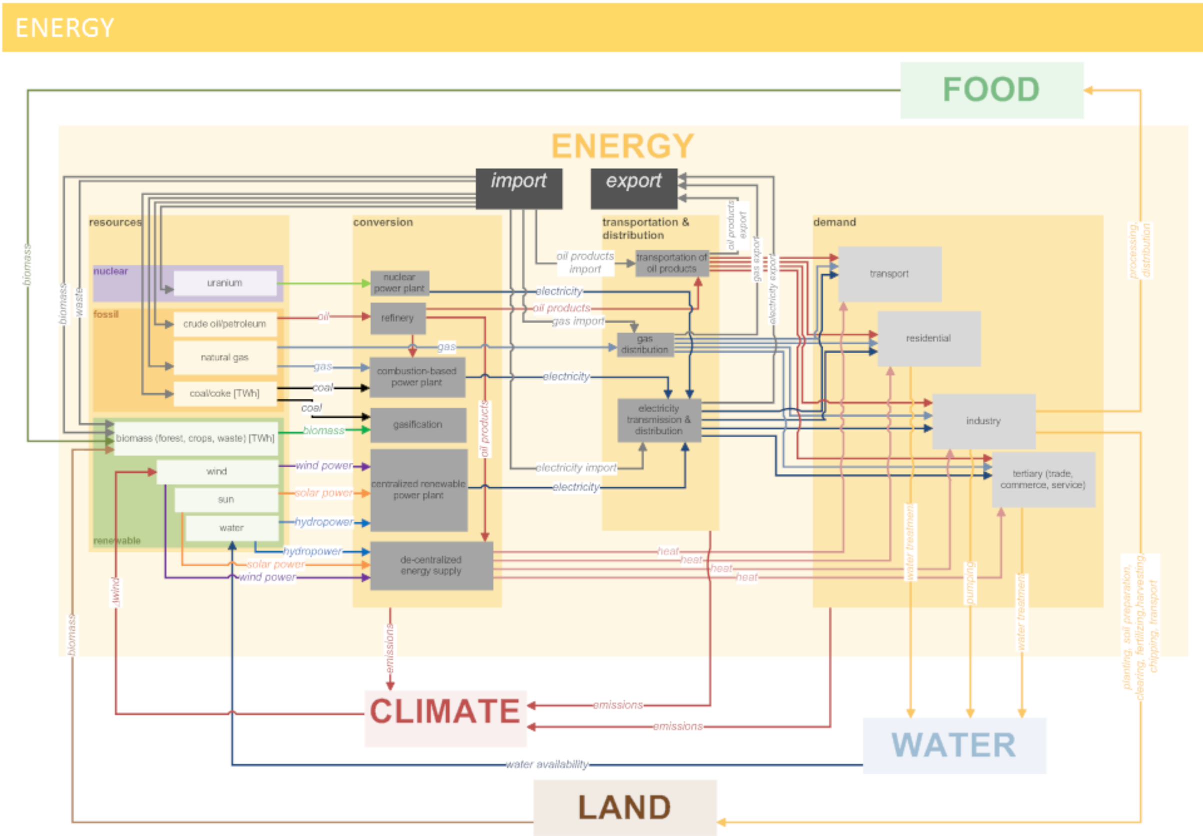


Figure 3.6.3: the final conceptual model for the Swedish case showing (a) the top level schematic indicating the links between all nexus components and then details for (b) the land sector, (c) the food sector, (d) the climate sector, (e) the water sector, and (f) the energy sector.

In the water sector (Figure 3.6.3e), surface and groundwater sources are represented in terms of both quantity and quality. As with Latvia (Section 3.5), quality is relatively more important than quantity, of which there are sufficient volumes. Water demand is split into four main sectors, and the water demands of the energy sector in particular (via hydropower and cooling of thermal power stations) are made explicit. The link to the land sector is mainly through water quality parameters. Climate modulates both quantity and quality. Finally, the energy sector (Figure 3.6.3f) is extremely comprehensive. Energy import and exports are accounted for. Primary energy sources are highly detailed, and include nuclear and fossil sources, as well as renewables from biomass, wind, solar and hydropower. A number of energy conversion processes are highlighted, followed by the transportation of this energy (electricity, fuels, oil products) to a wide variety of end-users (transport, residential, etc.) who consume a variety of energy types (electric, heat, fuel). The climate impacts from the production and consumption sides are highlighted, as are links to the other nexus sectors (e.g. energy required for water treatment and pumping, water required in the energy sector, the trade-off between land for food and energy biomass). As with the Latvian case (Section 3.5), the comprehensive development of links between nexus sectors will allow for a whole-systems model to be developed that accounts for cross-sectoral impacts of changes to any single sector.

3.6.3 Description of the developed system dynamics model

Figure 3.6.4 shows the top-level SDM for the Sweden case. This corresponds to Figure 3.6.3, and shows the high-level connections between all the five main nexus sectors. Within each rounded box in Figure 3.6.4, the nexus sectors have been developed in considerable detail, and is described in this section. It is shown that population is important in driving water and food demand, while the land, food and energy sectors all contribute to the climate sector (via emissions and sequestration).

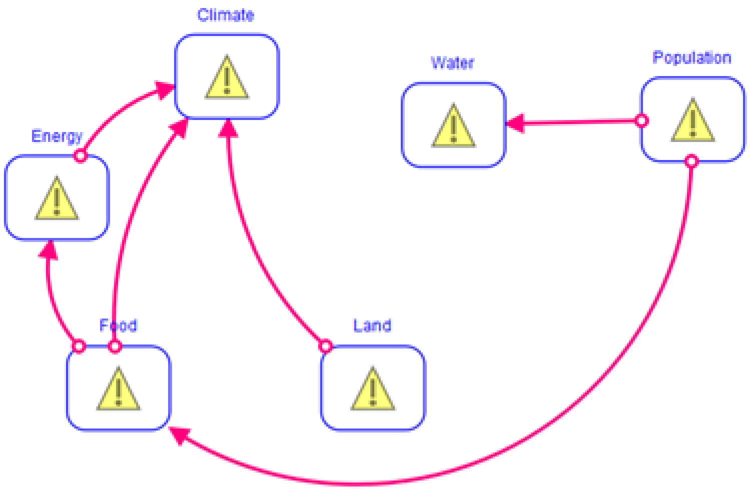


Figure 3.6.4: The top level SDM of the Sweden SIM4NEXUS model. All nexus sectors are represented, and population also drives water and food demand. Thick arrows denote nexus interconnections.

In all subsequent sub-model descriptions, the model structure is identical for the three regions in Sweden, though the data vary in each. The population sub-model simply contains a variable tracking population change over time.

In the water sub-model, quantity, quality and the water used in hydropower generation are quantified (Figure 3.6.5). Water quantity is measured in terms of water flows in the country (divided into three regions in Sweden). Water demand comes from the crop, livestock, domestic, industrial and 'other' sectors (other includes environmental flow considerations). For water quality (bottom right in Figure 3.6.5), wastewater is produced from water demand, some of which is subsequently treated. Of the treated wastewater, some is re-used, and some is discharged to the environment. Phosphate and nitrate loads, and their scaling upon treatment, will be used to track water quality. For hydropower (Figure 3.6.5, bottom left), the volume of water passing through turbines represents the demand, and when the turbine capacity and rating is known, the electricity generation can be attained and fed forward to the energy sector sub model.

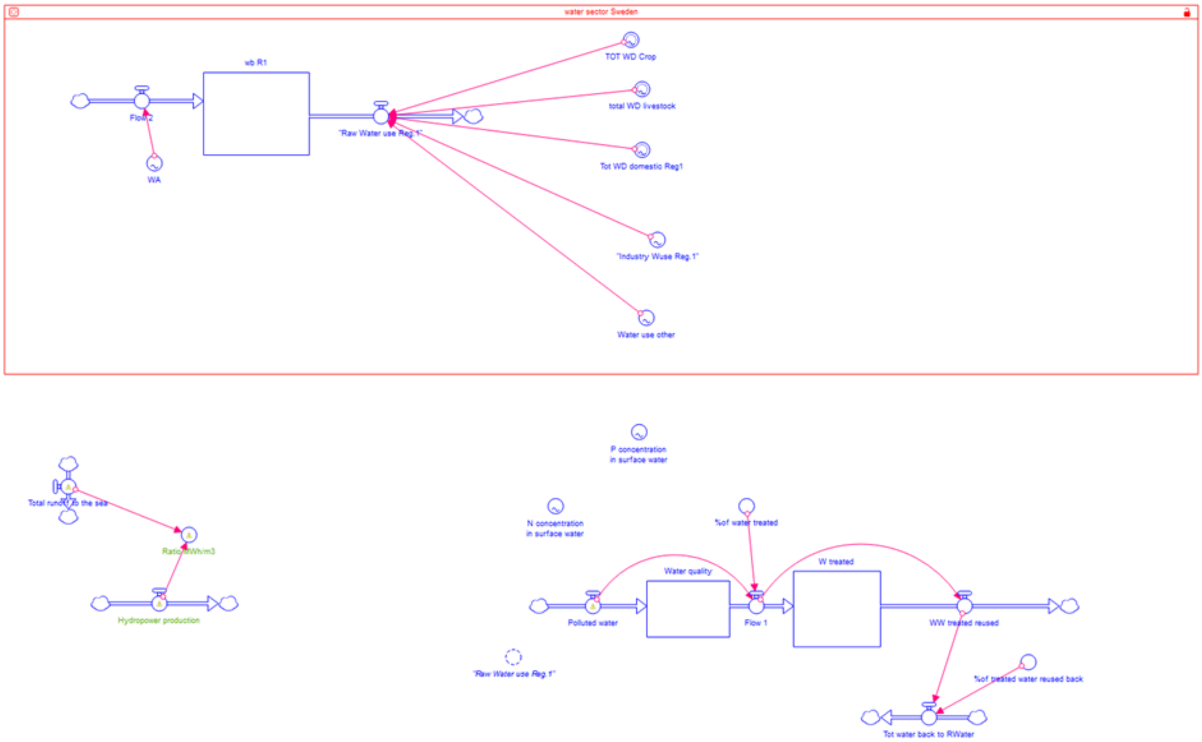


Figure 3.6.5: The water sub-model in the SIM4NEXUS Sweden case. Water quantity is defined in the box at the top of the figure, water quality is in the lower right, and hydropower water flow is in the bottom left.

Figure 3.6.6 shows the top level of the land sector sub-model. The land sector is split into forestry and agricultural land, both of which are defined in more detail in their own sub-models.

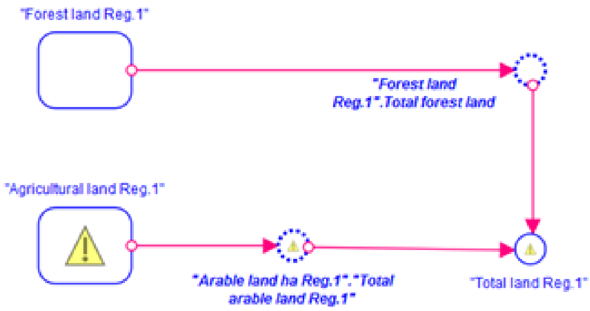


Figure 3.6.6: The top-level of the land sub-model, divided into forestry and agricultural land.

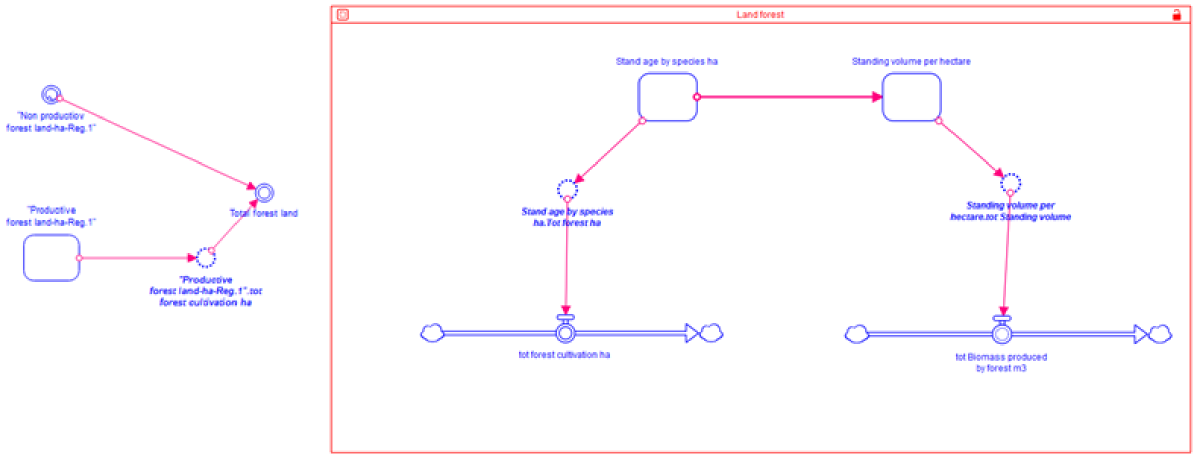


Figure 3.6.7: The forestry sector sub-model. Productive forests are further detailed (box on right). See text for details.

In the forestry sub-sector, non-productive and productive forest areas are specified (Figure 3.6.7) and summed to give the total forest land cover. The productive forestry sector is further elaborated in order to be able to assess the standing area by species and by age of tree (and therefore total standing areas) and also standing volumes (right hand box in Figure 3.6.7). The sub-models to compute standing area by species and age, and to compute standing volumes are further elaborated in considerable detail (Figure 3.6.8 and Figure 3.6.9). By assessing standing species and age distributions, a high level assessment of the diversity of forests in Sweden can be attained, which is important as a biodiversity indicator, and could help track trends towards environmentally damaging monocultures.

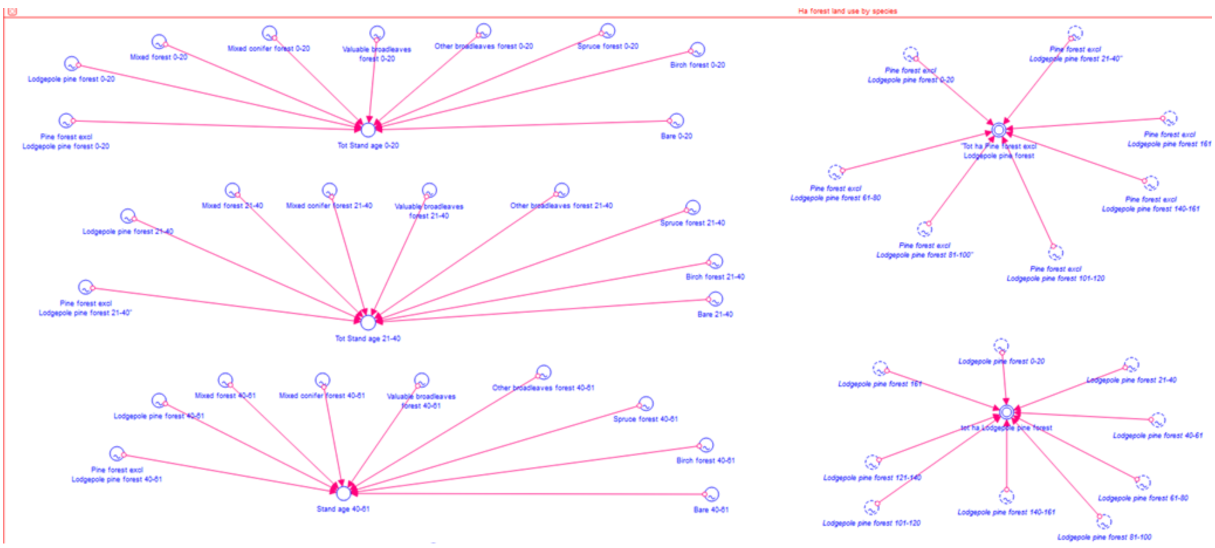


Figure 3.6.8: Extract from the sub-model to compute the standing area of different tree species by age for the Sweden case study.

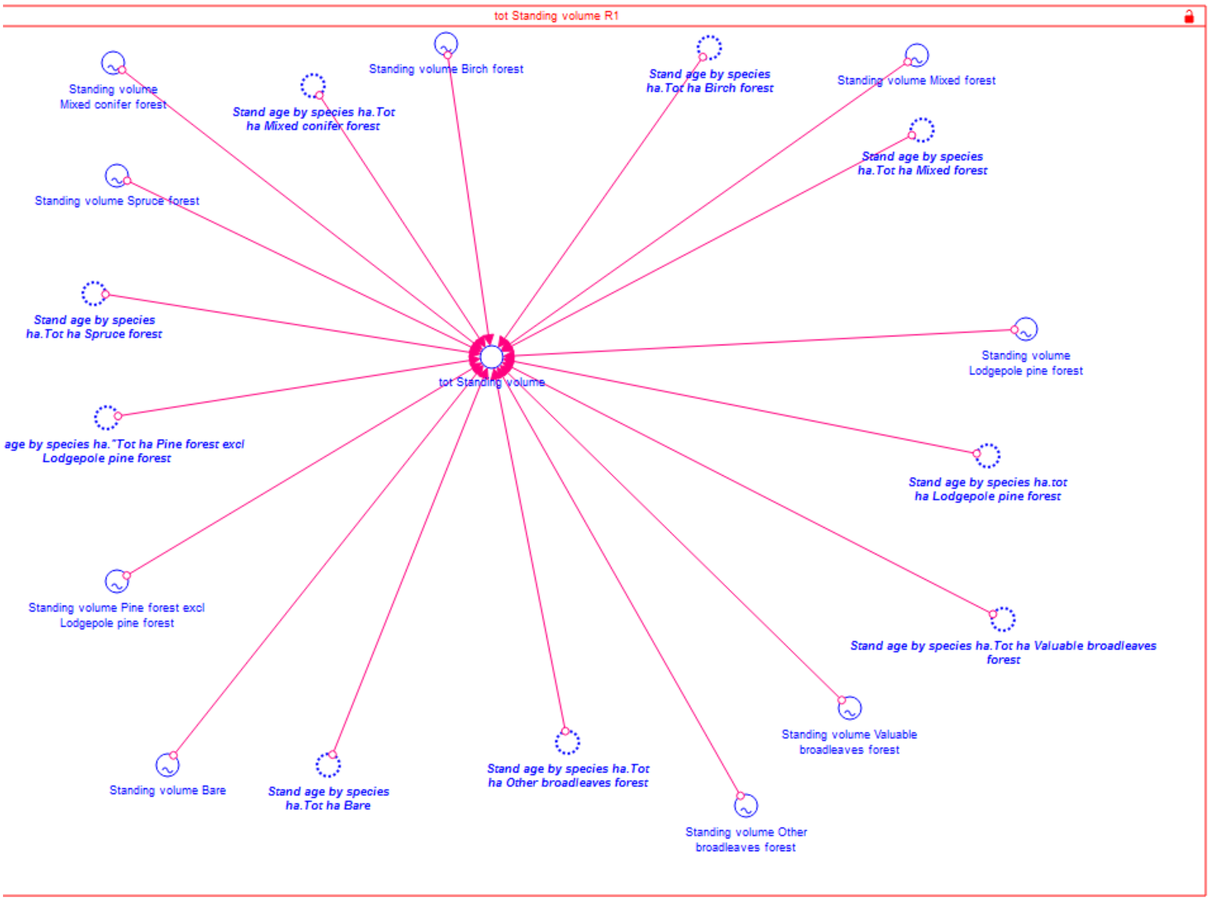


Figure 3.6.9: The sub-model to calculate standing volumes (by species and total) in Sweden.

With regard to standing area by age and species (Figure 3.6.9), this is approached from two angles: the standing area by age (combining the areas of all species in given ages classes; left hand side of Figure 3.6.8) and; the standing area by species (combining the areas of all ages of a given species; right hand side of Figure 3.6.8). The sum of all ages and species yield the total forest area in Sweden (and sub-regions thereof). In total, nine tress species are identified (pines excluding lodgepole pine), lodgepole pine, mixed forest, mixed conifer forest, valuable broadleaves, other broadleaves, spruce, birch, and bare. In addition, nine age classes are defined: 0-20, 21-40, 41-60, 61-80, 81-100, 101-120, 121-140, 141-160, 160+. In Figure 3.6.9, the area of each tree species is multiplied by average standing volumes per hectare per species, yielding tot standing forest volume, giving a biomass production indicator.

Agricultural land is split into livestock and arable lands (Figure 3.6.10 and Figure 3.6.11). Livestock is divided into cattle, sheep, pigs and fowl/chickens, which in turn are further sub-divided. In arable lands, 17 types are defined and quantified. Arable and livestock lands are summed to give total agricultural land in Sweden.

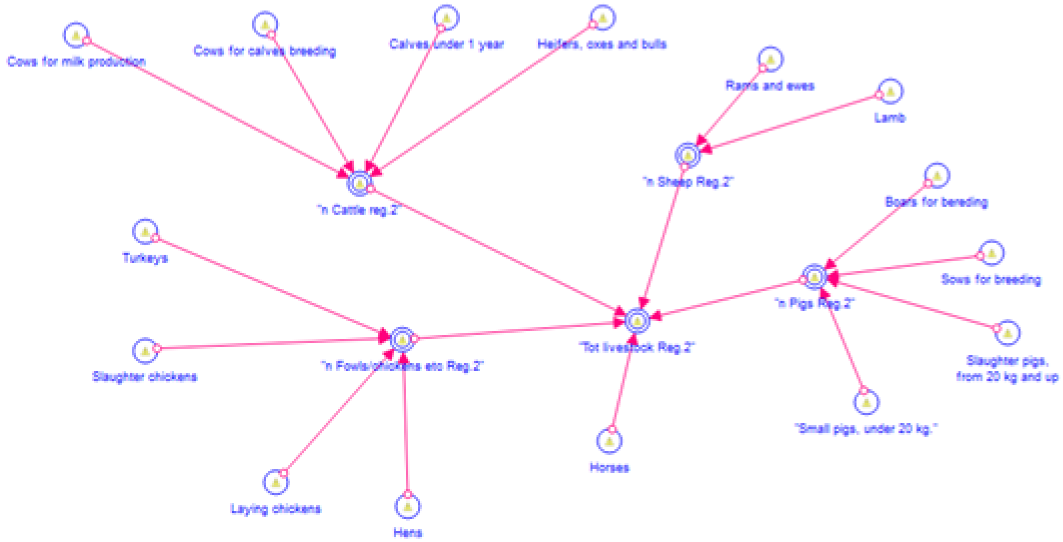


Figure 3.6.10: Livestock sub-model in the land sector.

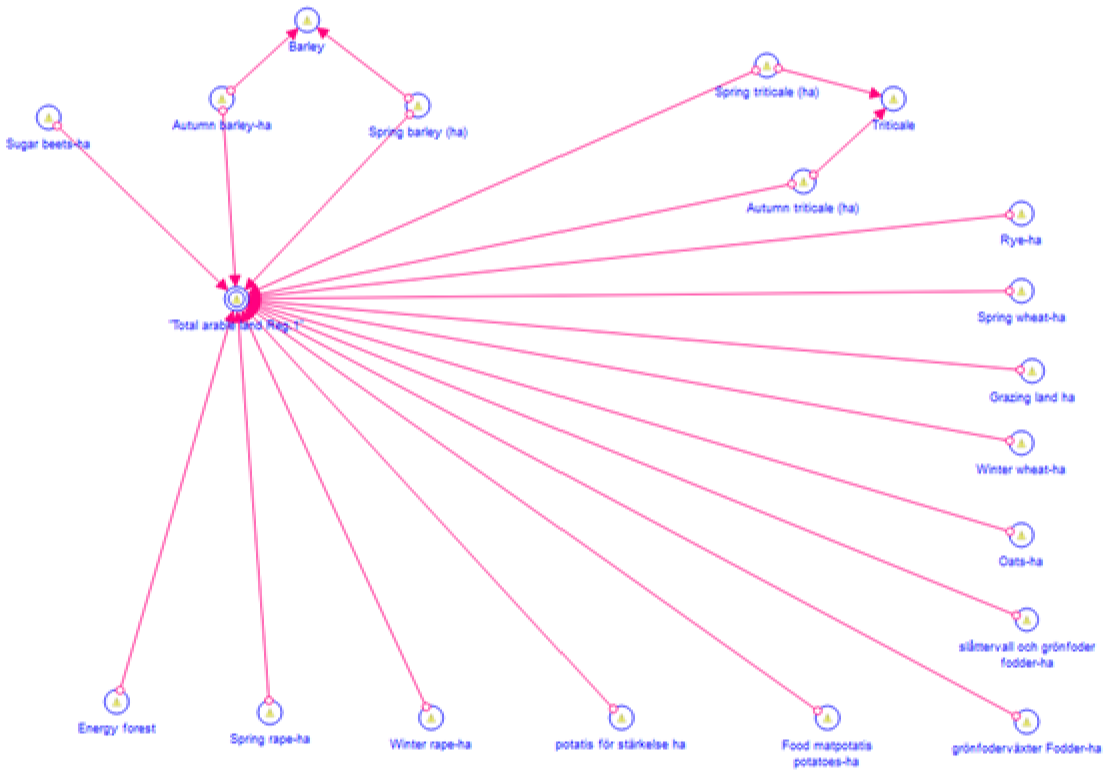


Figure 3.6.11: Arable land sub-model in the land sector.

For the food production and consumption sector, the top-level sub-model is shown in Figure 3.6.12. Food crops, livestock and other crops production are specified in terms of production, and are further detailed (Figure 3.6.13), while for consumption, this is calculated simply by the average per-capita food consumption multiplied by the population. A certain fraction of food consumption goes as waste to be re-used as biomass for energy generation. For crops, potatoes, sugar beet and rape are specified. In livestock, beef cattle, chickens, sheep, pigs and horses are defined, and for other crops, cream, sour products, cheese, butter, milk and eggs are defined.

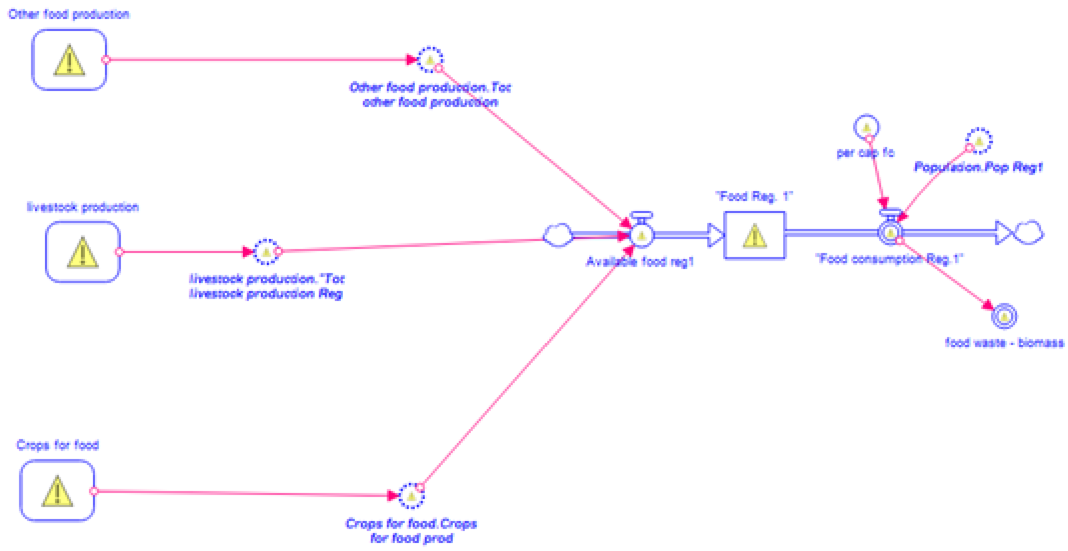


Figure 3.6.12: Top level food sector sub model for the Sweden case study.

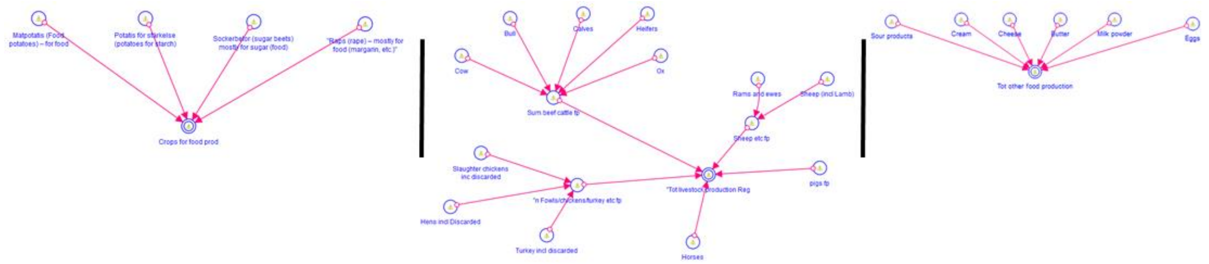


Figure 3.6.13: The crop, livestock and other food production sub-models in the food sector.

The top-level energy sector sub-model is shown in Figure 3.6.14. An energy balance is computed from estimation of the energy supply and demand. Primary energy sources are quantified, along with their conversion to secondary energy. The energy demand in different sectors is then calculated. Primary, secondary energy production and energy demand have their own sub-models.

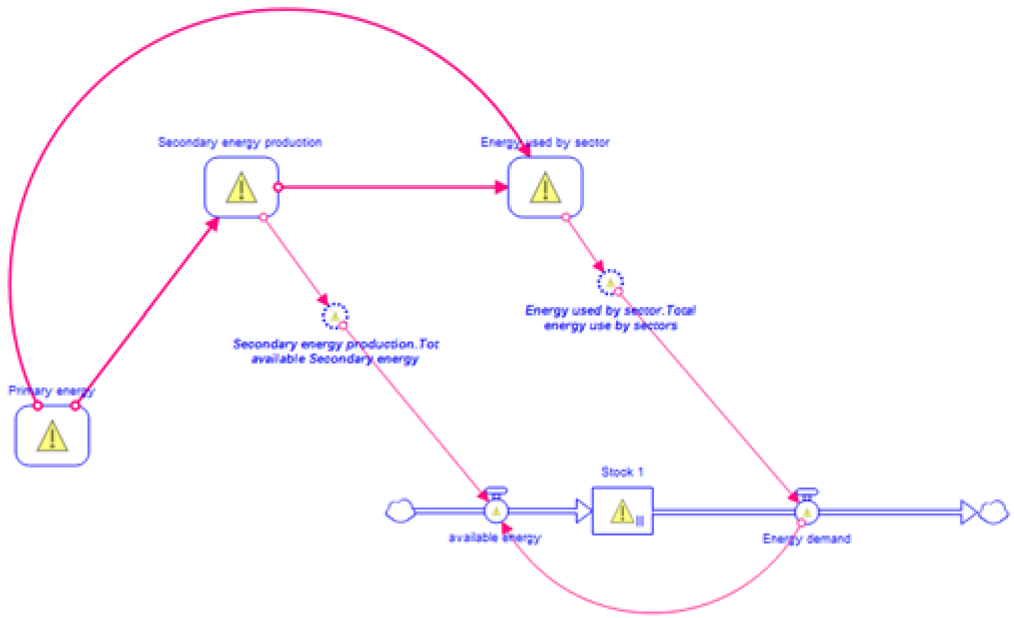


Figure 3.6.14: Top-level energy sector sub model in the Sweden case study.

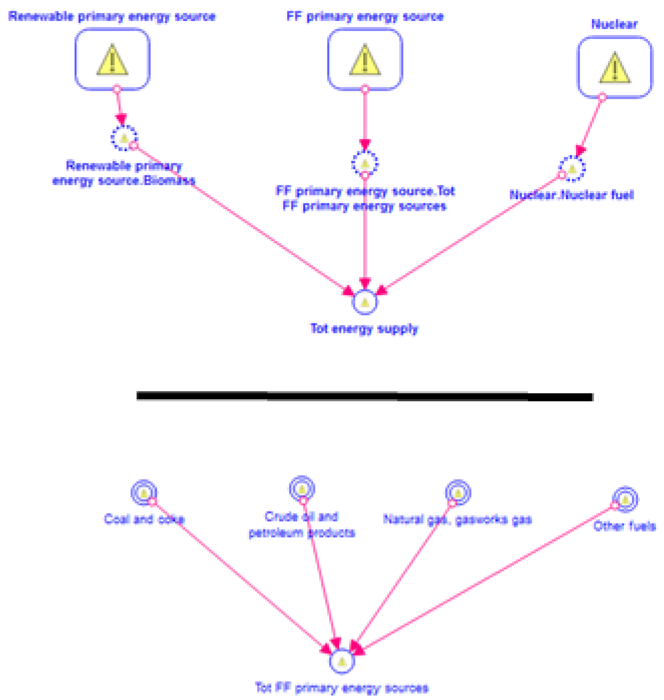


Figure 3.6.15: The primary energy sub-model (top) and the fossil-fuels specific model (bottom) for the Sweden case study.

In terms of primary energy (Figure 3.6.15), renewables, nuclear and fossil sources are quantified. Renewables consist of biomass, food waste and manure, while fossil fuels include coal, crude oil, natural gas and other fuels (Figure 3.6.15, bottom).

In terms of secondary energy, Figure 3.6.16 shows that this is accounted for from many sources. Import and exports of electricity are quantified along with hydropower production, wind and solar geothermal. Heat and electricity generation are further detailed in their own sub-models (Figure 3.6.17 and Figure 3.6.18).

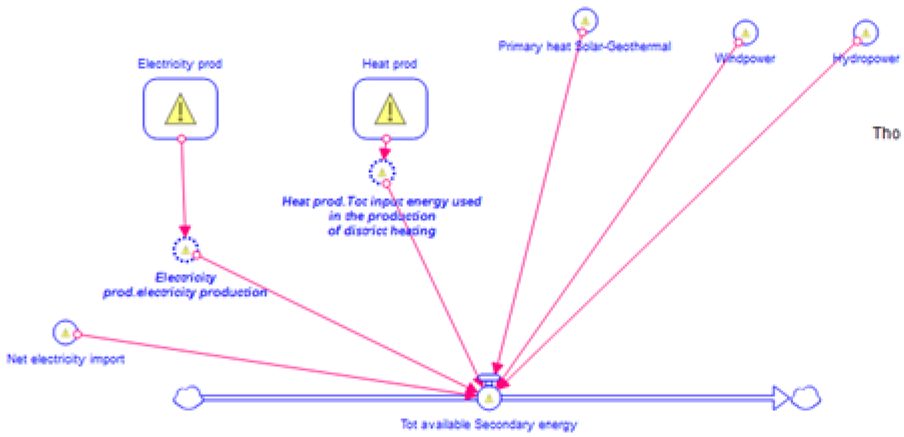


Figure 3.6.16: The secondary energy sub-model for the Sweden case study.

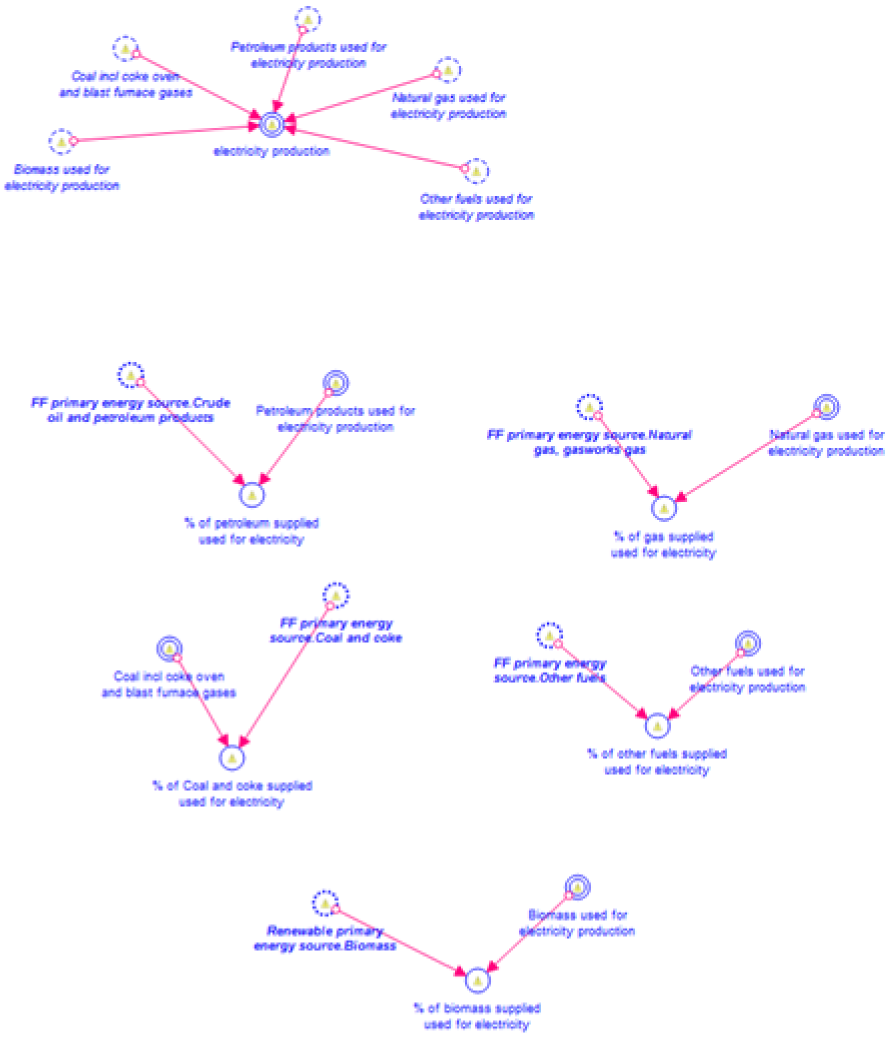


Figure 3.6.17: The electricity generation sub-model of the Sweden case study.

Electricity generation is comprised of biomass, coal, petroleum products, natural gas and other fuels (Figure 3.6.17), while heat is generated from electricity (in district heating), biomass (in district heating), coal, petroleum products, natural gas, other fuels, heat pumps and reclaimed waste heat (Figure 3.6.18). Together with the other categories above, the total electric, heat and fuel energy is assessed, along with the total energy available.

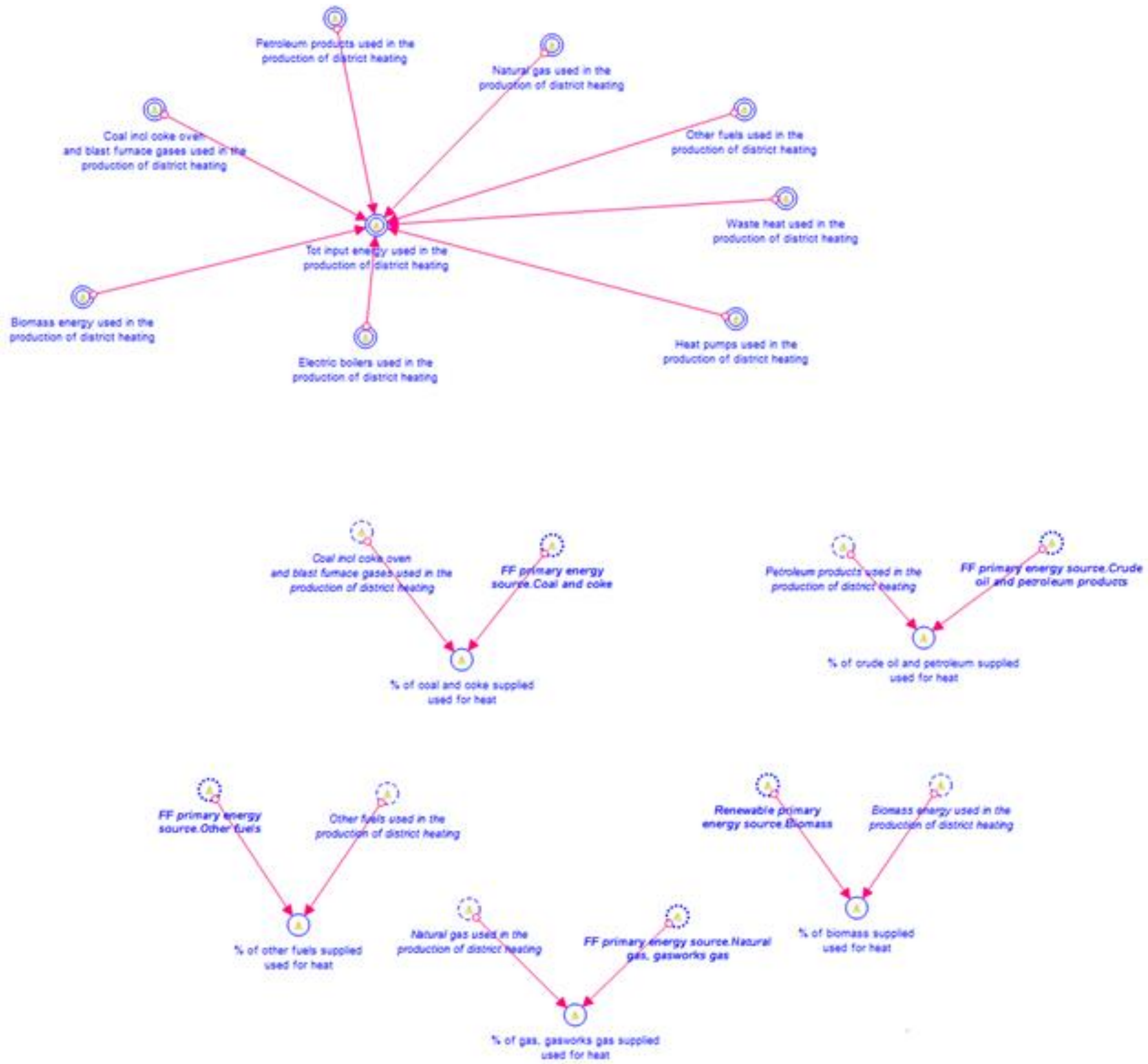


Figure 3.6.18: The heat generation sub-model of the Sweden case study.

In terms of energy demand, five sub-sectors define this: losses in distribution, electricity use in district heating, domestic transport, industrial energy use and, residential and services consumption (Figure 3.6.19). The last three categories are further elaborated in their own sub-models (Figure 3.6.20).

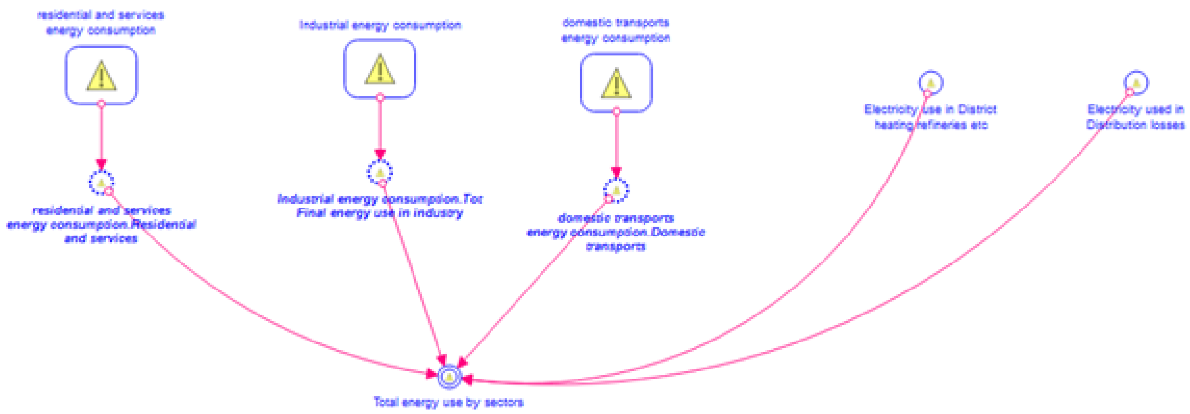


Figure 3.6.19: Energy demand sub-model of the Swedish energy sector.

Figure 3.6.20: The sub models for the residential (left), industrial (centre) and domestic transport (right) sectors.

In the residential sector, energy sources come from biomass, coal, natural gas, oil, electricity, other fuels and district heating. For industrial use, sources include coal, petroleum, others fuels, district heating, electricity, natural gas, and biomass. For transport, the fuels specified are diesel, light fuels, heavy fuels, aviation fuel, biofuel, natural gas, electricity, and petrol.

The final sector in the Swedish case is the climate nexus sector, the top level model for which is shown in Figure 3.6.21. Emissions emanate from food production and consumption, land use, energy production and energy consumption. Sequestration is from both productive and non-productive forest land.

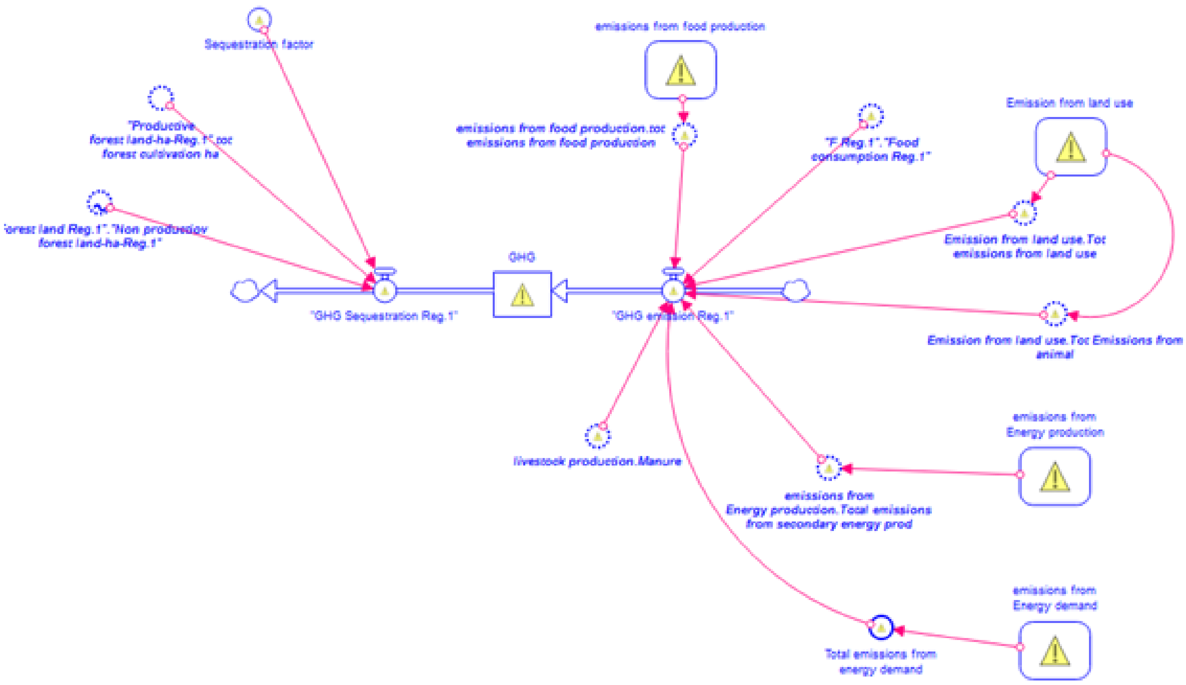


Figure 3.6.21: Top-level climate sector sub-model, accounting for emissions from many sectors and sequestration potential.

In terms of food production, emissions come from crops, livestock and other food production, and is therefore linked to the food sub-model. For land use, emissions emanate from productive forests (machine use, etc.), arable land, and livestock. In terms of energy production, all the sources involved in the generation of electricity and heat (see Figure 3.6.17 and Figure 3.6.18) account for GHG emissions, expect for renewable sources, while consumption emissions come from the residential, industrial and transport sectors.

3.7 Netherlands case study

3.7.1 Short description of the case study

The Netherlands case study in SIM4NEXUS has a focus on identifying low carbon and research-efficient pathways for the water-energy-food-land-climate nexus in the face of climate change. Exactly which (policy) pathways are to be followed in the Netherlands to achieve this overall objective are uncertain, however, for SIM4NEXUS there is a focus on energy saving, electrification, a transition towards a bio-based economy and increased carbon capture and storage (CCS). All strategies are supposed to meet an 80-95% reduction in GHG emissions by the middle of the century. The main GHG emitted was CO_2, which has been fairly stable since 1990. The other GHG emissions, such as CH_4 and N_2O-emissions, declined between 1990 and 2015. Agriculture is responsible for the majority of CH_4 and N_2O-emissions and for 12.5% of total Dutch GHG emissions (measured in CO_2 equivalents). Sources of agricultural emissions are animal production, the use of fertilizer, the use of fossil fuels for pumping, heating and tractor use. Therefore, assessing changes to the agricultural sector, and their corresponding emissions impacts, is also a key concern in this case study.

The overall objective of the Dutch case study in SIM4NEXUS is to identify low-carbon and resource-efficient pathways for the water-land-food-energy nexus in 2050. In particular, what is the potential role of biomass in the transition to a low-carbon economy considering the interaction with water, land, energy, food and climate? Biomass will be needed to achieve the 95% GHG emission reduction to develop a low-carbon economy. However, the application of biomass needs to be sustainable and therefore has requirements and limitations. The main nexus challenges are:

- Biomass should be produced and collected in a sustainable way. The domestic supply of sustainable biomass is limited and will be insufficient for the various demands in The Netherlands, so imports are needed. Sustainably produced biomass is a scarce resource;
- Application of biomass for energy production at a large scale will affect the availability and quality of land, water, food and energy and will affect climate;
- It is debated whether the use of biomass for energy generation contributes to a net reduction of GHG emissions or not. The sustainability criteria for biomass are also debated;
- In addition, biomass has a negative image because it is often associated with the use of coal for energy production (co-firing) and with large scale deforestation. It is also associated with land grabbing and competition with local food production;
- In addition, there are knowledge gaps by politician and the public about the diversity of biomass and the best application of these different types.

3.7.2 Evolution and description of the conceptual diagram

Figure 3.7.1 shows the first version of the Netherlands conceptual model. This version differs somewhat from the previous two initial conceptual models. Climate is represented as modulating and being modulated by the activities of the other sectors, which in this initial model were represented as water (water management), energy production and trade, agriculture and forestry (to represent the bio-based sectors), transport and storage (of energy products specifically) and 'consumption' (both of energy products and agricultural and forestry products). The implied emphasis in this early conceptual model is indeed on energy and the proposed increasing important of bioenergy sources, with the potential implications for the agricultural sector and the climate.

Through a series of consultative expert stakeholder workshops, this initial conceptual model was refined over a number of iterations, being more specific in the issues it was supposed to represent. Detail and complexity was added to those sectors which represent the focus of this case study, in particular, energy generation (by source) and strongly related, the land sector, differentiating how much land is to be transformed in bioenergy producing land, potentially at the expense of endogenous crop production.

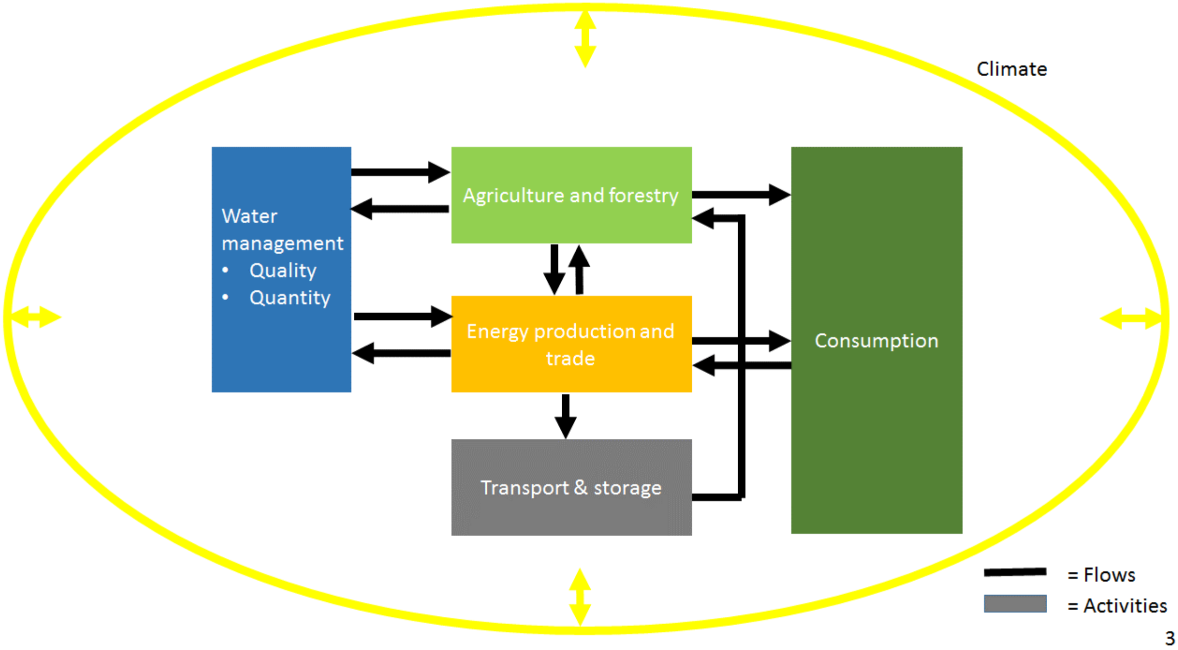
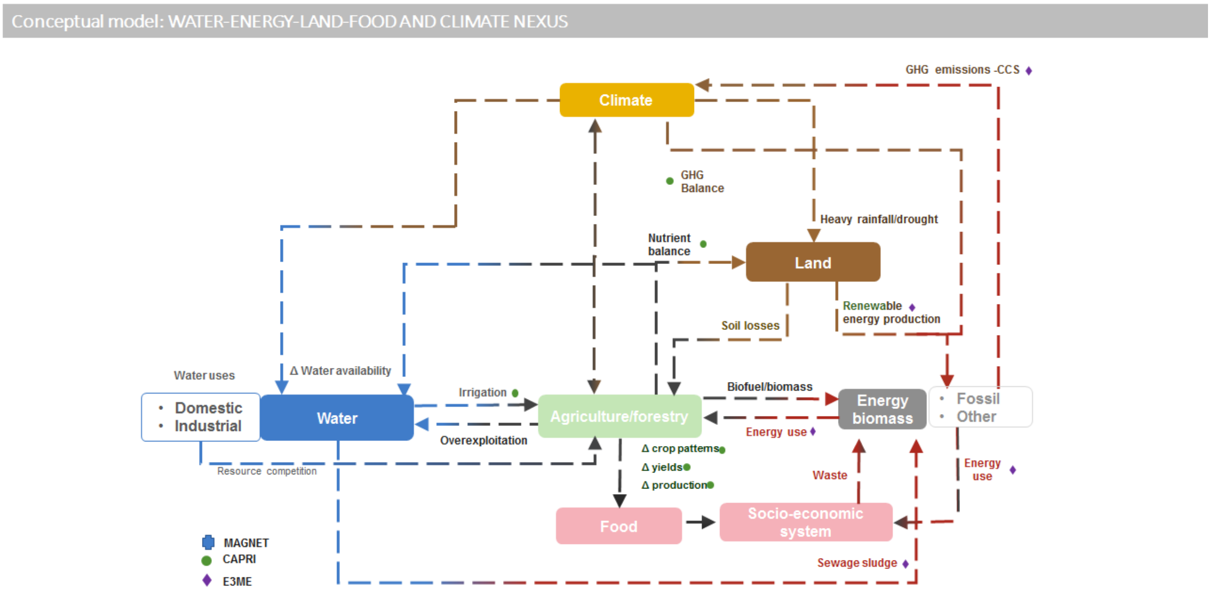


Figure 3.7.1: First version of the Netherlands conceptual model.

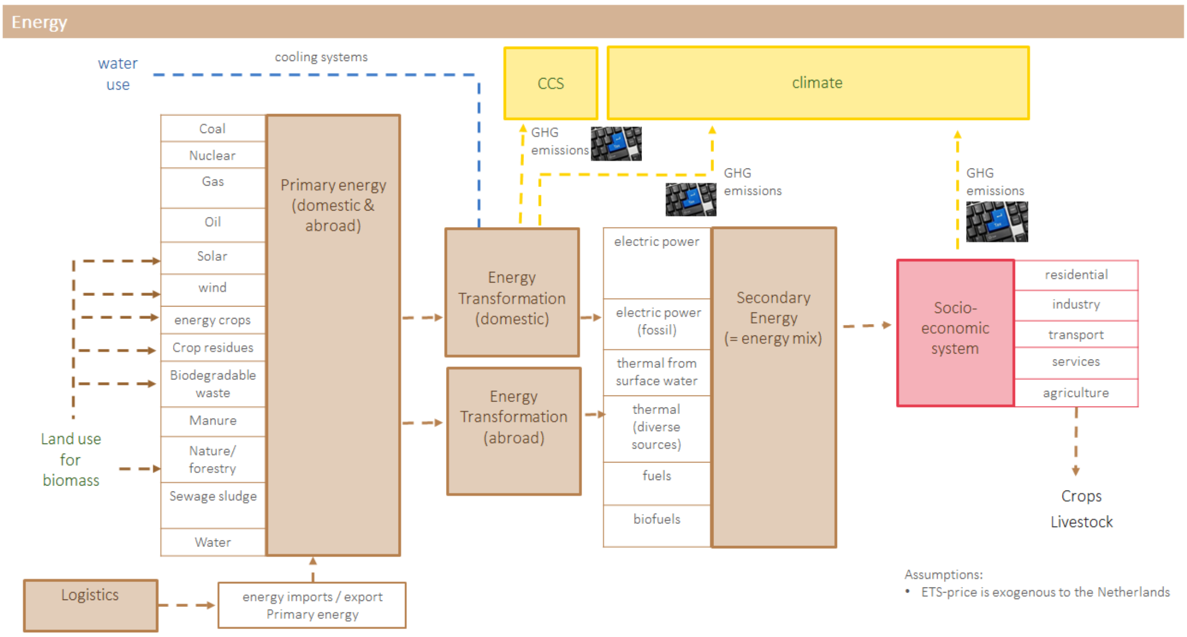
Figure 3.7.2 shows the final conceptual model for the Netherlands, with Figure 3.7.2a representing the top-level nexus overview of the system. The initial model (Figure 3.7.1) has clearly be refined considerably. Land, agriculture/forestry, and energy biomass form the core of the model, but are linked to the food, water, climate and (uniquely), socio-economic systems. In addition, this top-level overview proposes the SIM4NEXUS thematic models that may be exploited for data purposes (i.e. MAGNET, CAPRI and E3ME). Figure 3.7.2b-f detail each of the nexus sectors more comprehensively, including the specific inter-sector linkages.

(a)



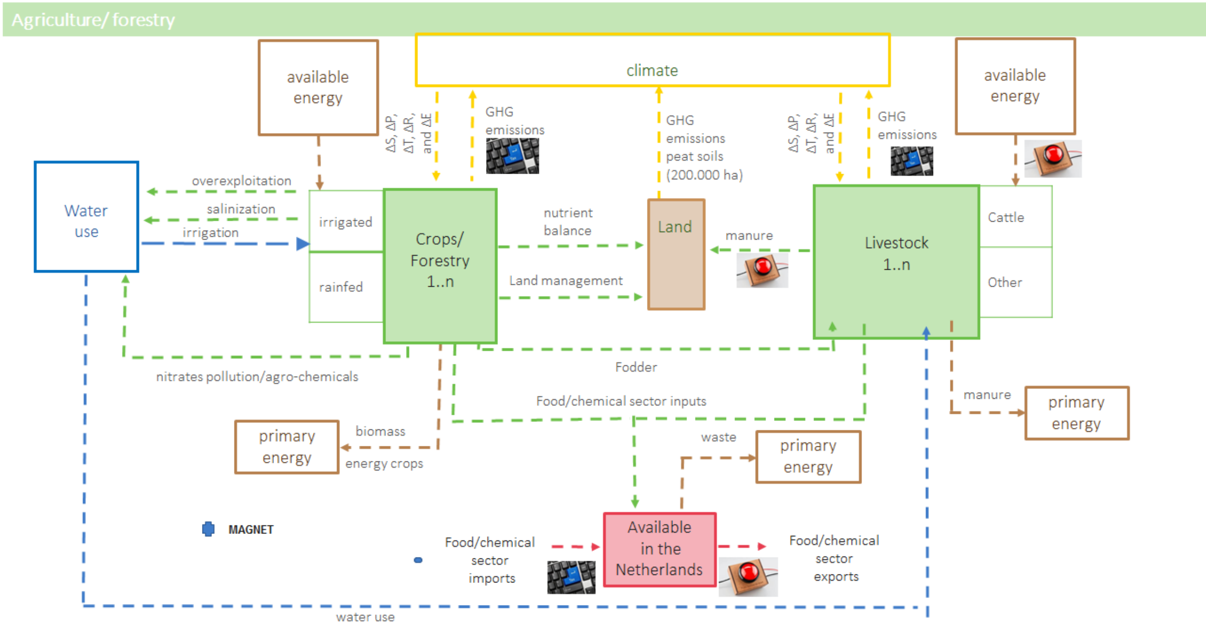
Conceptual model: WATER-ENERGY-LAND-FOOD AND CLIMATE NEXUS
GHG emissions -CCS
Climate
GHG Balance
Heavy rainfall/drought
Nutrient balance
Land
Renewable energy production
Soil losses
Water uses
Δ Water availability
Domestic
Industrial
Water
Irrigation
Agriculture/forestry
Biofuel/biomass
Energy biomass
Fossil
Other
Overexploitation
Energy use
Δ crop patterns
Δ yields
Δ production
Waste
Energy use
Resource competition
Food
Socio-economic system
MAGNET
CAPRI
E3ME
Sewage sludge

(b)



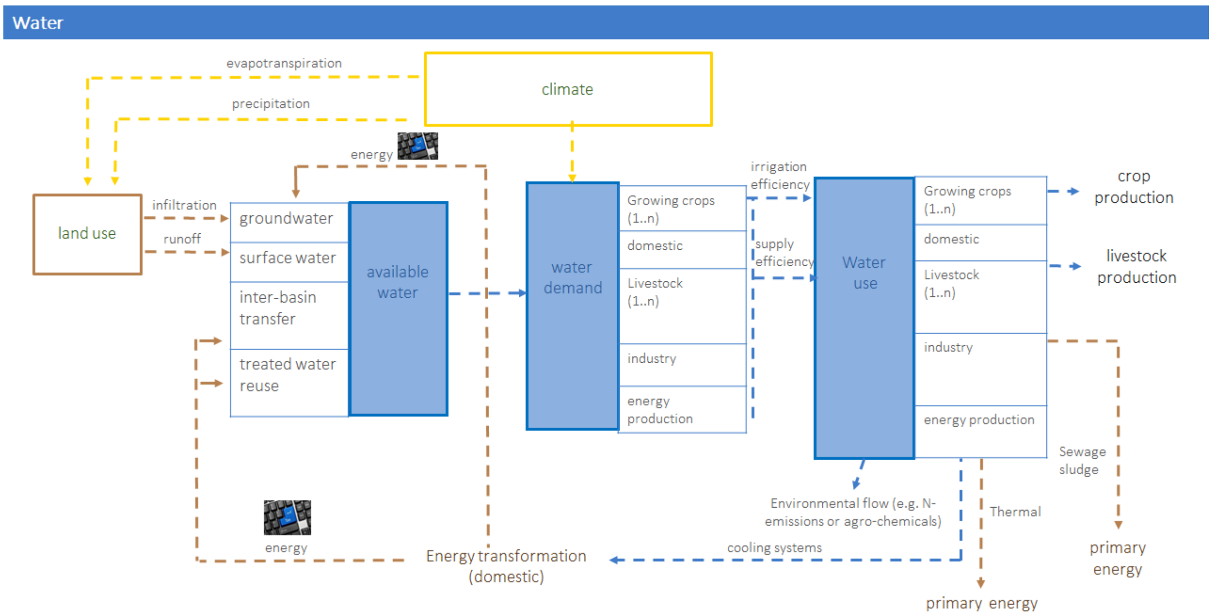
Energy
water use
cooling systems
CCS
climate
GHG emissions
GHG emissions
GHG emissions
Coal
Nuclear
Gas
Oil
Solar
wind
energy crops
Crop residues
Biodegradable waste
Manure
Nature/ forestry
Sewage sludge
Water
Primary energy (domestic & abroad)
Energy Transformation (domestic)
Energy Transformation (abroad)
electric power
electric power (fossil)
thermal from surface water
thermal (diverse sources)
fuels
biofuels
Secondary Energy (= energy mix)
Socio-economic system
residential
industry
transport
services
agriculture
Crops
Livestock
Land use for biomass
Logistics
energy imports / export Primary energy
Assumptions:
• ETS-price is exogenous to the Netherlands

(c)



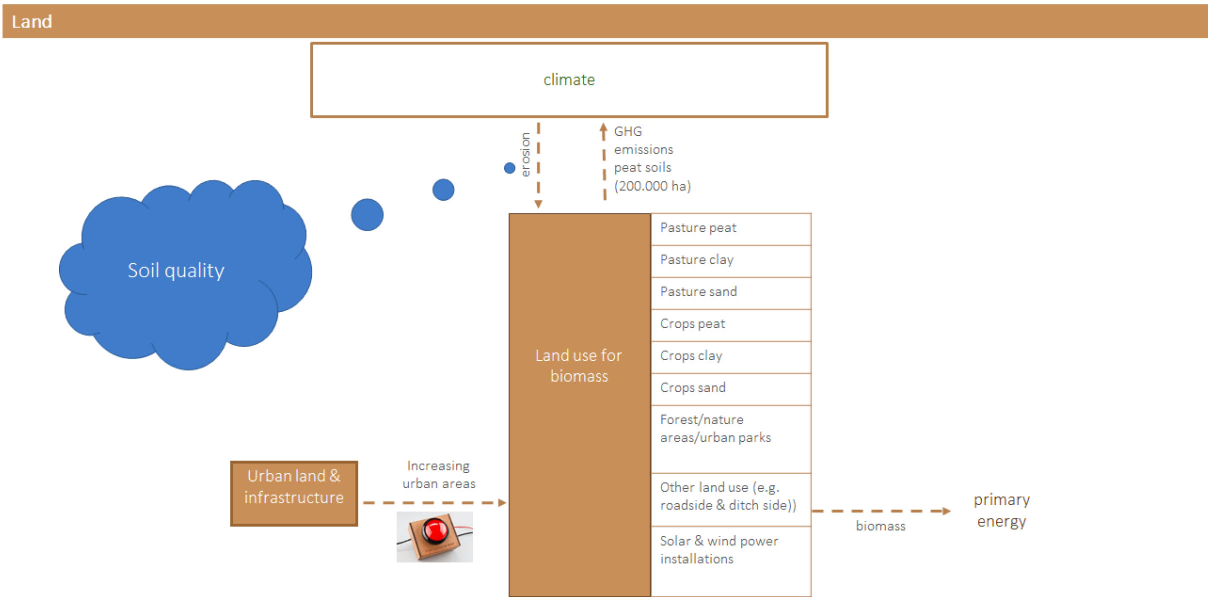
Agriculture/ forestry
available energy
climate
available energy
ΔS, ΔP, ΔT, ΔR, and ΔE
GHG emissions
GHG emissions peat soils (200.000 ha)
ΔS, ΔP, ΔT, ΔR, and ΔE
GHG emissions
Water use
overexploitation
salinization
irrigation
irrigated
rainfed
Crops/ Forestry 1..n
nutrient balance
Land management
Land
manure
Livestock 1..n
Cattle
Other
nitrates pollution/agro-chemicals
Fodder
Food/chemical sector inputs
manure
primary energy
primary energy
biomass
energy crops
waste
primary energy
MAGNET
Food/chemical sector imports
Available in the Netherlands
Food/chemical sector exports
water use

(d)



Water
evapotranspiration
climate
precipitation
energy
land use
infiltration
runoff
groundwater
surface water
inter-basin transfer
treated water reuse
available water
water demand
Growing crops (1..n)
domestic
Livestock (1..n)
industry
energy production
irrigation efficiency
supply efficiency
Water use
Growing crops (1..n)
domestic
Livestock (1..n)
industry
energy production
crop production
livestock production
Sewage sludge
primary energy
Environmental flow (e.g. N-emissions or agro-chemicals)
Thermal
energy
Energy transformation (domestic)
cooling systems
primary energy

(e)



(f)

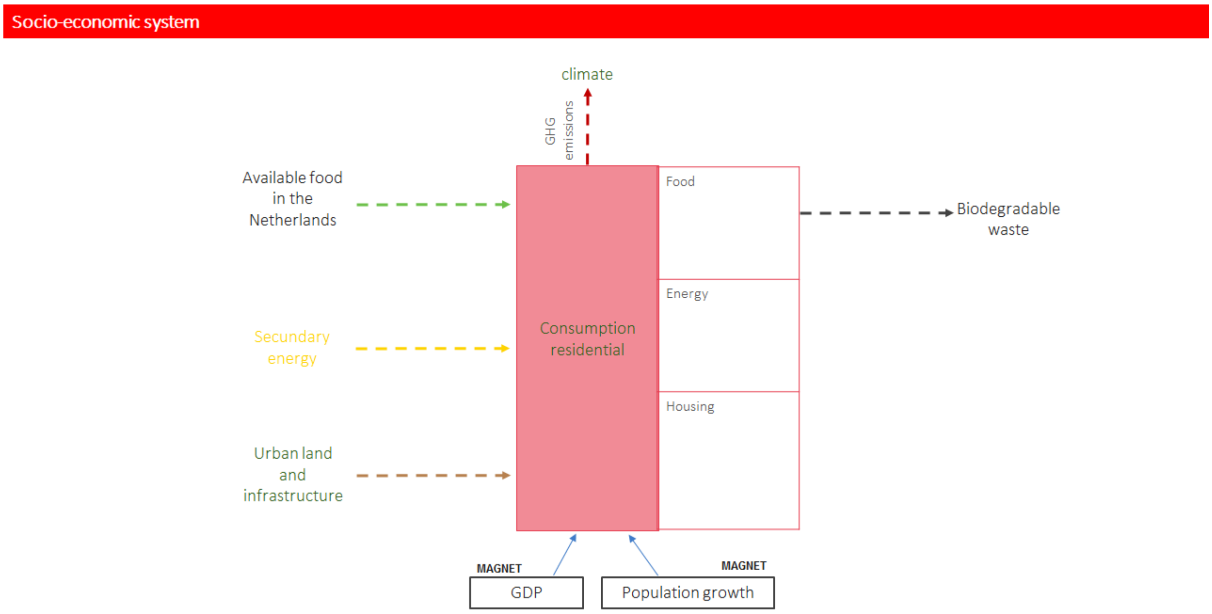


Figure 3.7.2: The final conceptual model for the Netherlands case showing (a) the top level schematic indicating the links between all nexus components and then details for (b) the energy sector, (c) the agricultural/forestry sector, (d) the water sector, (e) the land sector, and (f) the socio-economic sector. Although not explicitly represented, links from each sector to the climate system are indicated.

The energy sector (Figure 3.7.2b) is comprehensively detailed, as expected for this case study. A wide variety of primary energy sources are specified, including some of specific import for this case, namely crop residues, biodegradable waste, manure and sewage sludge. The primary energy is transformed to 'usable' secondary energy (electric power, thermal energy, and bio-fuels). These are consumed in the socio-economic system, and the consumption is driven by factors in this system (e.g. population, GDP). The link to water (for cooling) and the climate system (GHG emissions) is made clear, as is the link to land for biocrop production. The agricultural/forestry sector (Figure 3.7.2c) is also comprehensively developed. A number of crops and forestry products are to be specified, together with livestock products. The implications of this production on the land sector (area required/utilised), water sector (water demand, quality impacts), energy sectors (e.g. via energy generation through various biomass sources) and the climate sectors (via emissions and sequestration of GHG) are indicated. In the water sector (Figure 3.7.2d), a number of water sources are specified (including the reuse of treated wastewater), and water demand and final consumption are separated out in this case, with the use in a number of sectors accounted for. The links to the energy sector (water used in the energy sector, energy required in the water sectors), land (via pollutant runoff) and climate (here modulating water demand) are all brought out. The land sector (Figure 3.7.2e) is relatively simple. It accounts for the amount of land used for different biomass categories (e.g. pasture, crops, forestry) and for urban land and infrastructure. The links to energy (biomass for energy) and climate (emissions and sequestration) are highlighted. The socio-economic system (Figure 3.7.2f) is unique for the Netherlands case study. It focuses on consumption values of different products (e.g. food, energy), and this may be influenced by the available of food, energy and infrastructure, along with GDP and population changes. Biodegradable waste is an output potential resource) from this sector, and emissions to the climate are mentioned.

3.7.3 Description of the developed system dynamics model

The main elements of the SDM for the Dutch case are the energy and land use elements of the nexus. Therefore, we present those two parts of the model.

Energy

The energy sub-model is presented in Figure 3.7.3. On the right-hand side of Figure 3.7.3, demand for energy is five sectors (domestic sector, agriculture, industry transport and other sectors) is distinguished. The key factors of energy demand are population, value added and energy intensity of a sector. Moreover, each sector distinguishes a demand for renewable energy and non-renewable energy which depends on the relative the price of renewable energy over non-renewable energy. The demand for both renewable and non-renewable energy determines the available energy or the produced secondary energy required. Other factors for the available energy are the availability of primary energy sources (like sun, wind, coal etc.) including the capacity of facilities and energy efficiency per primary energy.

Non-renewable energy sources include coal power, natural gas, oil and nuclear energy. In the case of renewable energy we distinguish on-shore wind energy, solar power, small-scale biomass energy and large-scale biomass energy. Large-scale biomass energy is defined as energy from biomass which is imported in bulk, like the co-firing of biomass in coal power plants, or the transformation of coal power plants into biomass power plants. Small-scale biomass is defined as energy from biomass produced in the Netherlands. Examples are organic waste from the domestic sector, energy crops, crop residues, manure, wastewater etc. One main aspect of making the distinction between large-scale and small-scale biomass production is the spatial pressure or the trade-off with food production in the Netherlands. Other renewable energy types are off-shore wind power or biomass production for energy for instance.

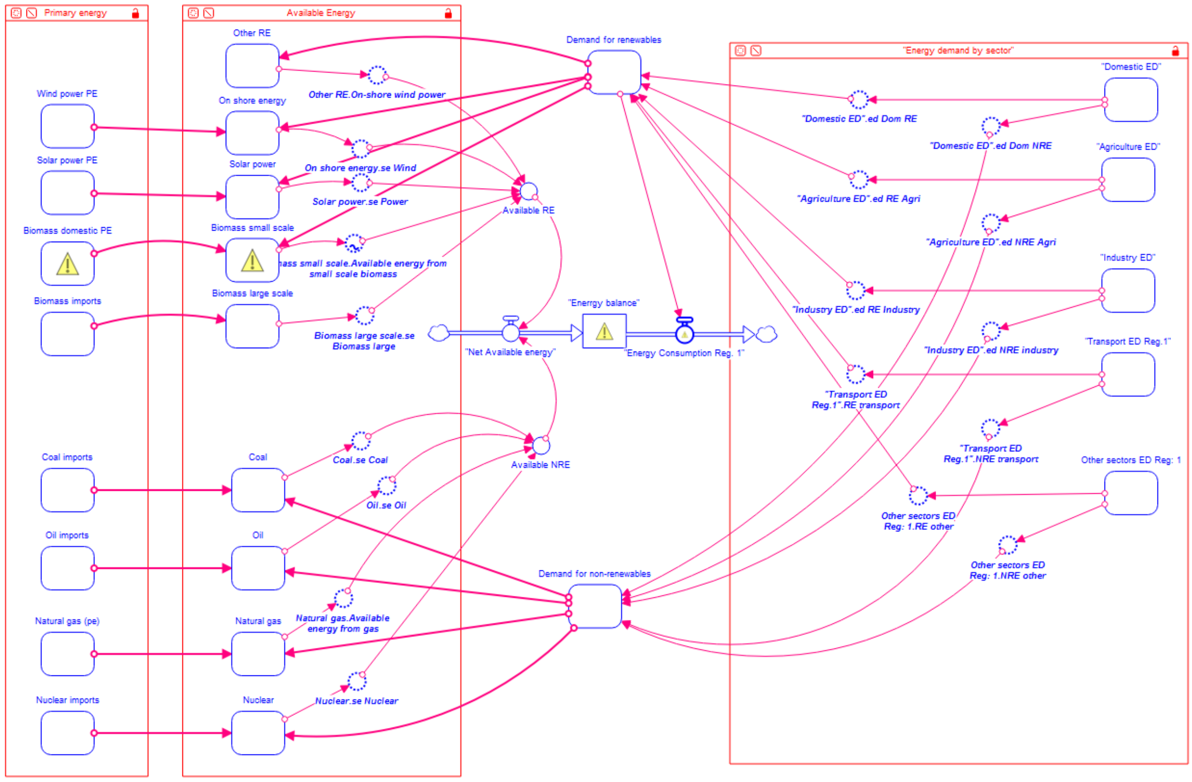


Figure 3.7.3: Energy in the Dutch SDM

Land use

The land-use sub-model concentrates on those elements that are relevant for biomass production and other types of renewable energy that depend on land (solar and wind). Wind mills and solar meadows are expected to have a significant effect on land-use in the Netherlands (more than 40.000 ha in the coming decades). We skipped details in Figure 3.7.4 because the graph would become too crowded and less informative. Land-use (LU) in the Netherlands (LU_Netherlands) is the total area. Agricultural LU consists of food & fiber production, fodder and land for energy crops. LU in natural areas consists of forests and protected areas. LU biomass and urban infrastructure is included to take into account biomass production from urban areas like grass from roadsides or ditch sides. The total amount of dry matter available for energy is calculated in the agricultural sub-model for every category in a more or less similar way and depends on (1) the area of land-use category; (2) dry matter (DM) production per ha; (3) DM harvested and transported per ha; and (4) the share of DM that is available for energy production. For example, DM available for energy production depends on the total area, the total dry matter production per ha, the amount that is harvested and transported (hence excluding harvest losses). For energy crops, it is assumed that 100% will be available for energy production.

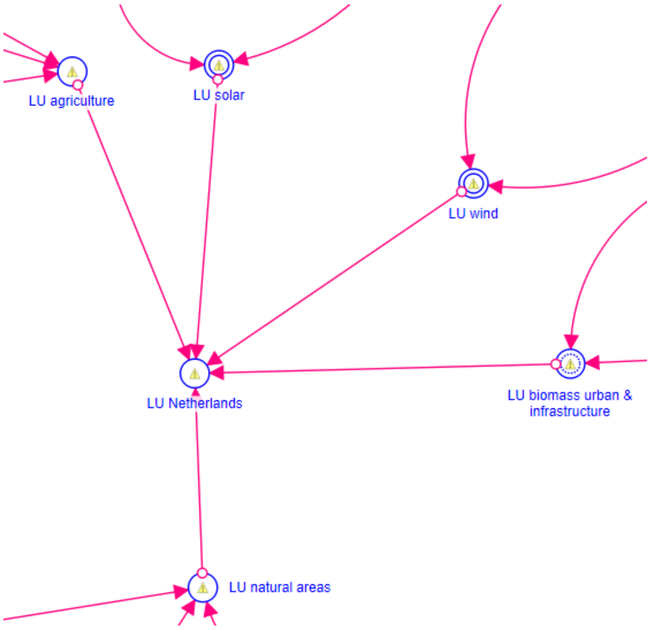


Figure 3.7.4: Land-use in the Dutch SDM

3.8 Azerbaijan case study

3.8.1 Short description of the case study

Azerbaijan is located in the southern Caucasus region (Figure 3.8.1). It is bordered by the Russian Federation, Iran to the North, and Georgia; with the Caspian Sea to the East. The Republic of Azerbaijan has a territorial area of 86,600 km^2 and a population of 9.81 million people. Not much difference exists between the share of rural and urban population, with 52% living in urban areas in 2011. In terms of topography, it is characterized by extreme altitude variations, from very high elevation in the mountainous part, to -28m in the Caspian Sea. Major industries include the extraction of crude oil and gas, and fields spread all across the country. Oil and gas products represent over 90% of the country exports, 65% of which to European countries, with the top importers being Italy, Germany and France (MIT Observatory of Complexity).

The Republic of Azerbaijan, hereinafter Azerbaijan, is by definition a transition economy which aspires to open up to a more market oriented pattern. Following the collapse of the Soviet Union in the early 1990s, the country started focusing on the hydrocarbon industry (oil and natural gas), which led to massive economic growth from 2005 onwards. On the other hand, this dependence makes the country vulnerable to the oil and gas prices' oscillation. When the oil prices dropped in 2014/2015, the Azeri currency, the Manat, devalued 30% in February 2015 and 50% further in December of the same year (Pirani, 2016). Although fuel exports constitute the cornerstone of Azerbaijan's economy accounting for more than 90% of its exports (WTO, n.d.), agriculture is the largest employer - in 2014 (UN Data, n.d.) it accounted for 36.8% of employment.

Although Azerbaijan is technically an Asian country, its relations with the European Union have been gaining momentum. The European Union (EU) is the major trade partner of Azerbaijan while the latter is also part of several EU initiatives namely the European Neighborhood Policy (ENP), Eastern Partnership and the Council of Europe (EEAS, n.d.). Cooperation between both parties spans from trade to securing energy security. Consequently, Azerbaijan is linked to Europe in various aspects and therefore, analyzing certain aspects of the country in conjunction with drivers stemming from EU decisions should be pursued.

This case study aims at exploring the implications of Azerbaijan's transition to a low carbon economy to a range of nexus domains, which have their specific challenges and priorities. Additionally, the impact of external international and transnational policies will be investigated, since Azerbaijan's economy relies greatly on the export of crude oil to European countries, which also aim at decarbonising their economies. Stakeholders have been and are expected to be involved in the development of the case study, however this stakeholder engagement process has proven to be quite difficult to achieve.

Below follows a list of the systems under analysis in this study. This list is tentative as it is possible that other sectors will be deemed important after delving deeper in the study and interacting with stakeholders. It is worth noting that the overall analysis will cover both physical and policy related aspects.

- Water: over 70% of the water resources of Azerbaijan are transboundary. Water is a key resource to agriculture and dependence on external water resources increases the vulnerability of the food production sector. Water supply and demand will be investigated using a simplified accounting framework.

- Land Use: Reforestation is a key priority to the country, due to the importance of forest cover to ecosystems services, hydrology and mitigation potential.
- Food: explore food production and consumption under pressures driven by other systems, for example, climate and land use; the food nexus domain is considered in this case study to include livestock production.
- Energy: investigate decarbonisation diversification pathways of energy supply, spanning from resources to final consumption of all energy forms in every sub-sector;
- Climate: understand the potential implications of climate change across the nexus; assess the greenhouse gas emissions of main economic activities and largest emitting sectors; and investigate corresponding adaptation and mitigation solutions.

Four thematic models were selected to explore the nexus interlinkages across the nexus domains of water – land – food – energy and climate. These are E3ME, OSeMOSYS, and MAGNET. The application of the thematic models cover the geographical scope of the Republic of Azerbaijan, with the exception of the CAPRI model where other former Soviet republics, namely Armenia, Georgia, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan and Uzbekistan (along with Azerbaijan).

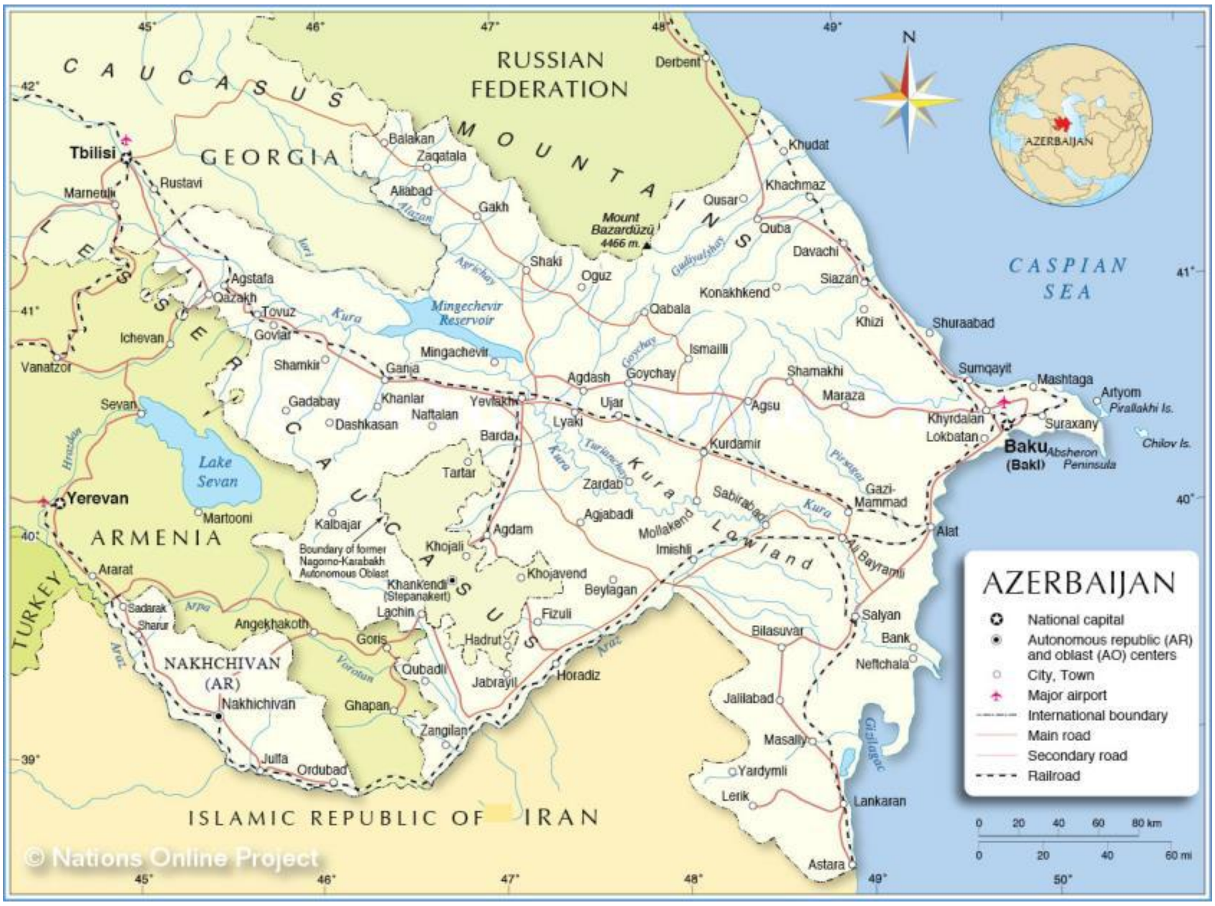


Figure 3.8.1: Map of the SIM4NEXUS Azerbaijan case study.

3.8.2 Evolution and description of the conceptual diagram

Figure 3.8.2 shows the first version of the Azerbaijan conceptual model. In this first version, all nexus sectors are treated equally, even though there is an implied focus on energy and in particular a move away from the current reliance on fossil energy production and consumption. Energy and water are linked (water for energy process, energy production polluting water bodies). Water and food are linked via the water required in agriculture. Land, in the centre, is linked to water again through water demands in different land types. It is linked to food as food is produced on land and erosion is mentioned. With respect to climate, the main impacts are indeed from the currently fossil-fuel dominated energy sector. Therefore, any changes to energy generation should be represented by changes in GHG emissions to the climate sector. In addition, pollution, inefficient resource management and erosion due to poor land management practices are also highlighted in this initial version.

Through a consultative stakeholder workshop, the initial conceptual was refined over a number of iterations, becoming more specific in the issues that are key for this case study. Detail and complexity was added to those sectors which represent the focus of this case study, in particular, energy generation.

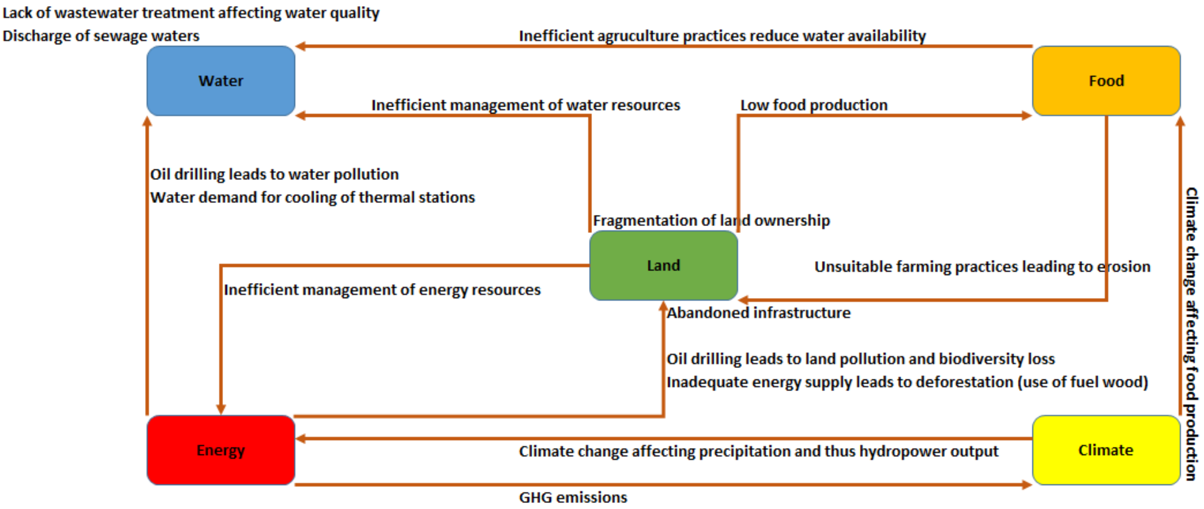
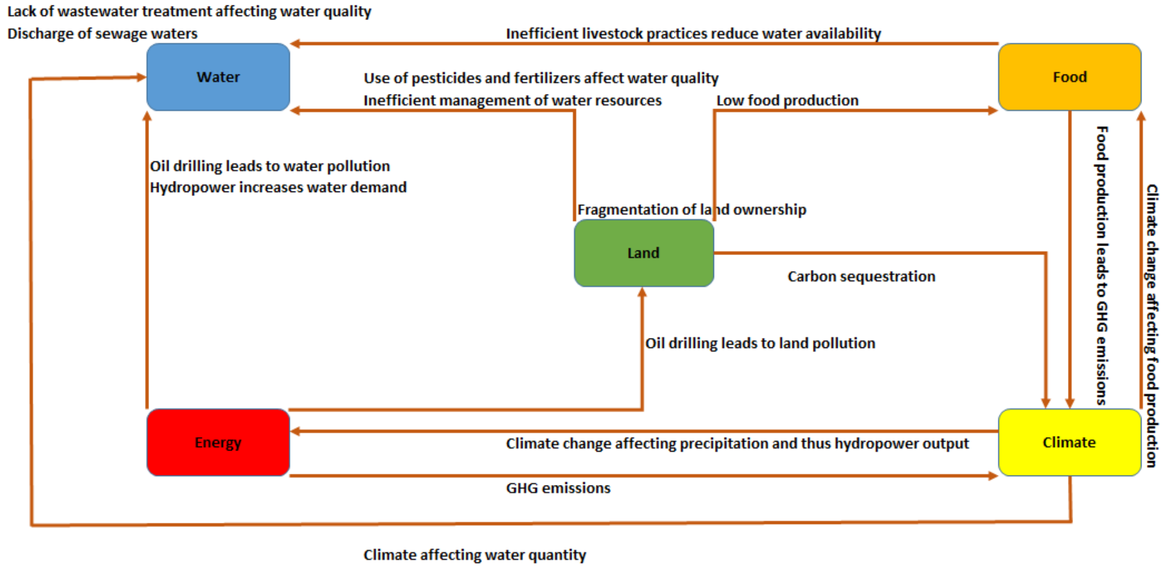


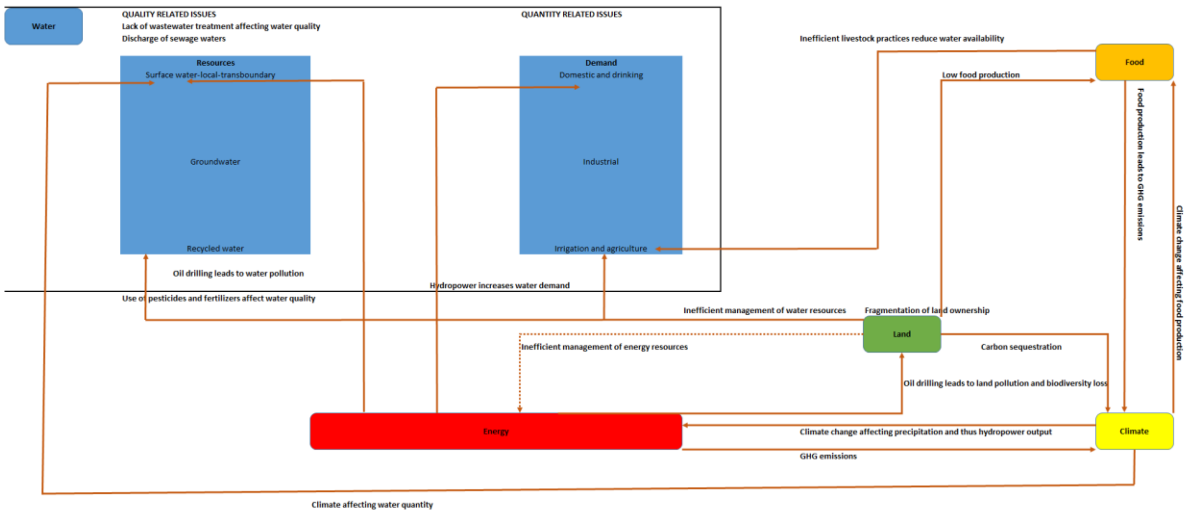
Figure 3.8.2: Initial conceptual model for the Azerbaijan case study.

Figure 3.8.3 shows the final version of the Azerbaijan conceptual model. The top-level model (Figure 3.8.3a) showing the major nexus interlinkages has not changed appreciably since the first iteration, although some links have been slightly elaborated or made more specific. However, the specific sub-sectors are now developed in detail (Figure 3.8.3b-f).

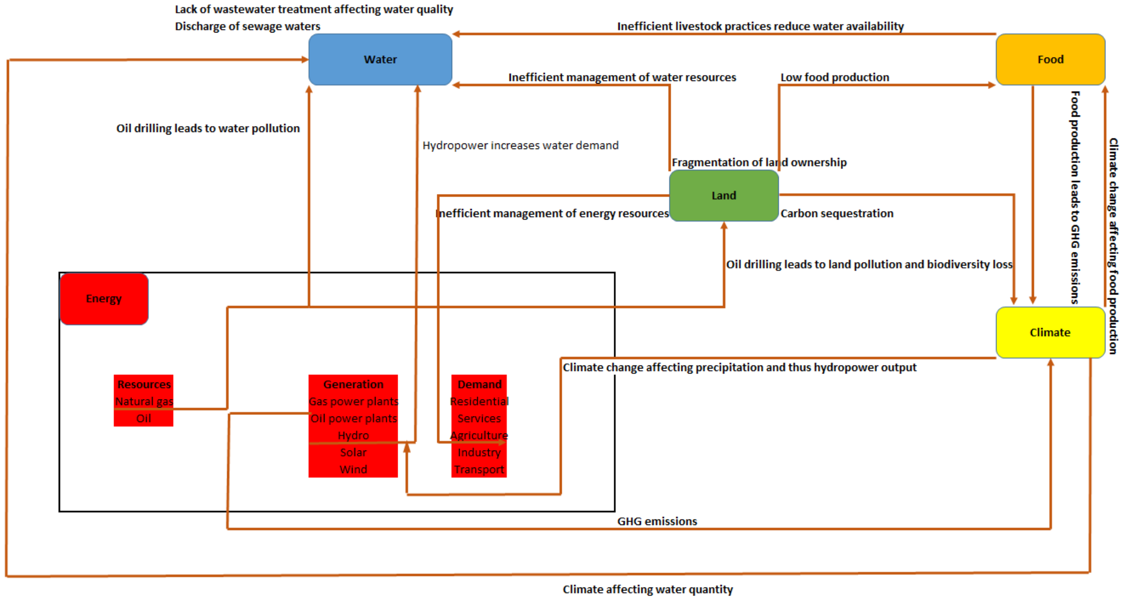
(a)


Lack of wastewater treatment affecting water quality
Discharge of sewage waters
Inefficient livestock practices reduce water availability
Water
Food
Use of pesticides and fertilizers affect water quality
Inefficient management of water resources
Low food production
Oil drilling leads to water pollution
Hydropower increases water demand
Fragmentation of land ownership
Land
Carbon sequestration
Oil drilling leads to land pollution
Food production leads to GHG emissions
Climate change affecting food production
Energy
Climate change affecting precipitation and thus hydropower output
Climate
GHG emissions
Climate affecting water quantity

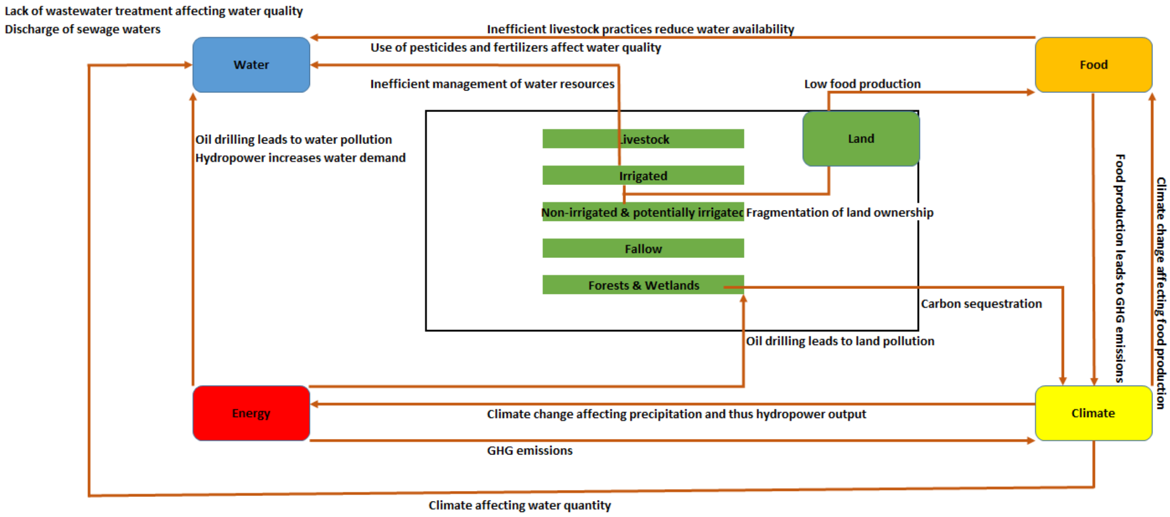
(b)


Water
QUALITY RELATED ISSUES
Lack of wastewater treatment affecting water quality
Discharge of sewage waters
QUANTITY RELATED ISSUES
Resources
Surface water-local-transboundary
Groundwater
Recycled water
Demand
Domestic and drinking
Industrial
Irrigation and agriculture
Inefficient livestock practices reduce water availability
Food
Low food production
Food production leads to GHG emissions
Climate change affecting food production
Oil drilling leads to water pollution
Hydropower increases water demand
Use of pesticides and fertilizers affect water quality
Inefficient management of water resources
Fragmentation of land ownership
Land
Inefficient management of energy resources
Carbon sequestration
Oil drilling leads to land pollution and biodiversity loss
Energy
Climate change affecting precipitation and thus hydropower output
Climate
GHG emissions
Climate affecting water quantity

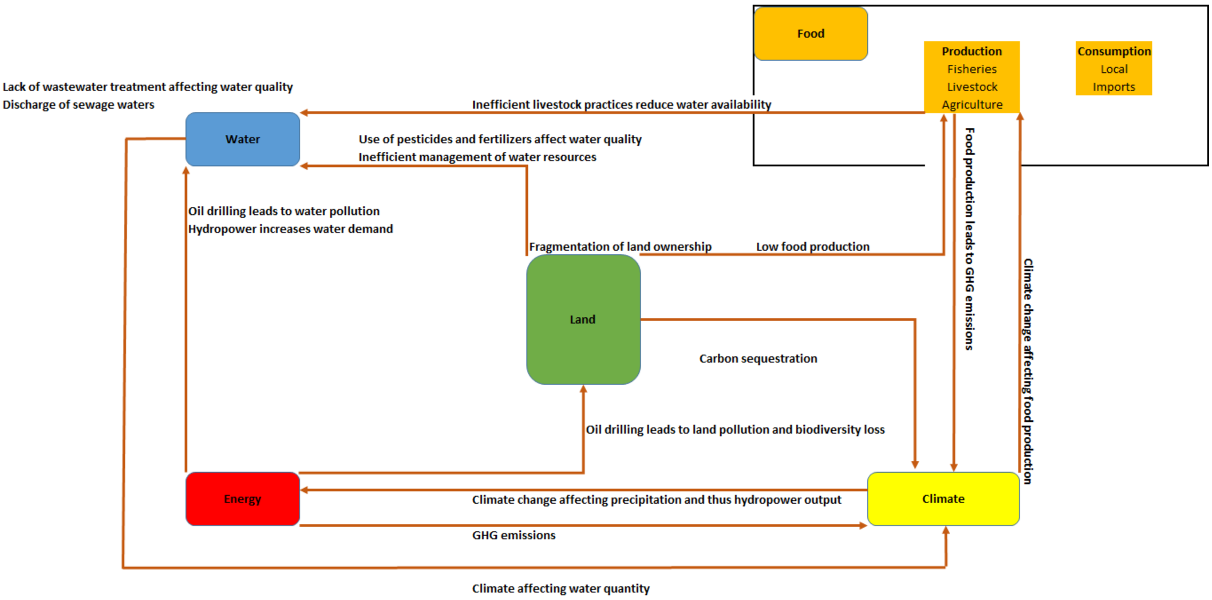
(c)


Lack of wastewater treatment affecting water quality
Discharge of sewage waters
Inefficient livestock practices reduce water availability
Water
Food
Inefficient management of water resources
Low food production
Oil drilling leads to water pollution
Hydropower increases water demand
Fragmentation of land ownership
Food production leads to GHG emissions
Climate change affecting food production
Land
Inefficient management of energy resources
Carbon sequestration
Oil drilling leads to land pollution and biodiversity loss
Energy
Climate
Climate change affecting precipitation and thus hydropower output
Resources
Natural gas
Oil
Generation
Gas power plants
Oil power plants
Hydro
Solar
Wind
Demand
Residential
Services
Agriculture
Industry
Transport
GHG emissions
Climate affecting water quantity

(d)


Lack of wastewater treatment affecting water quality
Discharge of sewage waters
Inefficient livestock practices reduce water availability
Use of pesticides and fertilizers affect water quality
Water
Food
Inefficient management of water resources
Low food production
Oil drilling leads to water pollution
Hydropower increases water demand
Livestock
Land
Irrigated
Non-irrigated & potentially irrigated
Fragmentation of land ownership
Fallow
Forests & Wetlands
Carbon sequestration
Food production leads to GHG emissions
Climate change affecting food production
Oil drilling leads to land pollution
Energy
Climate change affecting precipitation and thus hydropower output
Climate
GHG emissions
Climate affecting water quantity

(e)



(f)

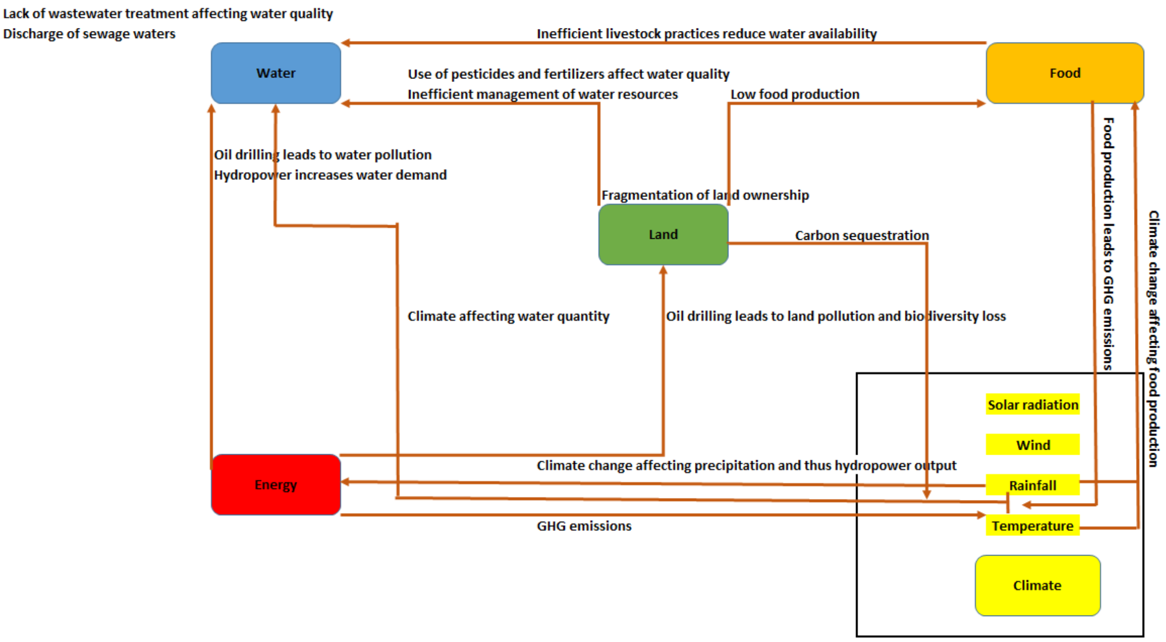


Figure 3.8.3: Final version of the Azerbaijan conceptual model showing: (a) the top-level nexus overview with the links between all nexus sectors; (b) the water sector; (c) the energy sector; (d) the land sector; (e) the food sector and; (f) the climate sector.

The water sector (Figure 3.8.3b) sub-sector specifies that quality and quantity should be accounted for, regarding groundwater and surface water resources, also accounting for transboundary water resources and the use recycled water. In terms of use, domestic, industrial and agricultural users are to be assessed. There are links to energy, in terms of the water requirements in the energy sector, and in terms of energy demanded in the water sector. Energy-related water pollution is highlighted. The link to food and land is made via water demands for (irrigated) agriculture. Climate impacts on water resources. For the energy sector (Figure 3.8.3c) is elaborated to include a number of specific items. There is obviously a focus on the fossil energy sector in terms of generation, although wind and solar are also represented. Demand comes from a range of sectors. In terms of links to other sectors, energy is connected to water (pollution from oil drilling, and demand via hydropower), land (in terms of pollution again), and climate, through GHG emissions from the generation and use of fossil energy. Land (Figure 3.8.3d) is relatively simple, and includes five main sub-sectors. Land is linked to water via water demand for agricultural activities, to food as food is produced on land, to energy via pollution impacts and to climate via carbon sequestration potential. The food sector (Figure 3.8.3e), being relatively unimportant in this case study, is not developed in detail, accounting only for food production and consumption in a very broad sense, and linking to the other nexus sectors, especially to climate and water. Finally, the climate sector (Figure 3.8.3f) is also relatively basic, mainly considering changes in GHG emissions and sequestration resulting from changes in energy generation sources and from changes in land cover and food production. It does however account for the climate impacts of major changes to the Azeri land and energy sectors - the most important for SIM4NEXUS.

3.8.3 Description of the developed system dynamics model

Figure 3.8.4 shows the top-level SDM for the Azerbaijan case. This corresponds to Figure 3.8.3, and shows the high-level connections between all the five main nexus sectors. Within each rounded box in Figure 3.8.4, the nexus sectors have been developed in considerable detail, and is described in this section.

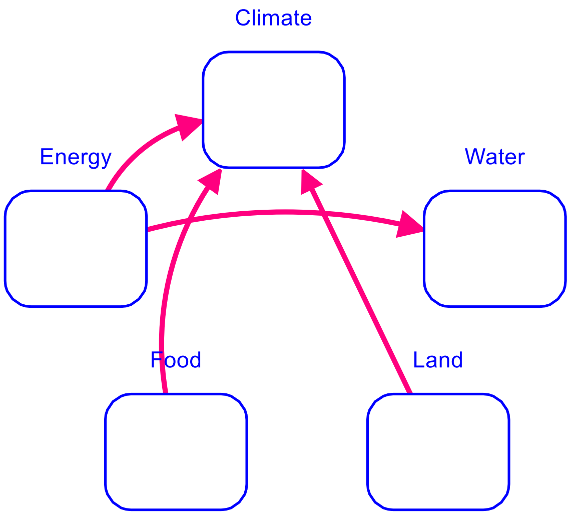


Figure 3.8.4: The top-level of the Azerbaijan SDM.

The water sector sub-model (Figure 3.8.5) accounts for water availability from ground and surface water resources, and demand from the domestic (linked to population), industrial, and irrigated agriculture sectors. Water for small scale hydropower is separately accounted for. Because of the importance of energy production in Azerbaijan, the water requirements of the energy sector are separately specified, and is estimated through knowledge of the generation type, the operation duration, the water consumed per-condensation unit and the annual power generated. A small of amount of water is recycled and reused, contributing to supply.

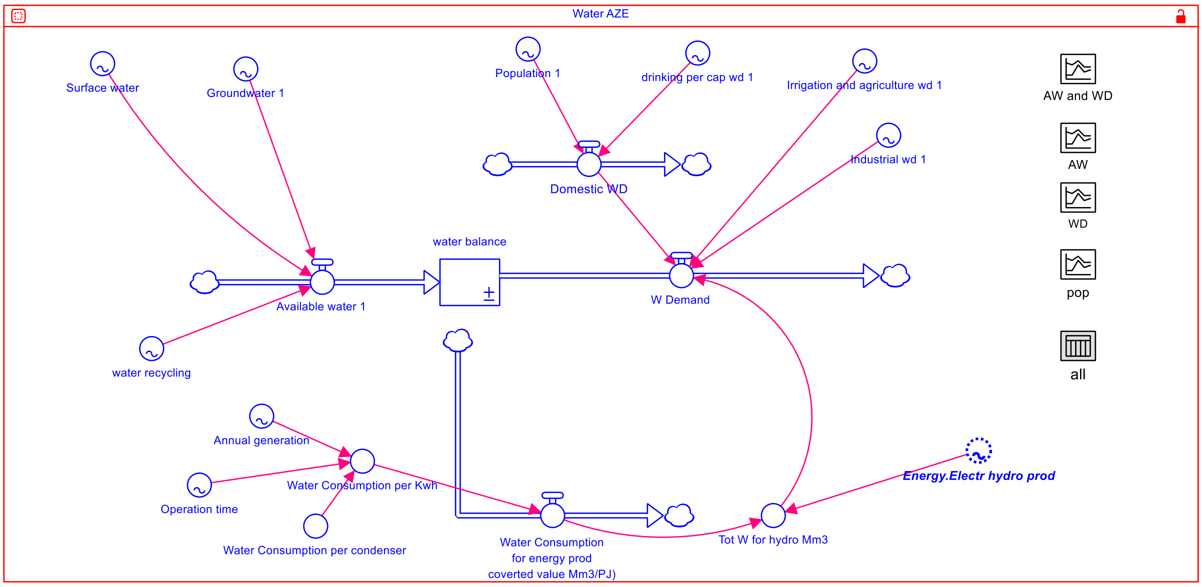


Figure 3.8.5: The water sector sub model for the Azerbaijan case in SIM4NEXUS.

Land use is relatively simply developed and shown in Figure 3.8.6. The total land area is split into forestry land, irrigated land, non-irrigated land and fallow land.

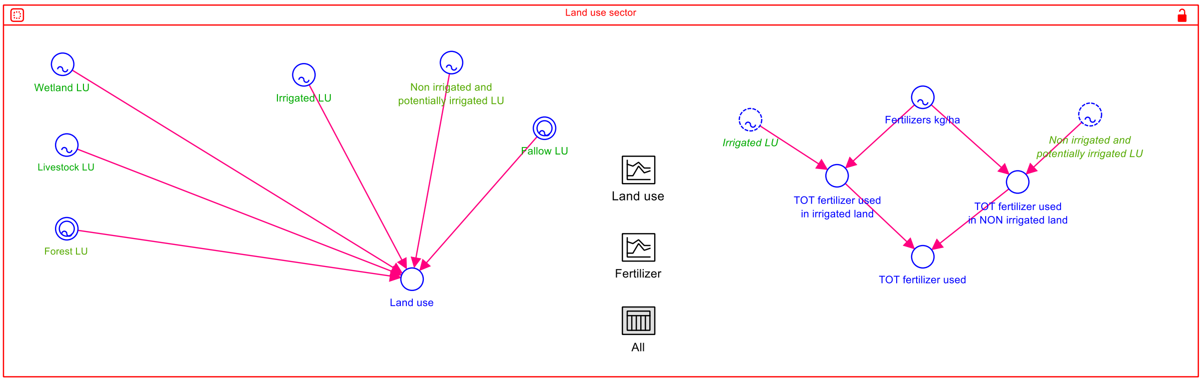


Figure 3.8.6: The land sector for the Azerbaijan case study.

The food production sector is developed in more detail (Figure 3.8.7). Food production consists of net imports, fishery production, livestock, and crop foods, both from irrigated and non-irrigated lands. Food production is determined by population and statistics on consumption per-capita, and also helps mediate local production volumes.

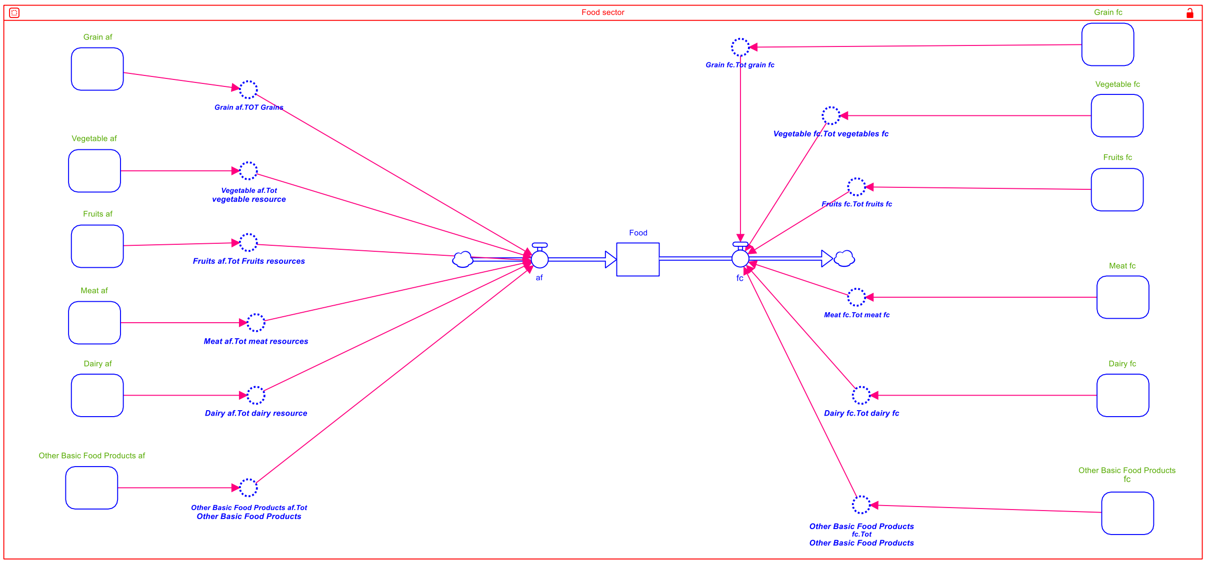


Figure 3.8.7: The developed food sector sub-model for the Azerbaijan case.

The energy sector is well developed, as expected given the central theme for the case study is the energy sector in Azerbaijan Figure 3.8.8. Electricity is produced from renewable and non-renewable sources. Non-renewable sources include natural gas and oil, while renewables include hydropower, solar and wind. Demand comes from a number of sectors, including residential (driven by population changes), services, irrigation and agriculture, industry and transport. Energy supply is largely driven to meet demand, hence a feedback mechanism between these aspects.

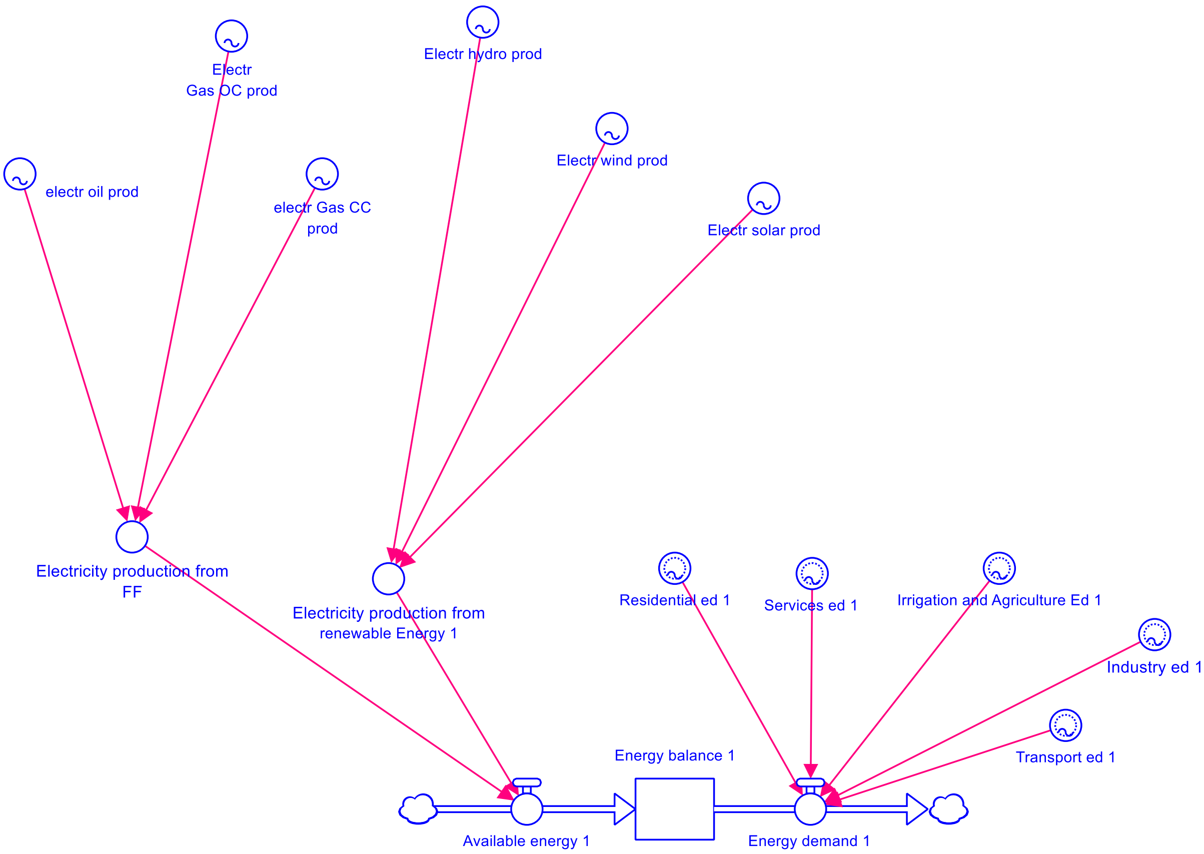


Figure 3.8.8: The energy sector sub model for Azerbaijan.

Finally, the climate sector is represented to account for emissions and sequestration (Figure 3.8.9). Carbon sequestration is facilitated through land use types. Emissions come from a number of sectors, each with their own sub-models: energy production, energy consumption, and food production.

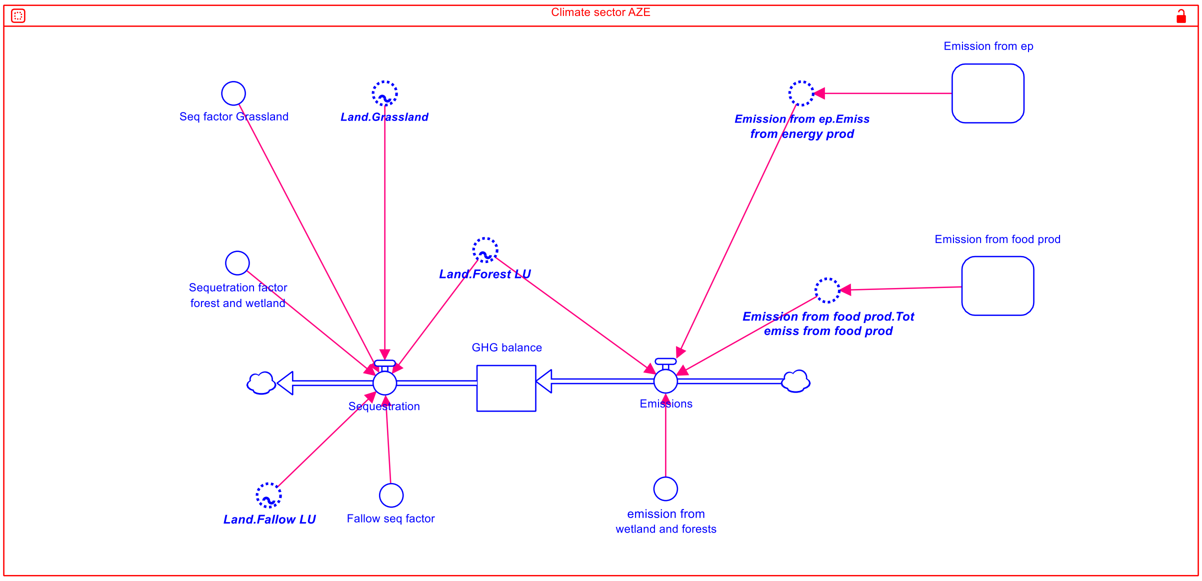


Figure 3.8.9: The climate sector-sub-model for the Azerbaijan case.

Emissions from energy production relate to the oil and gas sectors, while for consumption, all the energy-demanding sectors as described above are accounted for. In terms of emissions from food production, livestock, crops and fisheries are all accounted for. Finally, the impact of forestry activities is defined.

3.9 Transboundary France-Germany case study

3.9.1 Short description of the case study

The France-Germany transboundary Case Study (Figure 3.9.1) examines pathways to achieve the 2°C targets on climate change, as set by the Paris Agreement. It also confronts the implementation of the European directives (Common Agricultural Policy, Water Framework Directive, Flood Directive) and the national legislations on energy transition in a transboundary region.

Figure 3.9.1: The SIM4NEXUS France-Germany transboundary case study.

The specificity of this case study, compared to the other cases of the SIM4NEXUS project, is to put the emphasis on the consequences for aquatic ecosystems and riverine functionality. The case study focuses on the links and synergies between energy policy and the transition to a low-carbon economy as well as the management of natural resources and in particular water and ecosystems: here there is a clear trade-off. This case investigates the links between policy development and implementation on both sides of the Rhine, and whether there would be opportunities for enhancing cooperation and policy coherence between France and Germany for jointly achieving policy objectives. Stakeholders from both sides of the border have been met in order to understand their relations with the organisations of the neighbouring country and gather information about the main issues, present and future. The transboundary France-Germany case study is situated in the Upper Rhine region and covers the federal state of Baden-Württemberg (35 751 km^2) on the German side and the newly formed Grand Est Region1 (57 800 km^2) on the French side, with the (Upper) Rhine playing the role of physical and administrative border in its middle. The area along the Rhine is one of the most densely populated and highly industrialized area of the European continent.

3.9.2 Evolution and description of the conceptual diagram

Figure 3.9.2 shows the first version of the conceptual model for the France-Germany case study. As shown in Figure 3.9.2, energy and water feature prominently, consistent with the brief case study description, with less emphasis placed on the other nexus sectors. Of particular note is that water quantity and quality are explicitly mentioned, as is the ecological status of the water bodies. Multiple energy sources are identified. The major linkages between nexus sectors are indicated, although at this stage, no indication of the mechanisms of their interaction is given. Also, and unique to this case study at this stage of development, six potential policy entry points to the nexus are identified.

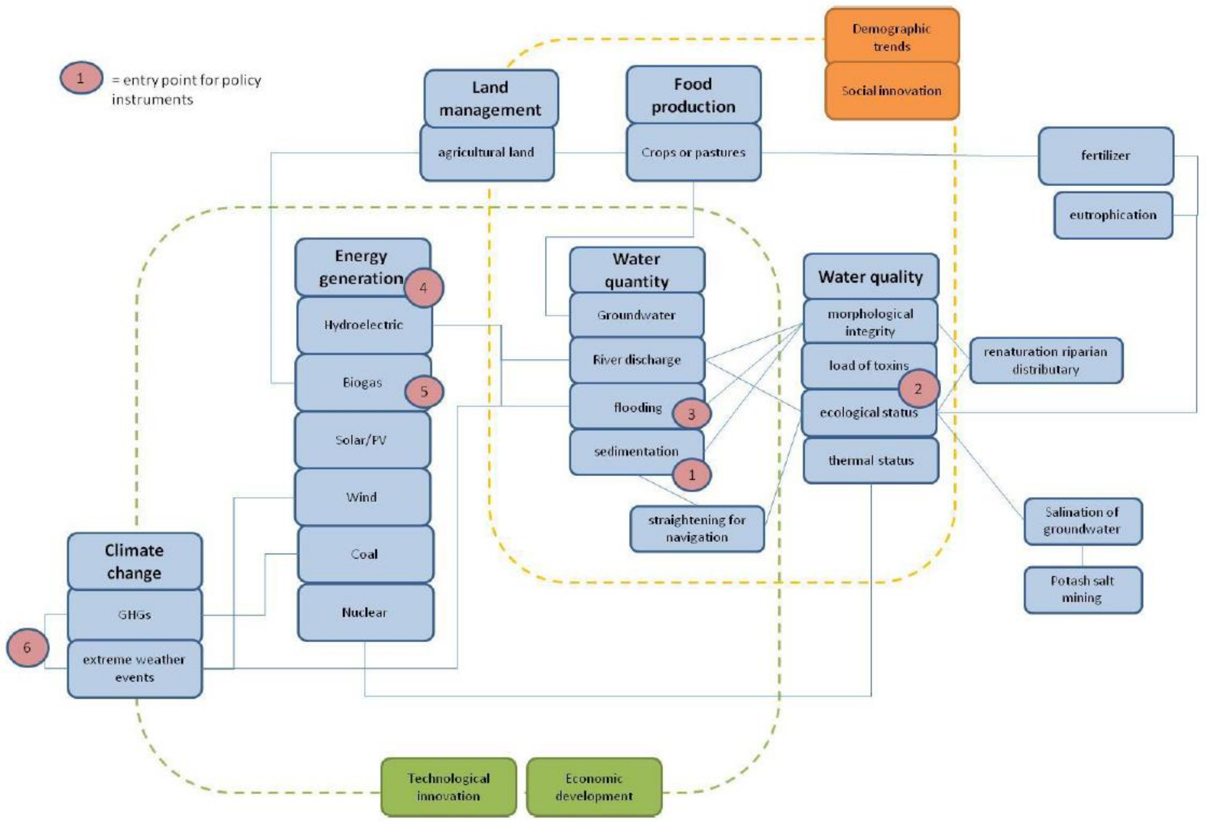


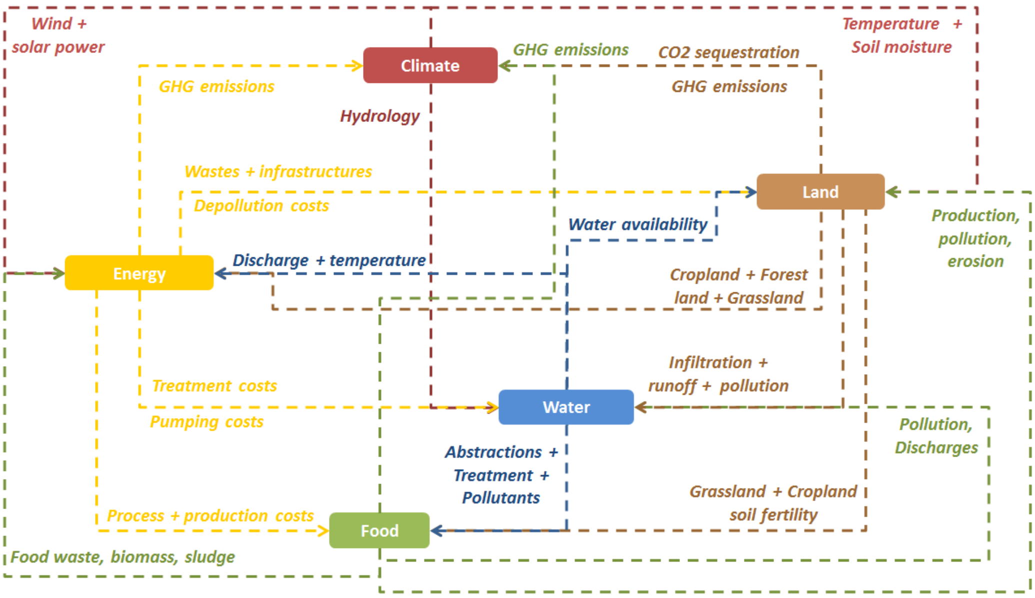
Figure 3.9.2: First draft conceptual model for the France-Germany SIM4NEXUS case study.

The final version of the France-Germany conceptual model is presented in Figure 3.9.3, with Figure 3.9.3a showing the high-level nexus overview, including all the interconnections. The overview shown in more detail than the initial version how the five main nexus sectors are important. Water pollution, abstraction and quantities are important (the link to ecosystem services). The climate impacts of energy production are highlighted, along with the energy costs of water distribution and treatment. Also of note at this high level are the land-related impacts on other nexus components, especially related to runoff and pollutant loads, soil fertility and GHG emissions resulting from land use practices. In bold lines or bold letters, the contributions from the participants to the stakeholder workshop are visualised and recognised.

Figure 3.9.3b shows the water sub-sector. Surface and groundwater sources are identified, along with climate change impacts. Many users are highlighted, and there is a differentiation between raw water use (e.g. in industrial processes) and treated water use (e.g. in the domestic sector). Land activities pollute water bodies, affecting aquatic ecosystems. Water generates energy, but also consumes energy for treatment, distribution and wastewater treatment. Some water is re-used, contributing to the resource base. Water is also consumed in the food sector.

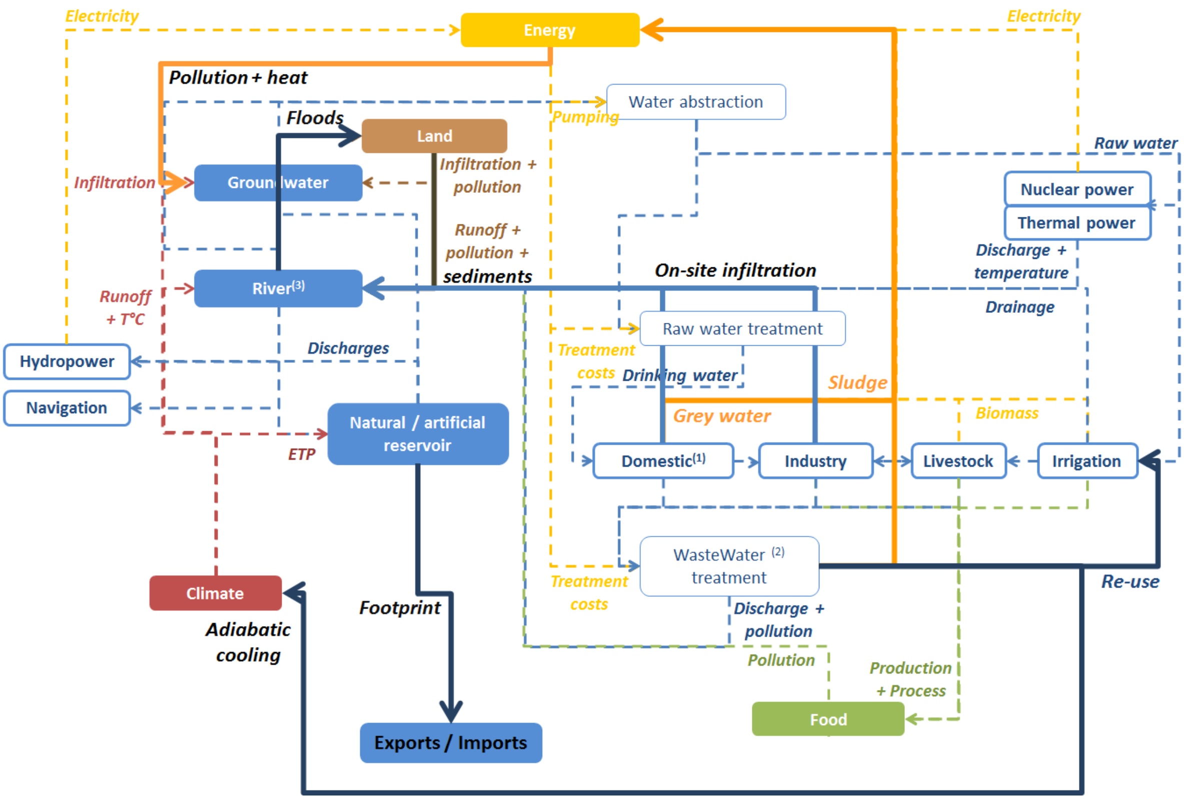
(a)

Complete model 5 Nexus dimensions in the France-Germany case study

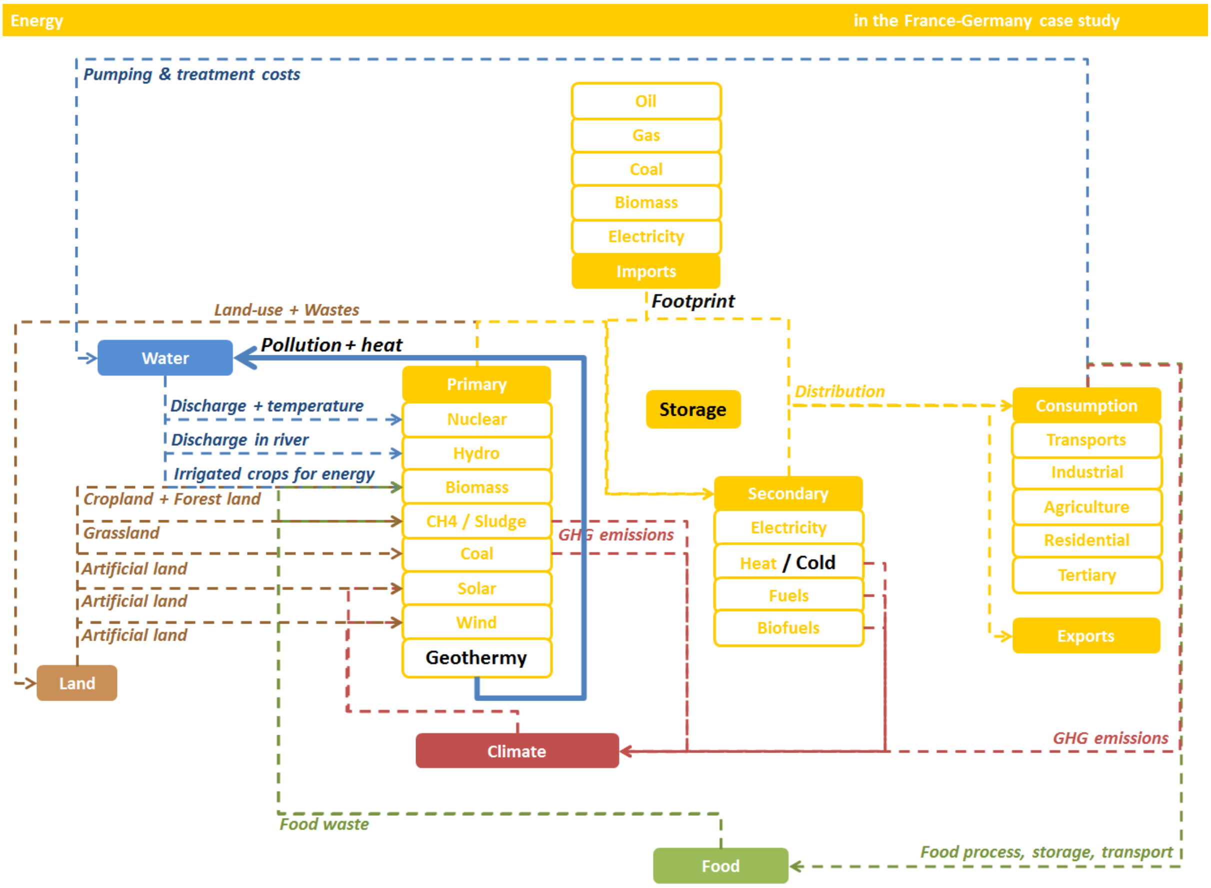


(b)

Water in the France-Germany case study

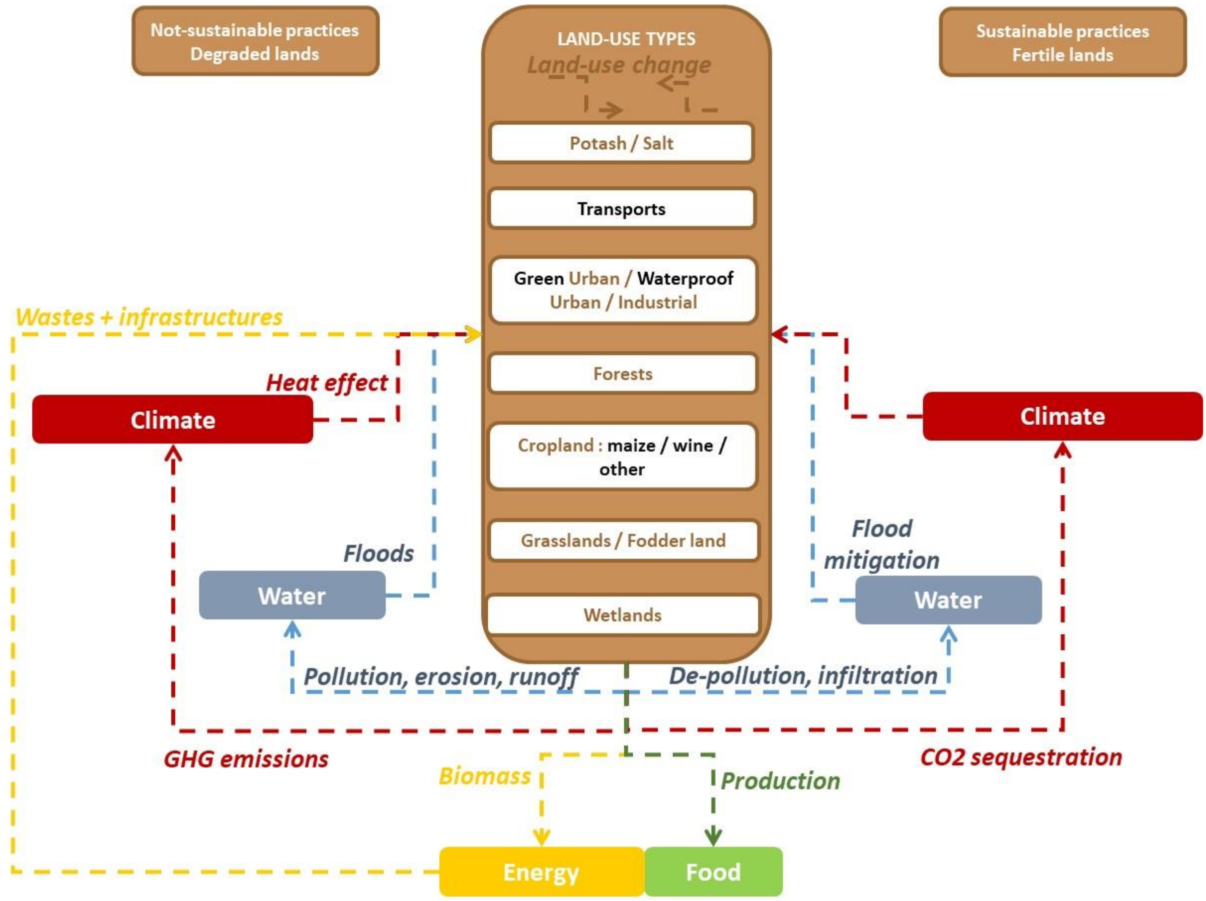


(c)

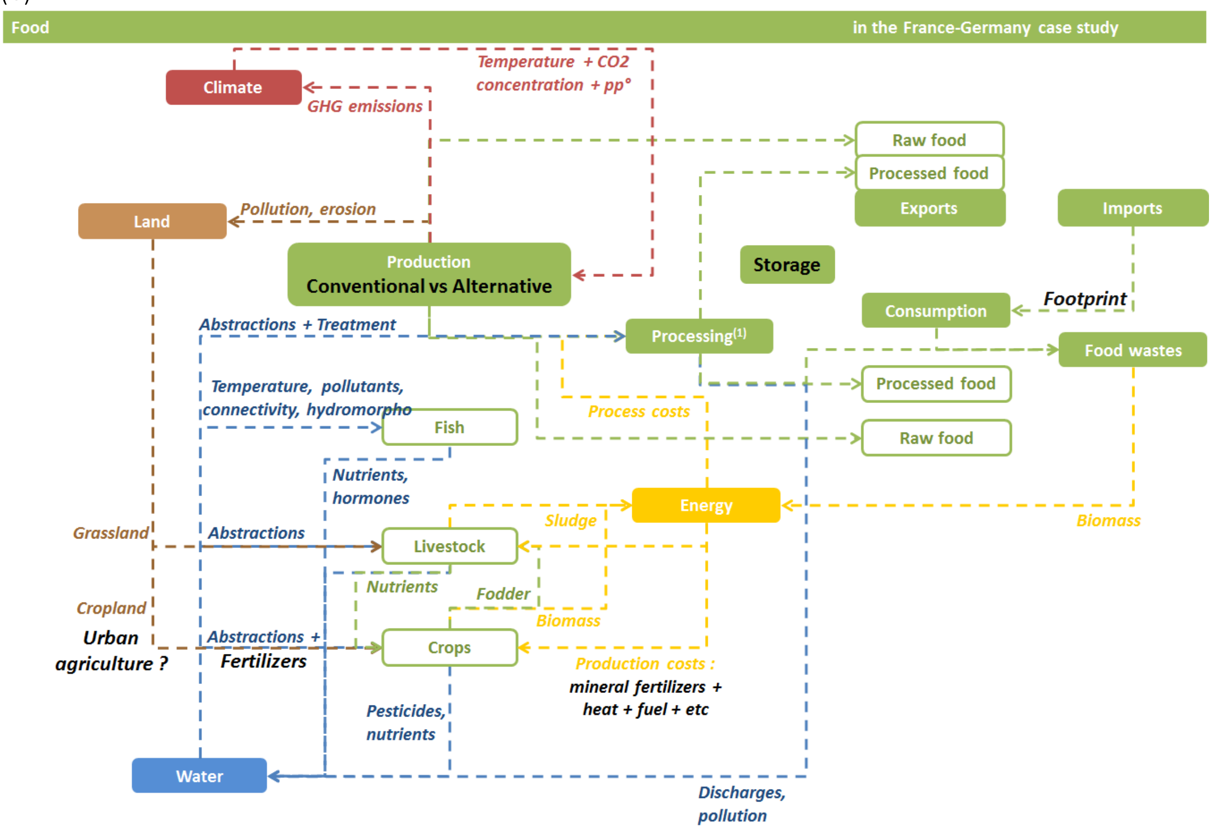


Energy
in the France-Germany case study
Pumping & treatment costs
Oil
Gas
Coal
Biomass
Electricity
Imports
Footprint
Land-use + Wastes
Water
Pollution + heat
Primary
Nuclear
Hydro
Biomass
CH4 / Sludge
Coal
Solar
Wind
Geothermy
Discharge + temperature
Discharge in river
Irrigated crops for energy
Cropland + Forest land
Grassland
Artificial land
Artificial land
Artificial land
Land
Storage
Distribution
Secondary
Electricity
Heat / Cold
Fuels
Biofuels
GHG emissions
Consumption
Transports
Industrial
Agriculture
Residential
Tertiary
Exports
Climate
GHG emissions
Food waste
Food
Food process, storage, transport

(d)

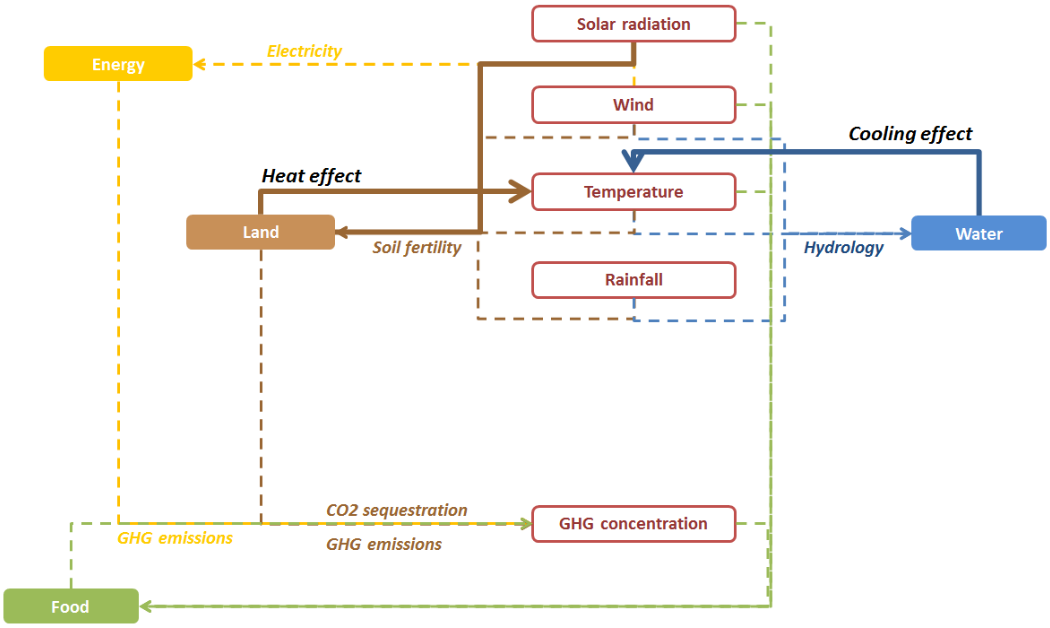

Not-sustainable practices
Degraded lands
LAND-USE TYPES
Land-use change
Potash / Salt
Transports
Green Urban / Waterproof
Urban / Industrial
Forests
Cropland : maize / wine / other
Grasslands / Fodder land
Wetlands
Sustainable practices
Fertile lands
Wastes + infrastructures
Heat effect
Climate
Climate
Floods
Water
Flood mitigation
Water
Pollution, erosion, runoff
De-pollution, infiltration
GHG emissions
CO2 sequestration
Biomass
Production
Energy
Food

(e)


Food
in the France-Germany case study
Climate
Temperature + CO2 concentration + pp°
GHG emissions
Raw food
Processed food
Exports
Imports
Land
Pollution, erosion
Production
Conventional vs Alternative
Storage
Consumption
Footprint
Abstractions + Treatment
Processing(1)
Food wastes
Temperature, pollutants, connectivity, hydromorpho
Processed food
Process costs
Fish
Raw food
Nutrients, hormones
Energy
Sludge
Biomass
Grassland
Abstractions
Livestock
Nutrients
Fodder
Cropland
Biomass
Urban agriculture ?
Abstractions +
Fertilizers
Crops
Production costs :
mineral fertilizers + heat + fuel + etc
Pesticides, nutrients
Water
Discharges, pollution

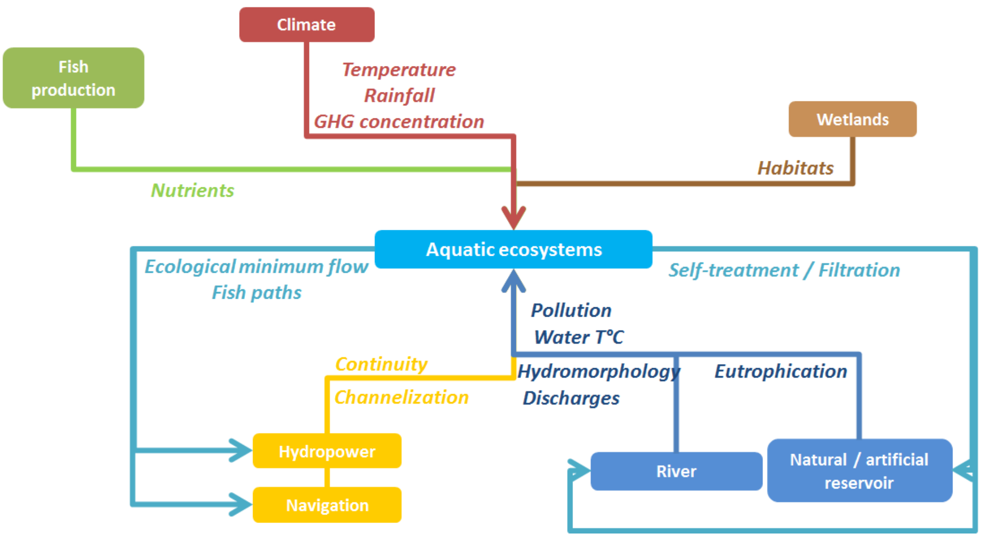
(f)

Climate in the France-Germany case study



(g)

Aquatic Ecosystems in the France-Germany case study



(h)

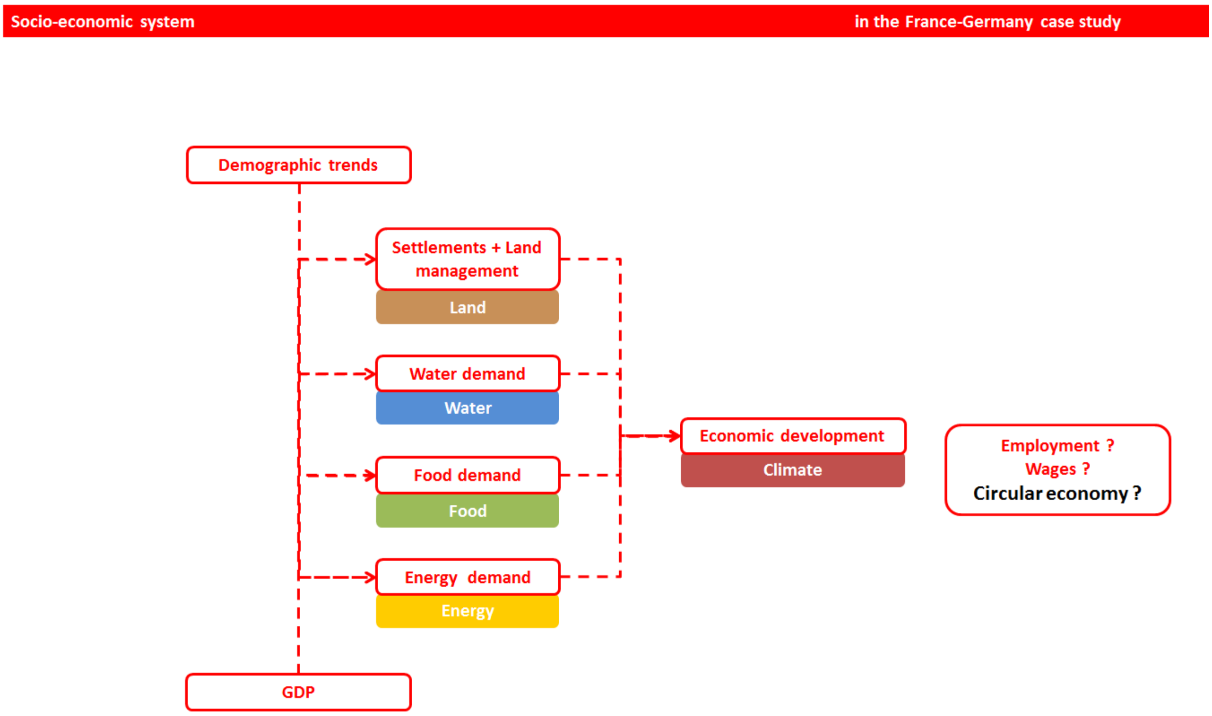


Figure 3.9.3: Final version of the transboundary France-Germany conceptual model showing: (a) the top-level nexus overview with the links between all nexus sectors; (b) the water sector; (c) the energy sector; (d) the land sector; (e) the food sector; (f) the climate sector; (g) the aquatic ecosystem sector and; (h) the socio-economic sector.

In the energy sector (Figure 3.9.3c), a wide variety of primary sources are identified including nuclear, hydro, coal, solar, and wind. These are converted into electricity, heat and (bio-)fuels, and used by many sectors, including transport, industry, residential and agriculture. The energy sector impact to climate are important, and are highlighted. The contributions from land to energy (biomass) are clearly indicated (therefore any policy in the land sector could have impacts for primary energy availability), and the link to and from the water sector is also brought out. Figure 3.9.3d shows the details of the land sector. Forests, cropland, grassland and wetlands are 'productive', and can be used to generate other resources such as food and energy. However they can also be degraded, making them less productive. Urban land is classed as degraded. Land can move in and out of a degraded classification. Land impacts water and food through pollution and erosion amounts, and also contributes to energy through biomass production. Land use can also be used to sequester GHGs, but land use can also emit GHGs (e.g. cattle farming), contributing to global warming. The quality of land available can direct affect the quantity and quality of food produced, and could also impact the biomass generated for energy production. Figure 3.9.3e shows the food sector. In the food sector, production and consumption are accounted for. Production is split into food, livestock and crops. Some of this food is consumed in a 'raw' state, but most is processed. Food production and consumption generates waste. Food production is affected by water quantity and quality (e.g. nutrients, temperature), and produces products and waste that can also be used to generate energy. The processing of food can impact on water quality and cause GHG emissions. Consumed food waste can in some cases be used to generate energy. Food production leads to climate emissions, and the climate sector may impact on food (especially crop) production. Change in land extents impact on total production values as given land uses expand or shrink. Figure 3.9.3f details the climate sector. This is very simple, with GHG emissions emanating from the four other nexus sectors and impacting on climate variables such are temperature and precipitation. Sequestration is represented as negative emissions. The case study has also developed two other sub-sectors that should be accounted for in the quantitative modelling. The first is the aquatic ecosystem (Figure 3.9.3g).

Aquatic ecosystems are impacted by changes in food production (via nutrient leakage), the climate (temperature changes in particular), water (especially via water quality parameters, but also by low-flow discharges and the volume and timings of flow peaks), and also by the energy sector (ecosystem continuity may be broken by hydropower plants for example. The exact processes are to be fully defined. Finally, the socio-economic system (Figure 3.9.3h), especially demographic and GDP trends, is used to drive changes in (domestic) demand for water, energy, food, and land, all having a subsequent climate impact.

3.9.3 Description of the developed system dynamics model

Figure 3.9.4 shows the top-level of the France-Germany SDM, depicting all the major nexus sector links.

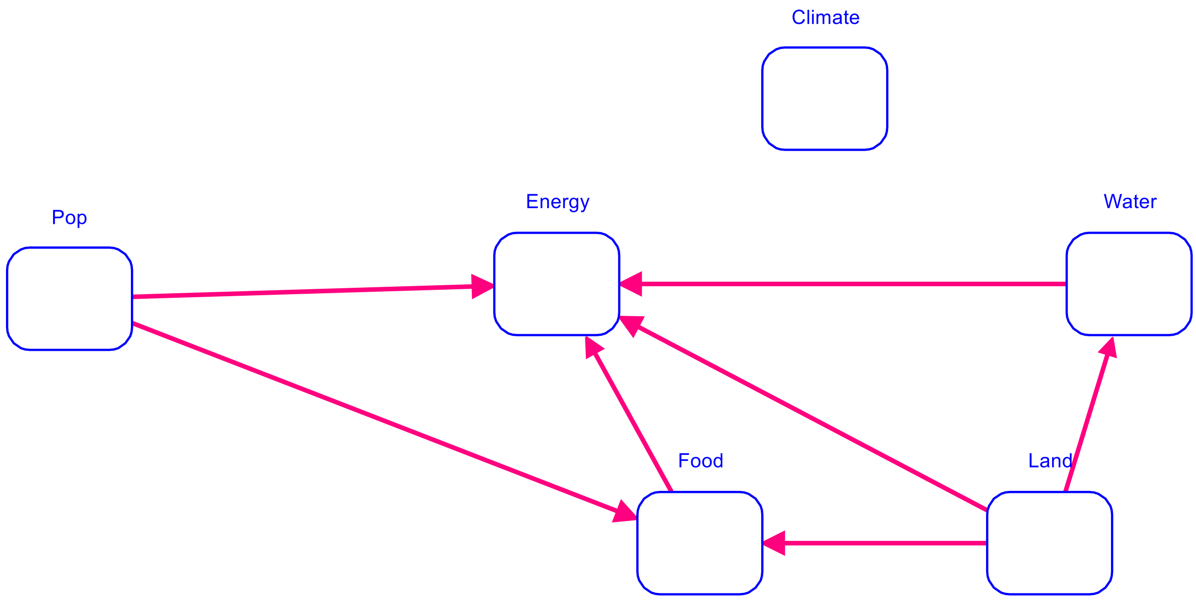


Figure 3.9.4: Top-level SDM representation of the France-Germany SDM.

The water sector is developed in some considerable detail (Figure 3.9.5). Water sources include both surface and ground water contributions to the Rhine. Groundwater is directly exploited for agricultural, industrial, and domestic water supply. From the Rhine water, some is used for hydropower generation, and some is lost as seepage to groundwater. Some seepage loss returns back to the Rhine, so not all of the seepage loss is really 'lost' water. Surface water from the Rhine is used both prior to and following treatment. Prior to treatment, the raw water is used in industry, energy generation, for cattle, and for crop water demand. Treated surface water is used in the public supply network. Of the public demand, wastewater is collected and treated, some of which is reused, therefore representing a resource.

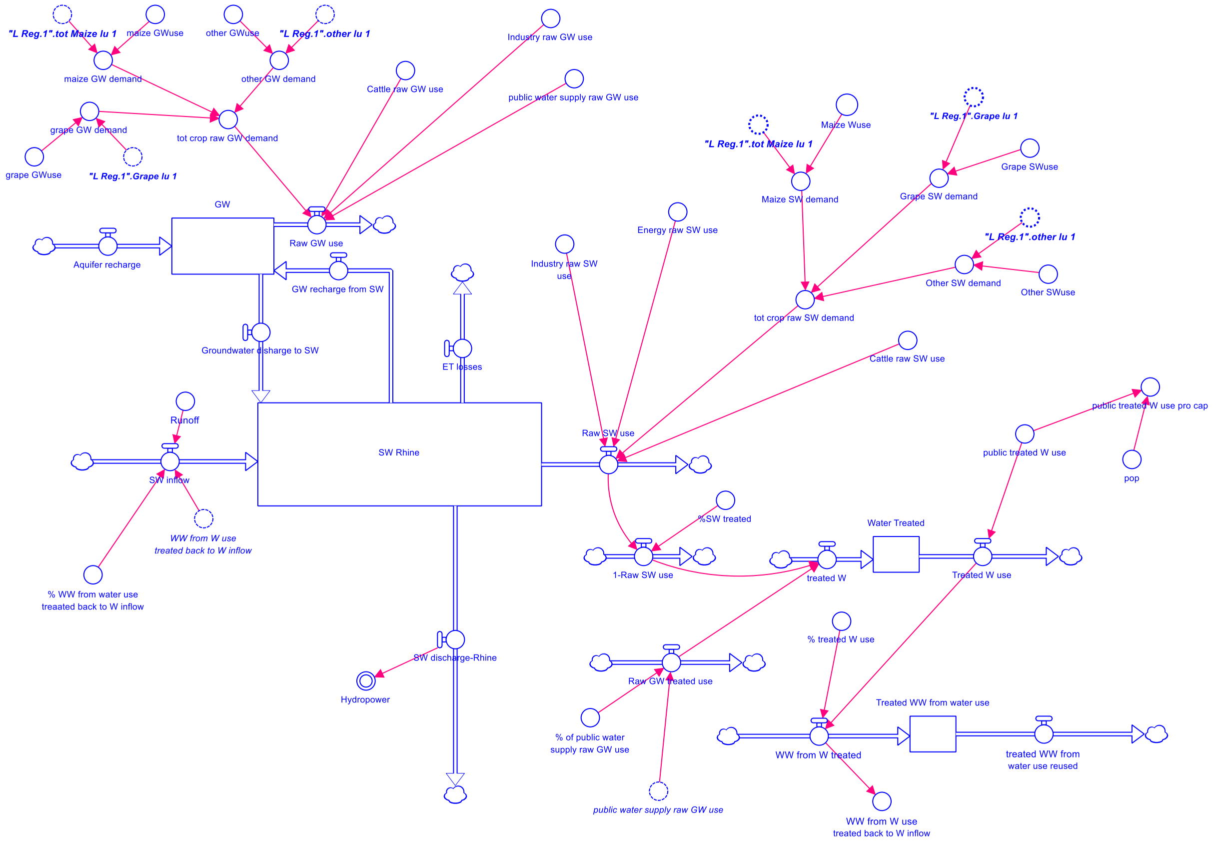


Figure 3.9.5: The water sector in the France-Germany transboundary SDM.

In the land sector (Figure 3.9.6), the areas of different land use are tracked. The areas of different crops for food and energy are tracked, as well as land for forestry applications. In addition, industrial lands, wetlands, urban areas (both green and sealed), grassland, and land dedicated to transportation infrastructure are tracked in the model.

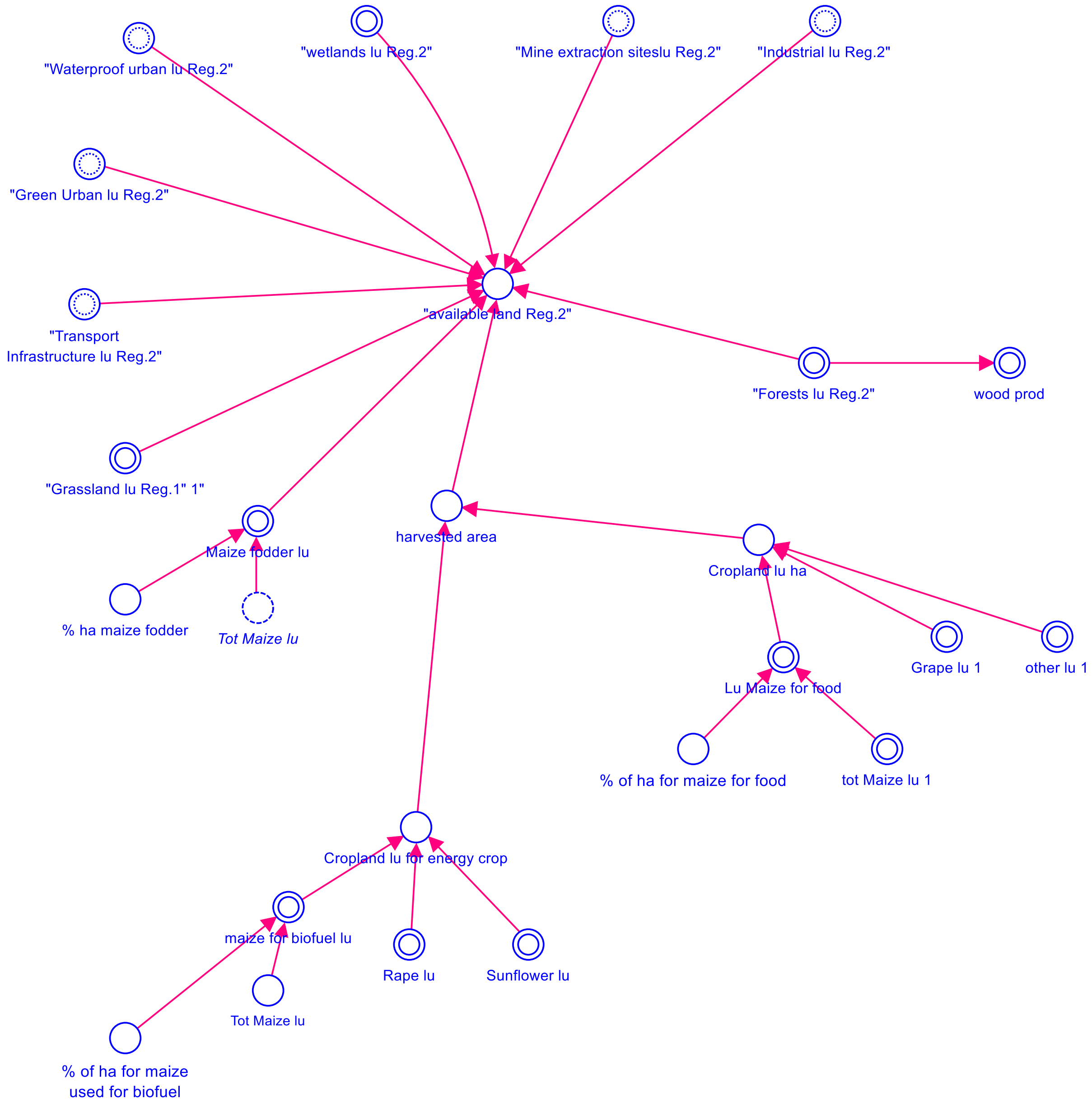


Figure 3.9.6: The land submodel for the France-Germany transboundary case.

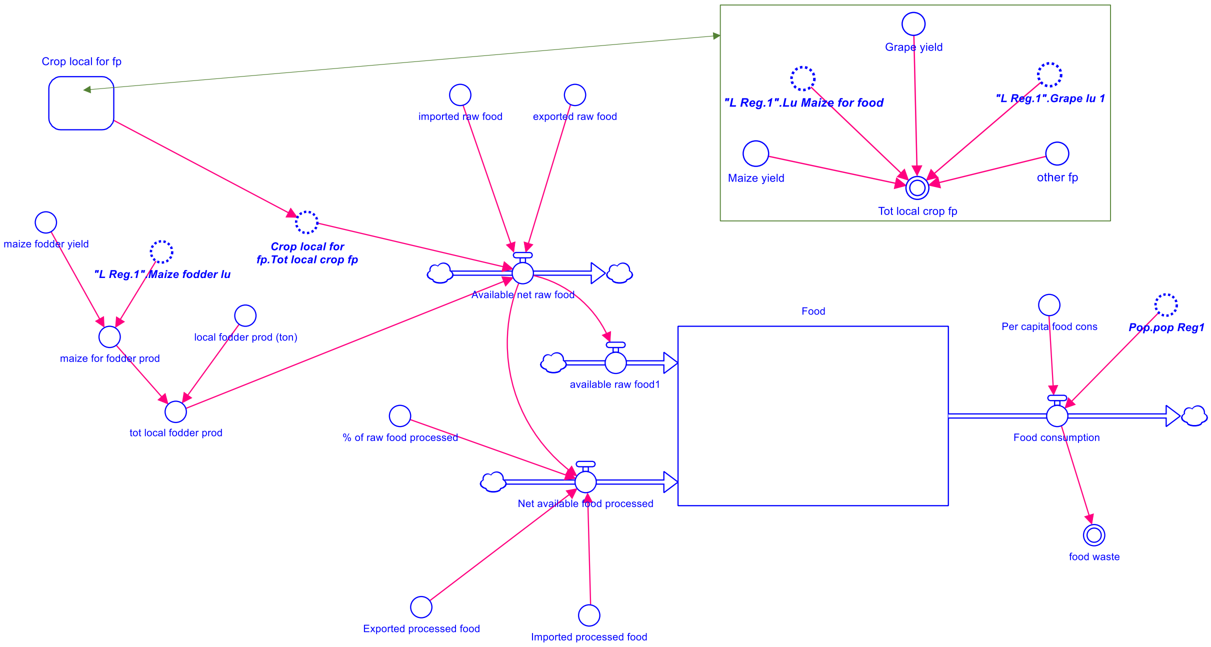


Figure 3.9.7: The food submodel for the France-Germany transboundary case.

The food submodel (Figure 3.9.7) distinguished crops for food (maize, grapes and other) and crops for fodder. Raw food is processed and available for consumption. Food consumption is calculated from knowledge of the population and per-capita food consumption values. Food waste is also modelled.

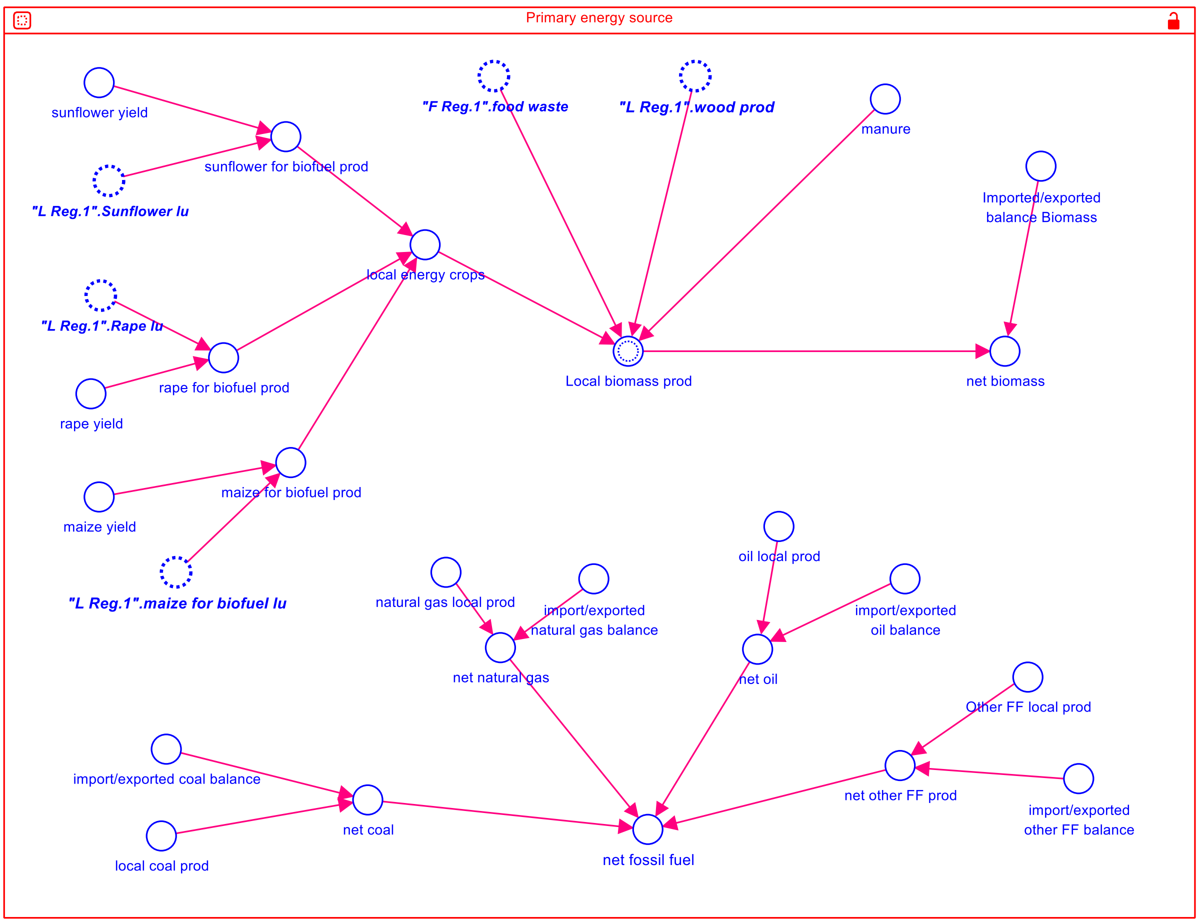


Figure 3.9.8: Primary energy submodel in the France-Germany transboundary case.

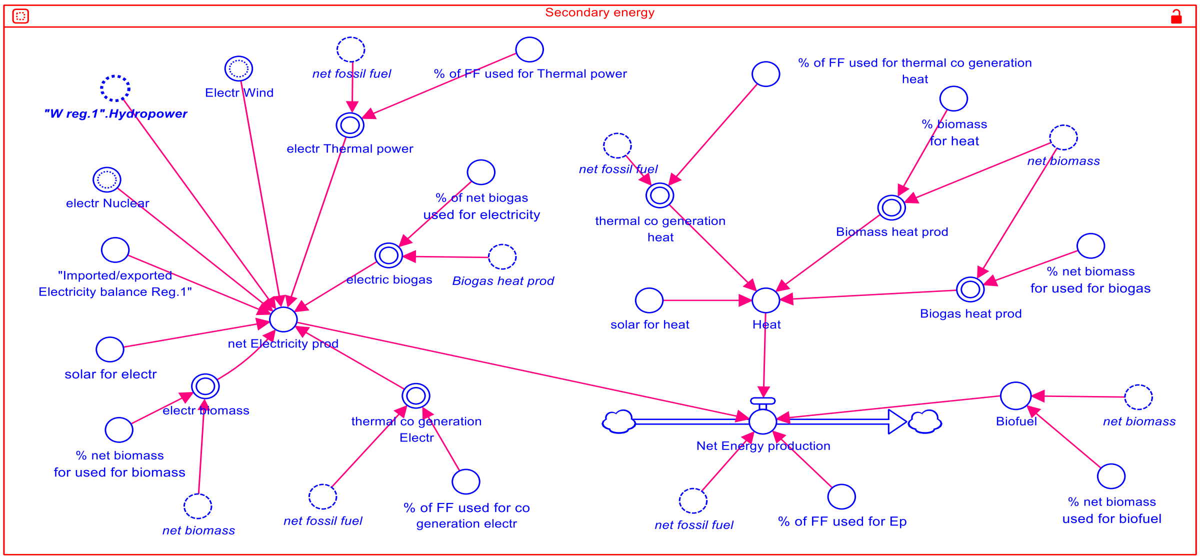


Figure 3.9.9: Secondary energy submodel in the France-Germany transboundary case.

Energy is dealt with in three separate sub-models (Figure 3.9.8, Figure 3.9.9 and Figure 3.9.10). Primary energy accounts for biomass from local energy crops, food waste, forestry waste and manure, coal, natural gas, oil, and other fossil fuel sources in the region. The secondary energy submodel (Figure 3.9.9) accounts for the production of electricity, heat and fuels. Electricity is derived from biogas, thermal energy sources, wind, solar, hydropower and nuclear sources. Heat is generated from biogas, biomass, thermal sources and solar, while biomass contributes to the production of biofuels. Energy consumption (Figure 3.9.10) derives from a number of sources, including the domestic sector, industry, transport, food processing, waste and raw water treatment, water pumping, and agriculture. For each of these sectors, the energy consumption is divided into energy source type: oil, biomass, other fossil fuels, electricity, and natural gas. As a result, the climate impact of energy consumption in each sector can be tracked, as can changes in the energy generation mix.

Finally, in the climate sector submodel (Figure 3.9.11, Figure 3.9.12 and Figure 3.9.13), the balance between emissions and sequestration is accounted for (Figure 3.9.11), with emissions from different sources developed in more detail (Figure 3.9.12 and Figure 3.9.13). For emissions, the crop production, electricity generation, heat, water energy consumption, wood production, industrial, domestic, agricultural, food processing and transport sectors are accounted for. In terms of sequestration, grassland, forests, and wetland contribute to climate abatement. Crop production emissions consists of emissions related to local crop food production, fodder crop production, and energy crop production, electricity emissions come from thermal power sources, co-generation sources, biogas, and biomass, and heat emissions come from thermal co-generation, biogas and biomass (Figure 3.9.12). For the water sector energy consumption, sources include raw water pumping (surface and groundwater), waste water treatment, and the treatment of raw water (Figure 3.9.13).

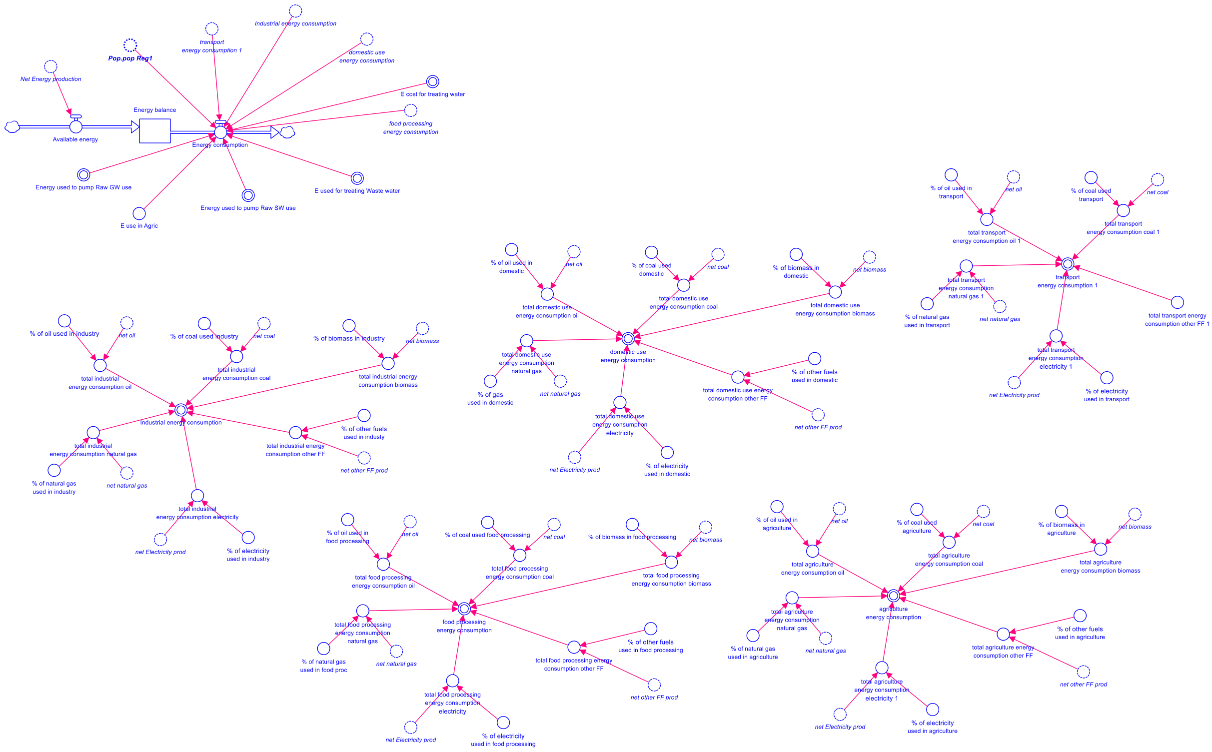


Figure 3.9.10: The energy consumption submodel for the FR-DE case study.

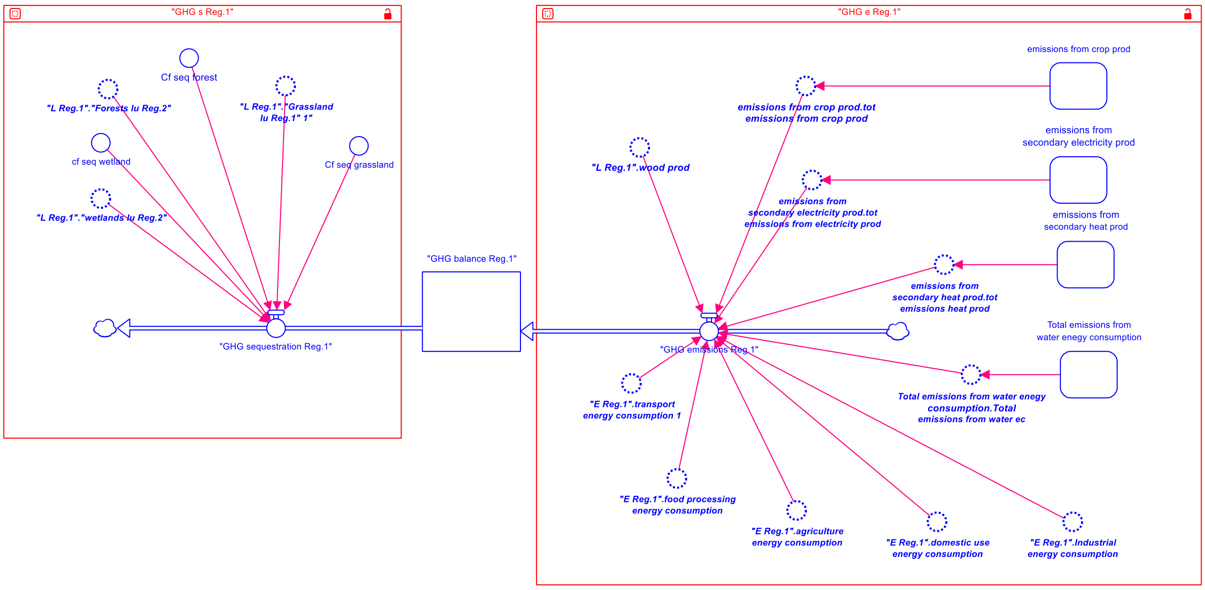


Figure 3.9.11: The climate sector submodel for the FR-DE case study.

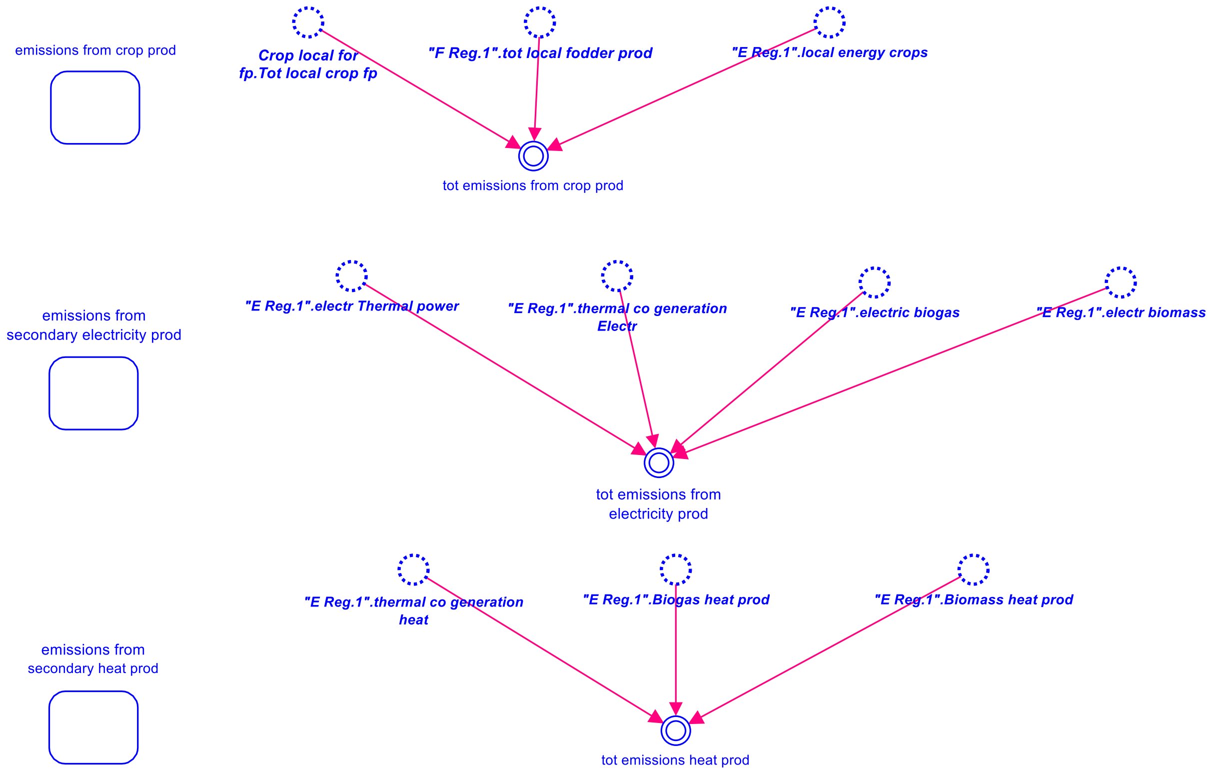


Figure 3.9.12: The detailed emissions model for the crop production, electricity and heat generation sectors in the FR-DE cases study.

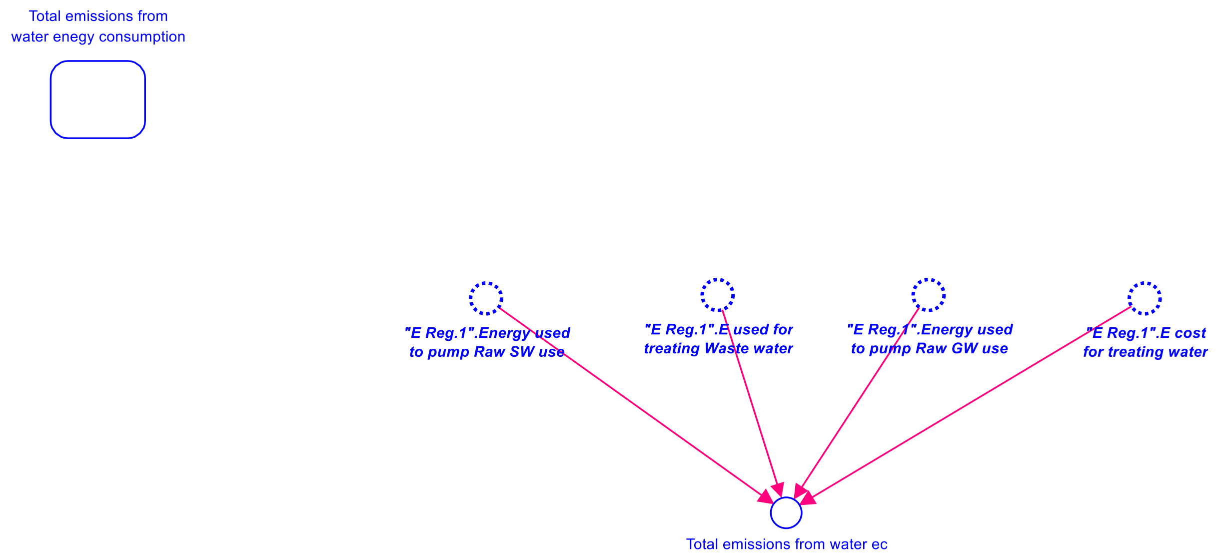


Figure 3.9.13: The detailed emissions model for the water sector in the FR-DE cases study.

3.10 Transboundary Germany-Czechia-Slovakia case study

3.10.1 Short description of the case study

The case study covers the eastern part of Germany and both the Czech Republic and Slovakia (Figure 3.10.1 and Figure 3.10.2). This area (236,736 km², 32.1 million inhabitants on 1 January 2016; EUROSTAT 2017) shares the common history of socialist rule which is still visible in the agricultural landscape: Average farm sizes, measured in total (agricultural) area in the year 2013, are 130 (81) ha in Slovakia, 193 (133) ha in the Czech Republic, and 241 (229) ha in Eastern Germany – about five times larger than average farms in Western Europe (EUROSTAT 2017).

In several German and Czech locations there are active open cast lignite mining sites where farmland, forests, and small settlements are converted to industrial pits. Excessive amounts of groundwater have to be pumped out during the excavation phase. There are many disused lignite mining areas being filled by river runoff and receding groundwater whose "renaturation" process is projected to extend past the middle of the century. Both the active mining as well as the renaturation phases impact the regional hydrological regime. Another issue between land, energy, and food is the recently extended production and use of bioenergy crops like rape and silage maize, contributing to the landscape effects on the regional climate. During recent decades decreasing precipitation is observed for the Czech and Slovak lowlands while the Slovak mountains received more water, however this was connected to more frequent thunderstorms. A shift of precipitation from agriculture lowland to near mountains deserves more attention. It should not be neglected as well that more land devoted to bioenergy production means less land for food production. Photovoltaics (PV) and wind power are problematic, too. Valuable crop land has been lost to PV installations (energy-land-food interactions) which are sealed surfaces contributing to sensible heat emissions. Wind power requires huge installations with negative impacts on the amenity quality of the landscape – in Germany, this led to a big movement of NGOs protesting against new wind power projects. Finally, PV and wind cause big pressures on grid stability, because there are hardly any storage possibilities for electrical energy, and the strong natural fluctuations in radiation and wind have to be buffered by fossil fuel power plants. There are only two double-line connections between Germany and the Czech Republic in the continental electricity grid (ENTSO-E 2017), and the general direction of electricity exchange between these countries has been swapped in the recent years: Historically, the Czech delivered (cheap nuclear) power in a one-way relation to Germany, but during the last years more and more renewable energy (especially wind) pushed the balance into the opposite direction.

There are neither more hydropower nor more wind power potentials in the Czech Republic, therefore biomass production (biofuel, biogas) is supported. Fast growing woods are cultivated only on 3000 ha in CZ; agroforestry has a potential in drained agricultural landscape for its ecological functions.
The main question of this case study is whether the landscape structure dominated by monoculture-like crop areas in some of the lower parts and its alterations by energy production affects the water cycle in an unfavourable way: The principal societal challenge is the resource-efficient and socially compatible decarbonisation of the energy sector.

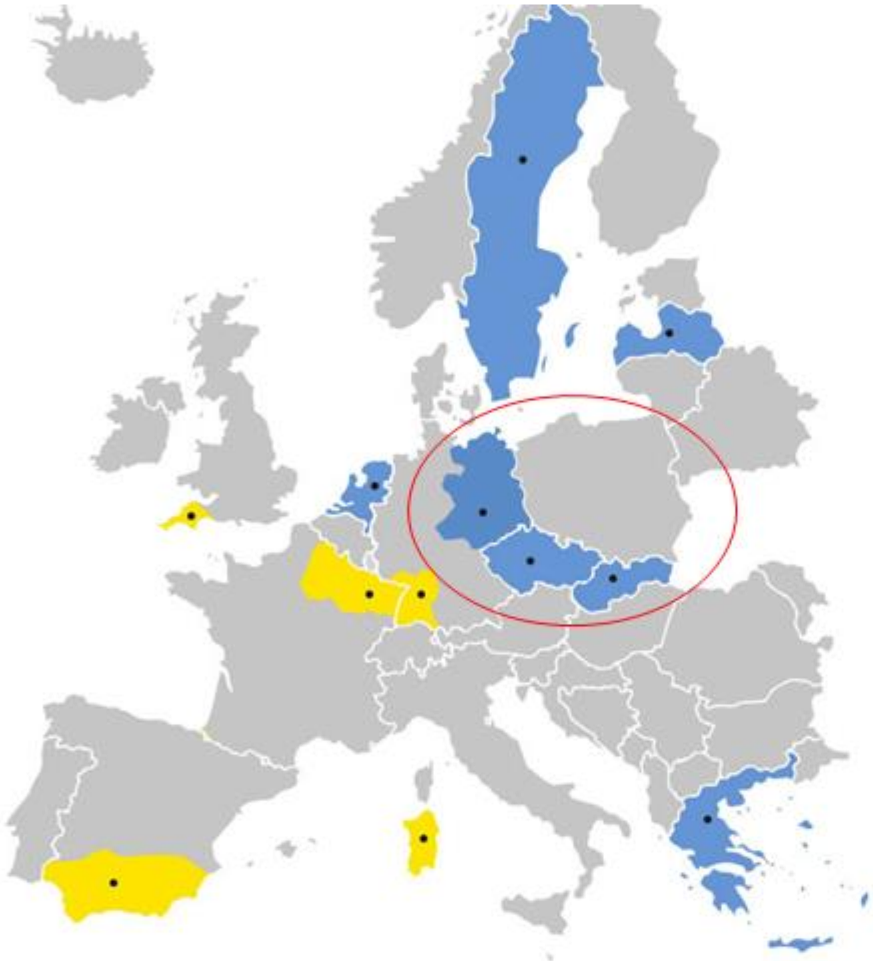


Figure 3.10.1: Map of the transboundary Germany-Czechia-Slovakia Sim4NEXUS case study.

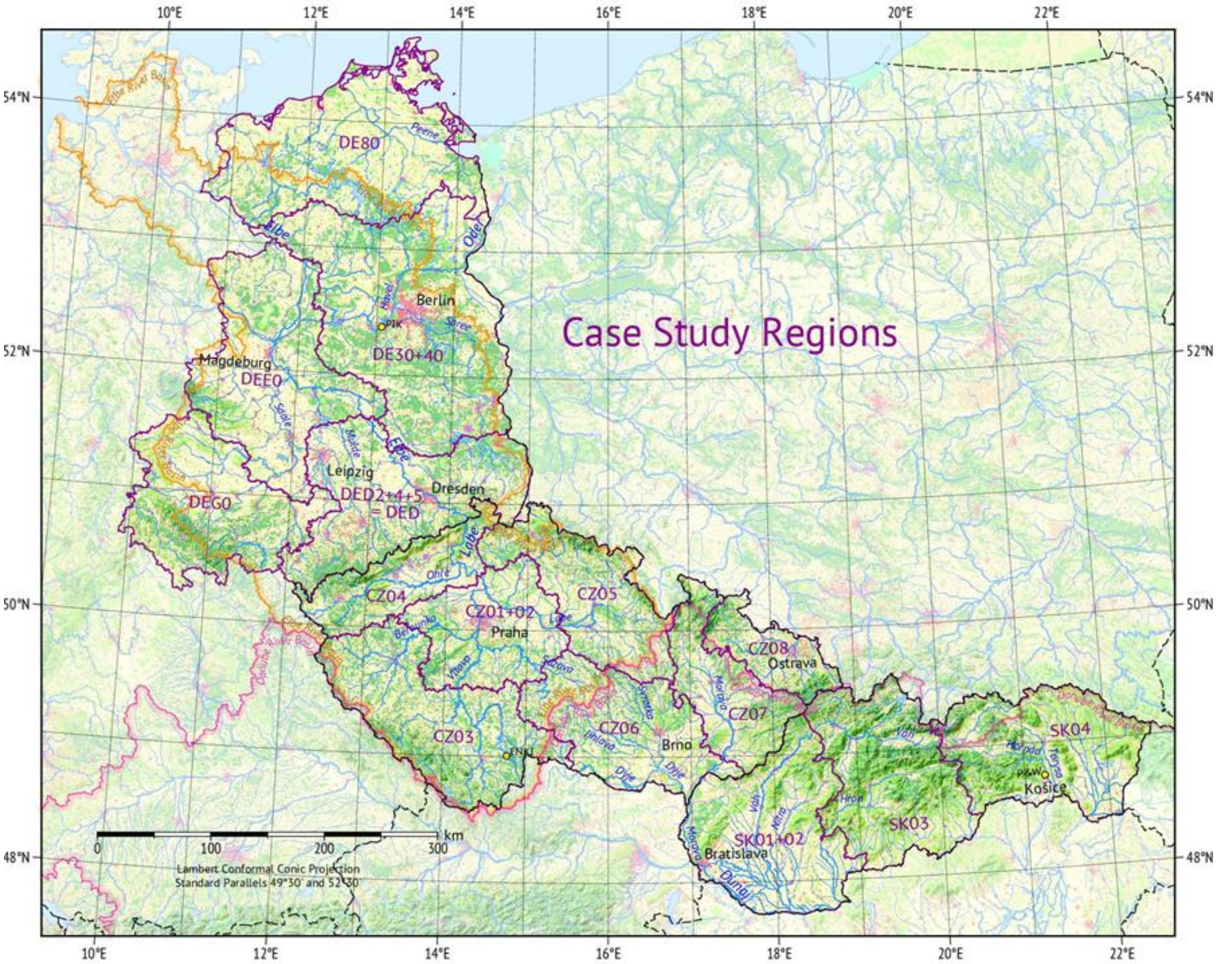


Figure 3.10.2: Close-up view of the NUTS-level regions to be modelled in the DE-CZ-SK case study.

The problems which are common to all three case studies states result from common history. For all three states there are typical changes in the structure of the agricultural landscape, i.e. the creation of large soil/field blocks and the removal of small landscape features, as well as complicated ownership relations. These factors are also related to extensive drainage of agricultural land (by technological drainage systems in soil, drying wetlands, etc.), and directly affect water retention ability of the landscape and local climate (Ellison et al. 2017; Pokorný et al. 2010; Hesslerová et al. 2012, 2013; Huryna et al. 2014; Ripl 2003). Agricultural landscape fundamentally influences the hydrological cycle and the climate, is experiencing deterioration in soil quality (erosion, sealing, nutrient losses, acidification), water scarcity and drying. Despite the EU's efforts to introduce various agro-environmental measures and measures to mitigate climate change. In these cases it is necessary to look at the main cause of the failure of these efforts.

In the past thirty years, there was not significant landscape structure change in the case study states, which would improve the retention and accumulation of water, the reduction of nutrient losses and decreasing surface temperature of the landscape. Associated phenomena include losses in agricultural yields, both quantitative (floods and droughts) and qualitative (high nutrient and matter losses from catchments) water-related problems. Less obviously affected than agriculture but nevertheless confronted with production shutdowns are thermal power plants relying on cooling water; studies suggest increasing problems due to climate change within the next decades (Koch & Vögele 2009, Koch et al. 2012, 2014), especially in Germany.

Principal condition for such an improvement is restoration of permanent vegetation, water retention measures (realized mainly on agriculture land), changes of landscape management and land cover.
The nexus context for the transboundary study was set up as a relationship of land-water-climate-energy, with crucial representation of agriculture activities that put a pressure on all four components. The study tries to find the answers for following questions:

- How can we encourage/achieve the complex and extensive changes of landscape structure and land cover, in national scale, in terms of increasing its water retention ability and decreasing surface temperature?
- What effect could be achieved by water retention measures which also stimulate sequestration of carbon and reduce water and nutrient losses?
- How can landscape restoration (change of landcover) be embedded into policy for climate change mitigation?
- How to increase an understanding of basic principles of NEXUS: incoming solar energy – water/absence of water – plants (biomass, food) – local climate. Because it is landscape management (land cover) what determine climate, water availability, food production.
- How threatened is the electricity supply in the area given the increasing amount of unstable renewable sources under climate change?
- What would be the consequences of an immediate shutdown of the lignite mining activities in Lusatia?
- How much food production is and will be sacrificed to biomass generation? What are the environmental consequences of this “green” energy in the area, especially regarding the water balance?

3.10.2 Evolution and description of the conceptual diagram

Figure 3.10.3 shows the first draft conceptual diagram for the DE-CZ-SK case study. There is emphasis on crop growth, water stored in the landscape, and energy production. Links to land use and landscape structure are made, and well as to potential impacts on water quantity and quality (to support ecosystem services). Changes in energy, land and crops feed into impacts on the climate system, which, as mentioned above, is impacting on precipitation, and therefore hydrological, patterns, especially in Czechia and Slovakia. As with most other first drafts, the nature of the interconnections is not defined, and the model lacks detail.

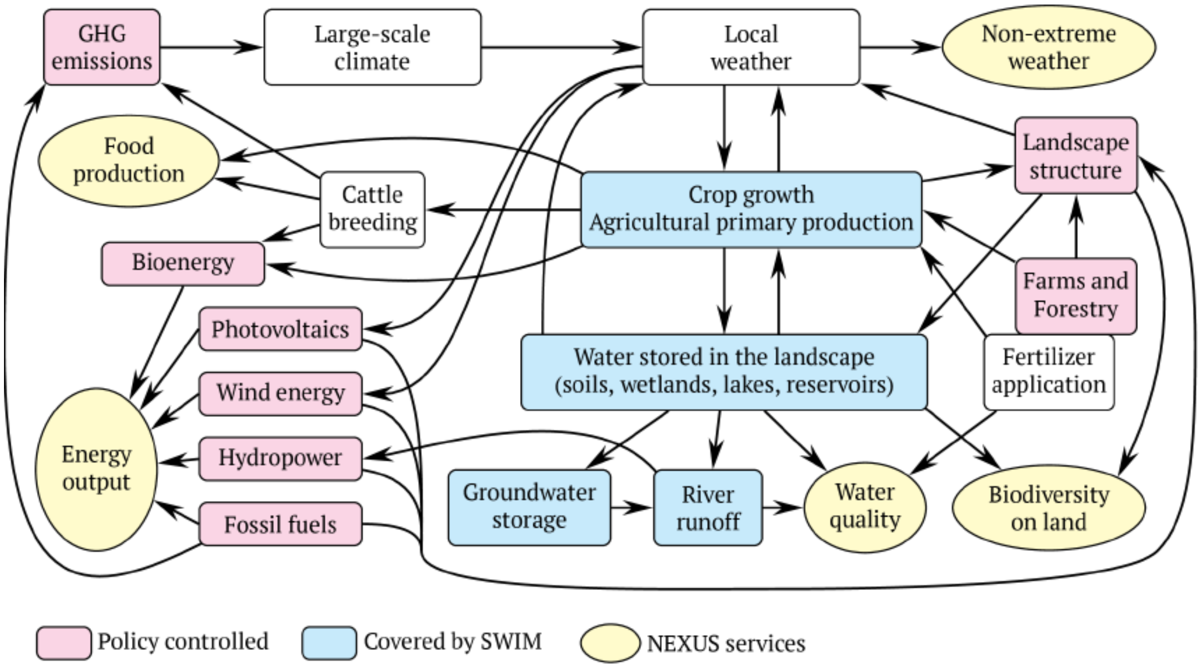
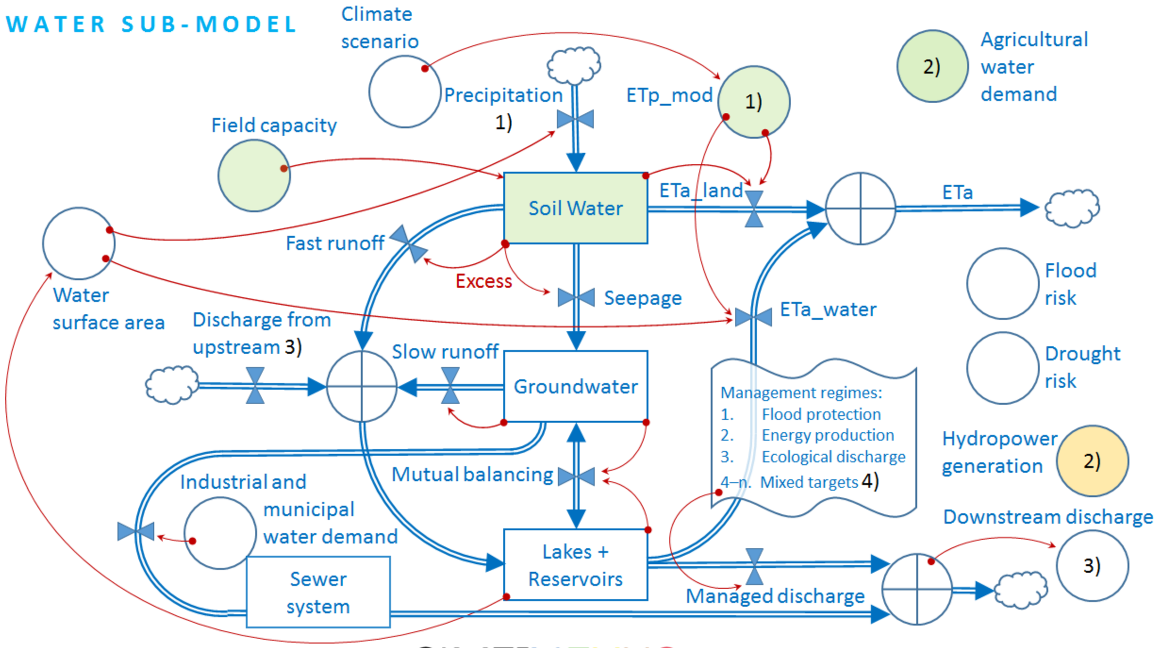


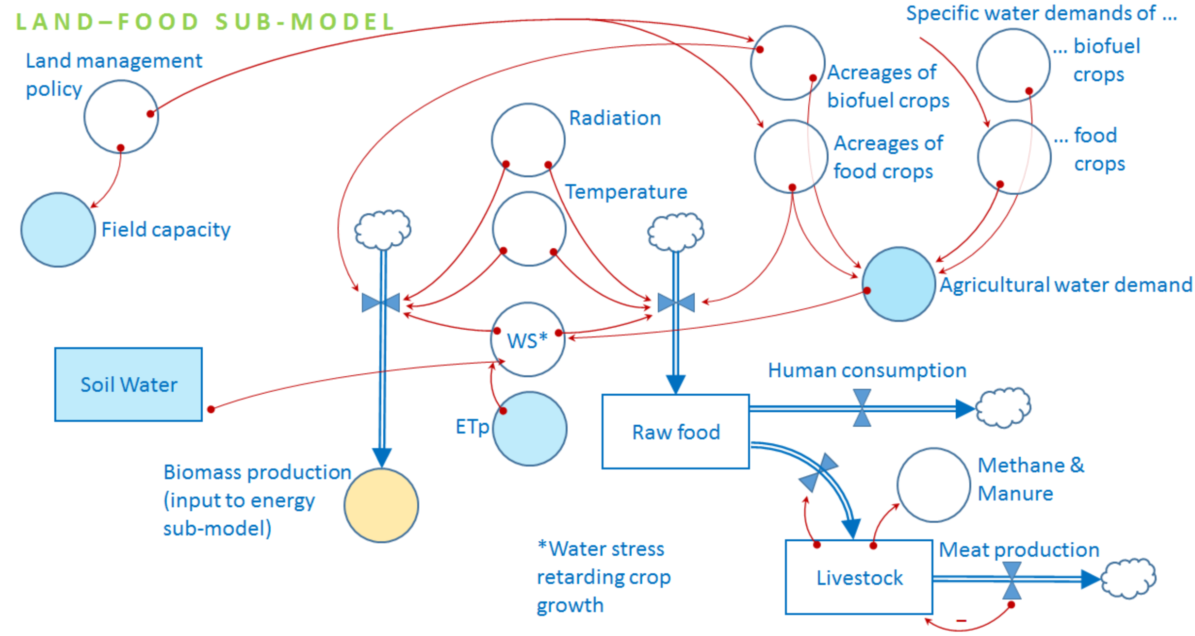
Figure 3.10.3: First draft conceptual model for the DE-CZ-SK case study.

The final version of the conceptual model is shown in Figure 3.10.4. Unlike other case studies, there is no high-level nexus overview figure for this case study. The water sector (Figure 3.10.4a) is highly detailed. Soil water features prominently as is affected by precipitation, itself changed by climate pressures. Soil water contributes to groundwater recharge and evaporation over land. The amount of water in the system is also controlled by demand, which in this case is industrial and domestic demand and agricultural water demand, which is of great importance for this case study. One central theme in this case is how to restore water held in the landscape to increase water availability and reduce increasing air temperatures, partly due to a dry landscape. Various water management options are identified.

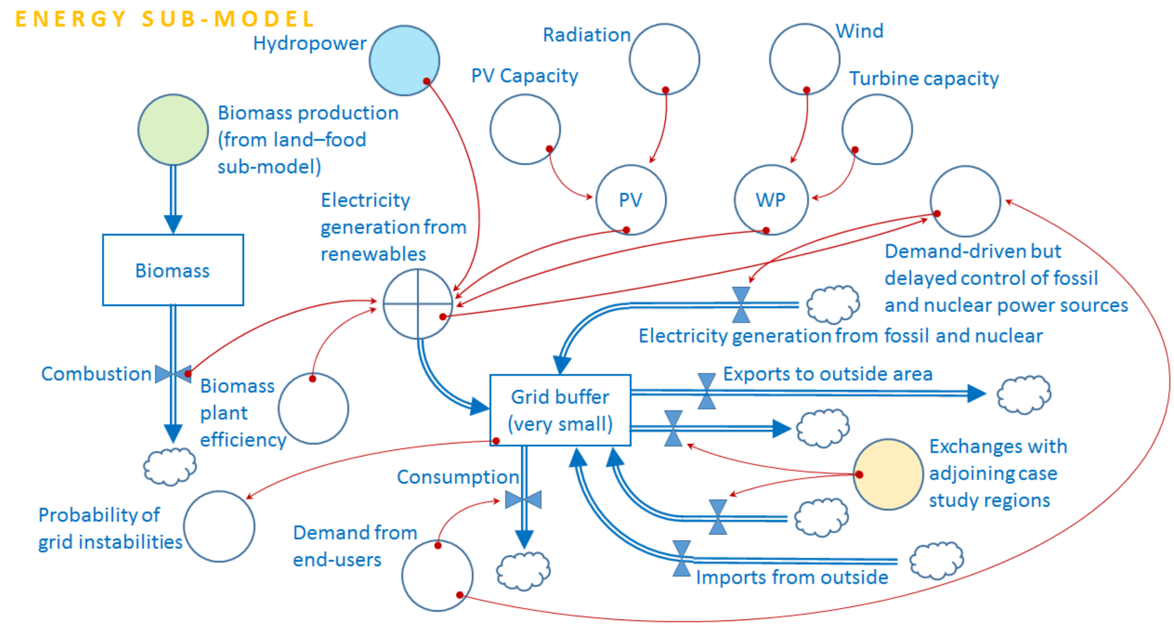
(a)



(b)


LAND–FOOD SUB-MODEL
Land management policy
Field capacity
Radiation
Temperature
Acreages of biofuel crops
Acreages of food crops
Specific water demands of ...
... biofuel crops
... food crops
Agricultural water demand
WS*
Soil Water
ETp
Biomass production (input to energy sub-model)
Raw food
Human consumption
Methane & Manure
Livestock
Meat production
*Water stress retarding crop growth

(c)


ENERGY SUB-MODEL
Hydropower
Radiation
Wind
PV Capacity
Turbine capacity
Biomass production (from land–food sub-model)
PV
WP
Electricity generation from renewables
Demand-driven but delayed control of fossil and nuclear power sources
Biomass
Electricity generation from fossil and nuclear
Combustion
Biomass plant efficiency
Grid buffer (very small)
Exports to outside area
Exchanges with adjoining case study regions
Consumption
Probability of grid instabilities
Demand from end-users
Imports from outside

(d)

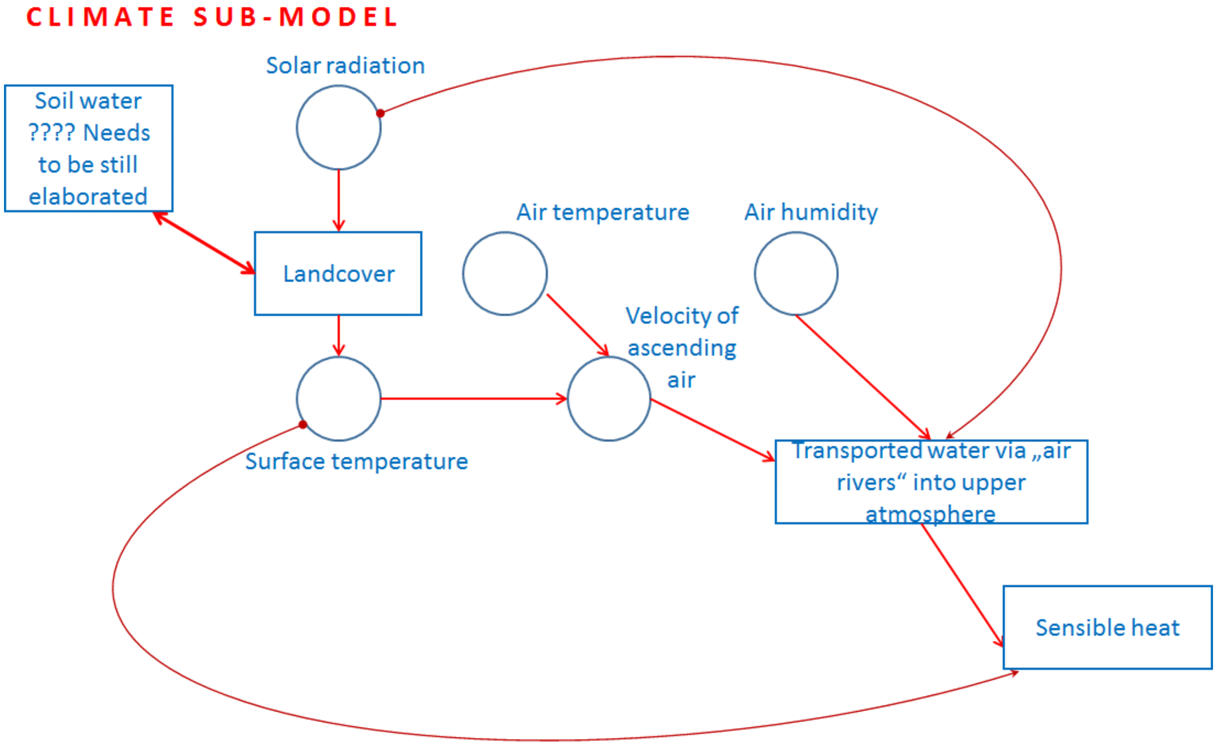


Figure 3.10.4: Final conceptual model for the DE-CZ-SK case study, showing in detail (a) the water sector; (b) the land-food sectors combined; (c) the energy sector and; (d) the climate sector.

The land-food sectors, which are specified together for this case study, are shown in Figure 3.10.4b. Water (blue circles) clearly has an important role in these sectors, and is affected by changes in these sectors in a mutual feedback loop. Biomass production is impacted by changes to the climate, and also by water availability and quality. It is also dependent on the land availability. The amount of food produced also depends on land use and yields, and also on climate variables. Consumption is driven by GDP. It is important to note (also see the brief description) that there is a tension in this case study between land for food and biomass production, land for energy, landscape water management, and landscape restoration, as well as how all this can be managed against a context of a transition to a low carbon economy promoting solar and wind energy, both of which require land (use changes). The energy sector (Figure 3.10.4c) shows the generation of power from biomass (with the concomitant impacts on the land sector and landscape restoration), hydro, wind, solar, and nuclear and fossil sources. Renewables are expected to gradually replace fossil and nuclear. Demand is driven by end-use consumption patterns. A major issue in this case is that of electricity grid stability. As renewables gain a greater share in production, there are concerns over storage of energy from renewables (especially electricity), which could lead to temporary blackouts at periods of peak demand due to relatively small buffers in the system. This sector is influenced by the water, land and food sectors, and greatly impacts on the climate sector. The climate sector (Figure 3.10.4d) consists of temperature and precipitation, and changes thereof. These changes can be modulated locally through soil moisture and land use and land cover (hence the link to landscape restoration). On top of local trends, global climate change is also a factor, and strongly related to the energy sector and GHG emissions.

3.10.3 Description of the developed system dynamics model

The top-level nexus mode for the DE-CZ-SK case study is shown in Figure 3.10.5. As with the other cases, each sector is developed in further detail.

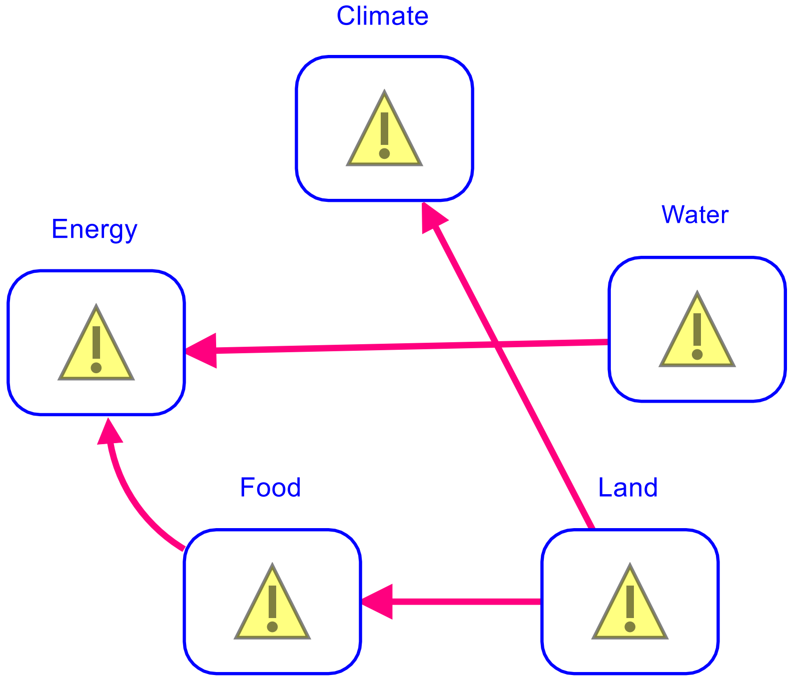


Figure 3.10.5: Top-level nexus model for the DE-CZ-SK case study.

The water sector (Figure 3.10.6) is somewhat unique in SIM4NEXUS, comprising three main water balances. The first is a soil water balance for each of the regions that the case study is split into. Water enters the 'stock' and interflow and seepage to deep groundwater deplete the stock. The second water balance is for agricultural soil water storage. The water balance of agricultural regions feeds this stock. Interflow, seepage and surface runoff deplete it, along with the consumptive demand of a number of different crops. The third water balance is that of surface water resources. Here, water is exchanged between regions (similar to an input-output economic model), and water within a region can also be lost by evaporation from surface water bodies. The input-output exchanges are defined for each modelling region in this case study.

The land submodel (Figure 3.10.7) tracks the areas of land used for different activities in the case study. Many different classes are accounted for including bare ground, pasture, meadows, forests, roads, water, and urban land. In addition, food crop land, fodder crop land and biofuel crop land are tracked, and each of these is developed in further detail (Figure 3.10.8, Figure 3.10.9 and Figure 3.10.10). In terms of food crops, the areas of vegetables, oilseeds, cereals, soft wheat, durum wheat, barley, oats, rye, soya, tomatoes wine (grapes), other oils, apples, pears and peaches, potatoes, arable crops, permanent crops, sunflowers, sugar beet, other fruits and other crops are tracked (Figure 3.10.8). For fodder crops, the areas of pulses, maize, root crops, fodder on arable land, and two categories of grassland are tracked (Figure 3.10.9). For biofuel crops, the areas of maize, rape and ligneous energy crops are tracked (Figure 3.10.10).

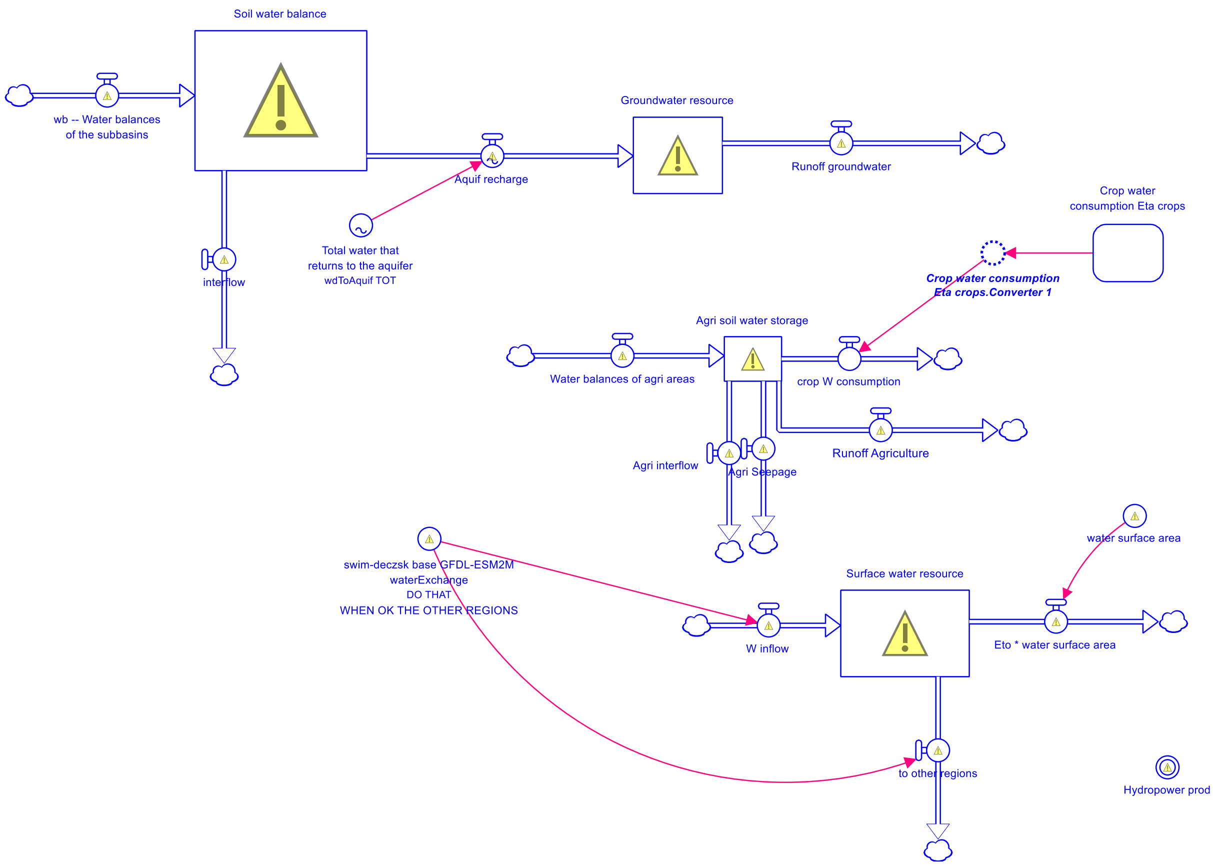


Figure 3.10.6: The water sector submodel for the DE-CZ-SK case study.

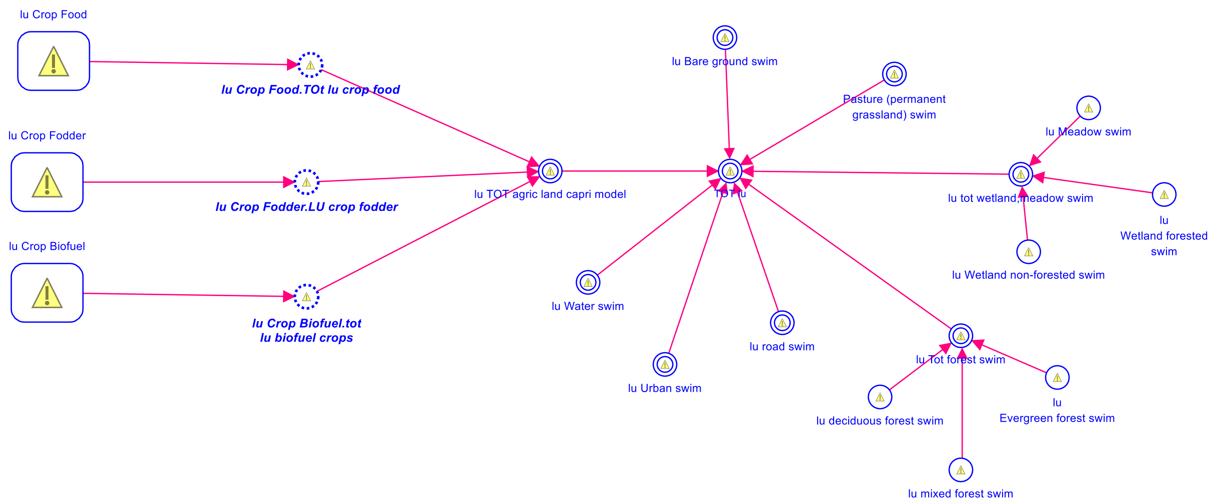


Figure 3.10.7: The land sector submodel for the DE-CZ-SK case study.

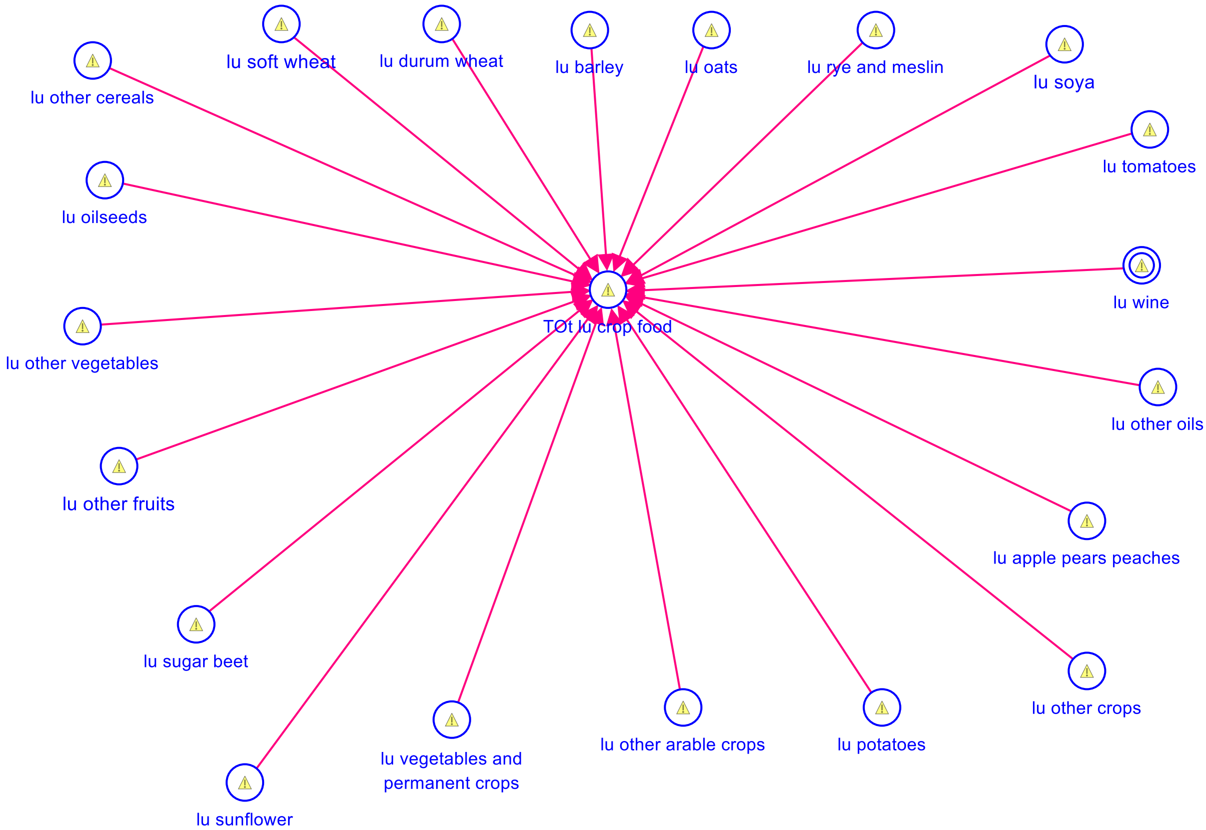


Figure 3.10.8: The food crop land model in the land sector submodel.

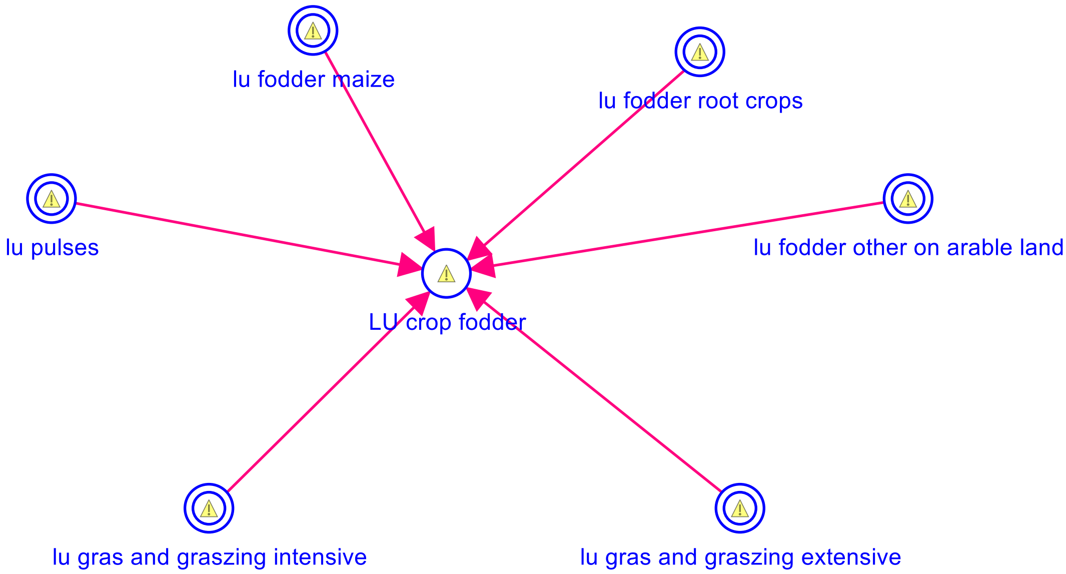


Figure 3.10.9: The fodder crop land model in the land sector submodel.

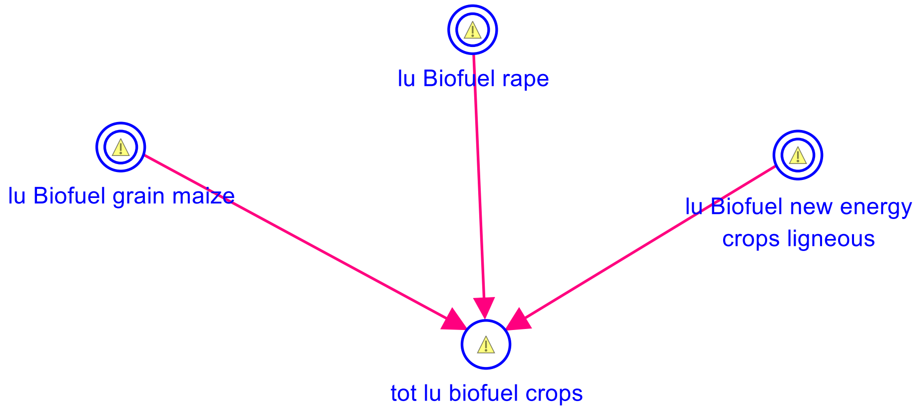


Figure 3.10.10: The biofuel crop land model in the land sector submodel.

In the food sector submodel (Figure 3.10.11) a balance is modelled between the production and consumption of food crops, fodder crops, and energy crops. In each of these three sectors, further submodels are developed to track the production and consumption of each (Figure 3.10.12, Figure 3.10.13 and Figure 3.10.14). In all three, for production the area of each crop is combined with the yield per unit area to calculate total production for that crop. All crops are summed. Changes in relative proportions can therefore be tracked. For consumption, model data from CAPRI is used.

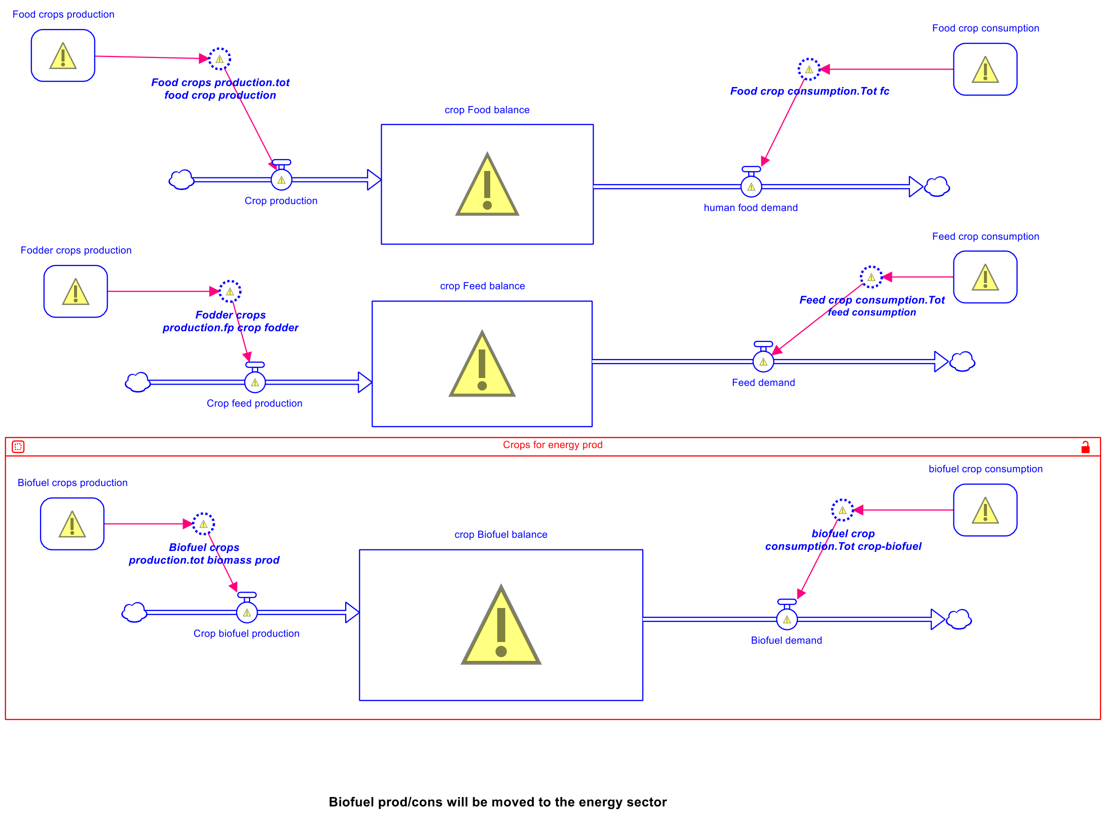


Figure 3.10.11: The food sector submodel of the DE-CZ-SK case study.

For food crops (Figure 3.10.12), production of soft wheat, durum wheat, barley, oats, rye, vegetables/permanent crops, other crops, potatoes, arable crops, sugar beet, oilseeds, apples, pears and peaches, other oils, other fruits, other vegetables, tomatoes, wine, soya, sunflowers and other cereals are modelled.

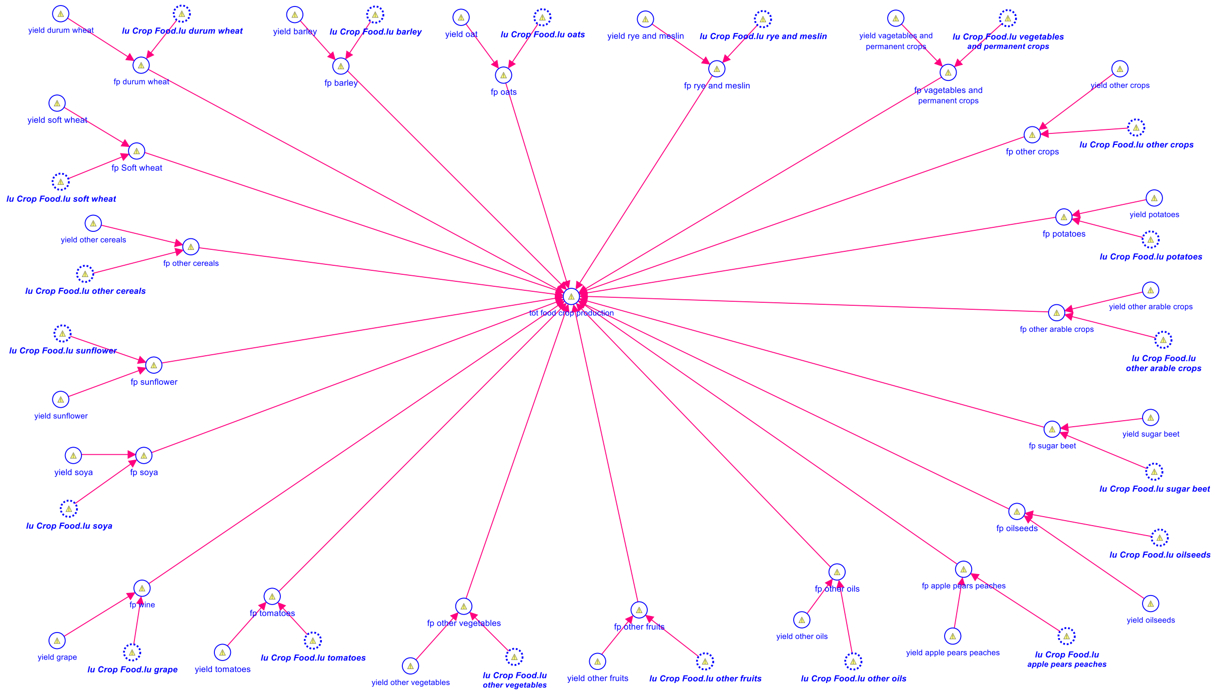


Figure 3.10.12: Submodel for food crops production.

For fodder crops (Figure 3.10.13) the production is accounted for the same crops described above in the land submodel, and the situation is the same for biofuel crop production (Figure 3.10.14).

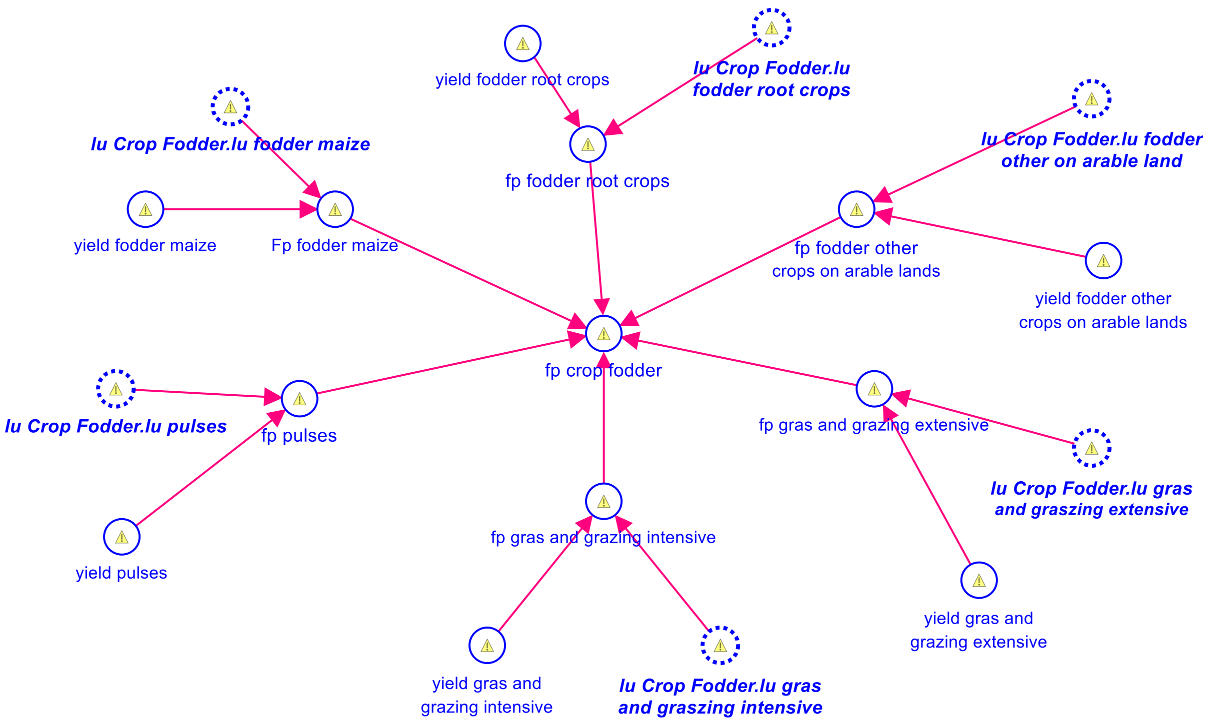


Figure 3.10.13: Submodel for fodder crops production.

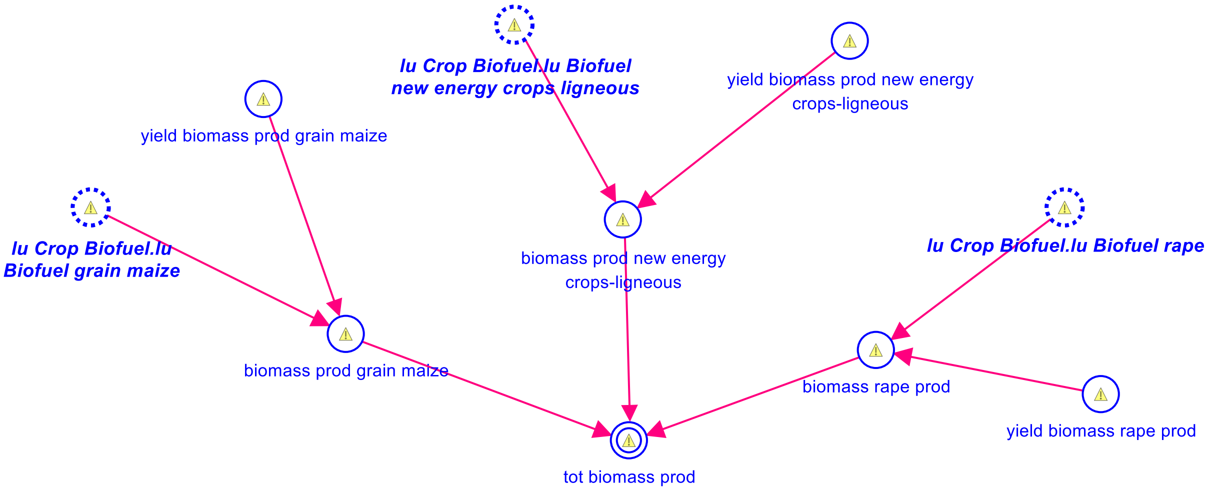


Figure 3.10.14: Submodel for biofuel crop production.

Consumption for the same crops modelled for production and in land use (see descriptions above). Figure 3.10.15, Figure 3.10.16 and Figure 3.10.17 show the models developed to calculate food, fodder, and biofuel crop consumption respectively. Again, individual crops are summed to arrive at consumption totals.

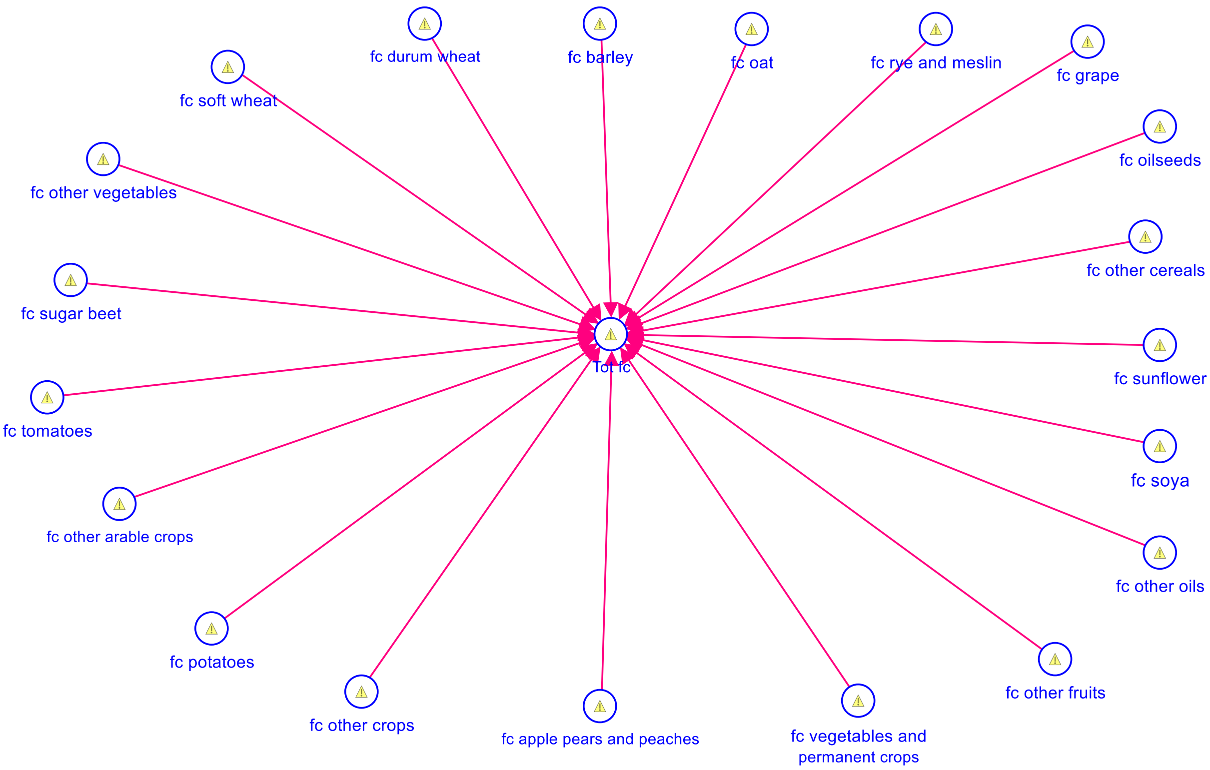


Figure 3.10.15: Submodel for food crop consumption.

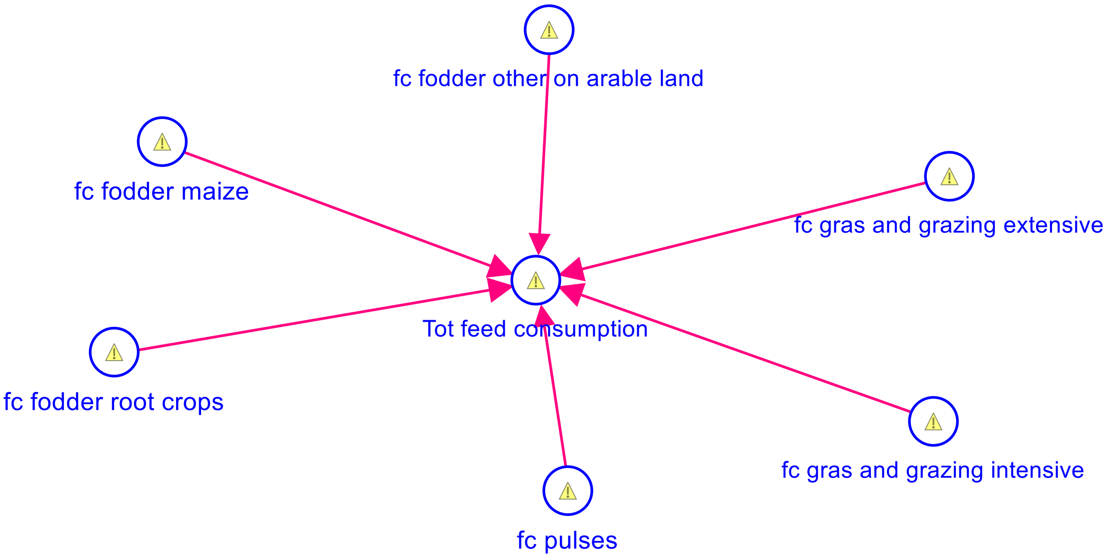


Figure 3.10.16: Submodel for fodder crop consumption.

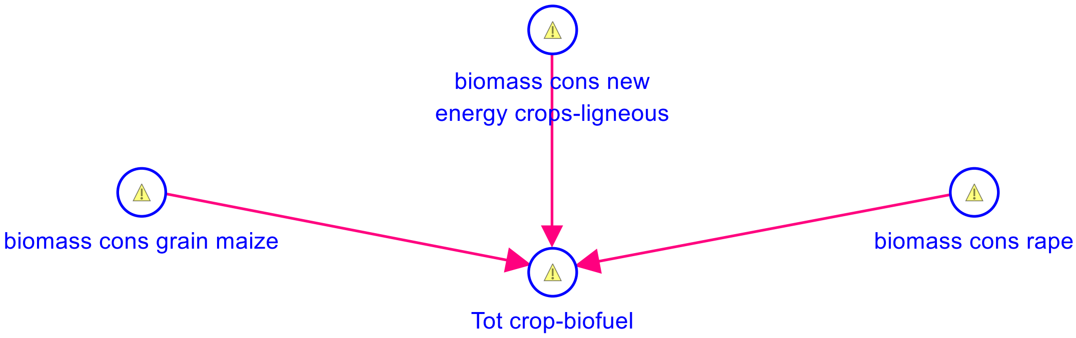


Figure 3.10.17: Submodel for biofuel crop consumption.

In terms of energy, this sector is not as developed as for other sectors as it is not a primary issue for this case study (Figure 3.10.18). Primary energy is modelled from biofuel crops, methane and manure (categorised as renewable sources), and fossil fuels (lumped together and classified as non-renewable sources). Electric energy is produced from hydropower, solar, wind, and fossil fuel generation, and the balance between regional imports and exports is accounted for. In terms of energy use, only the electric consumption by irrigation and water treatment are modelled for this case study.

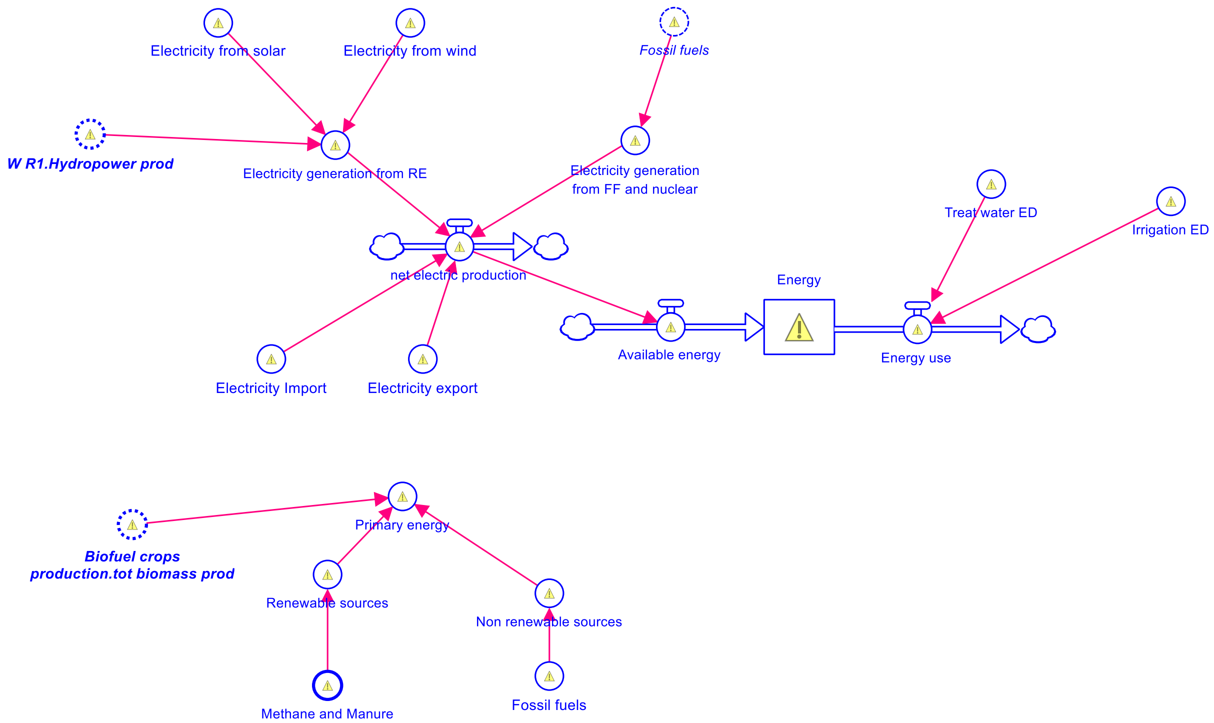


Figure 3.10.18: The energy sector submodel for the DE-CZ-SK case study.

The climate sector submodel for the DE-CZ-SK case is totally unique in SIM4NEXUS, and models how different land uses and land use change influences energy and water fluxes in the landscape. Land cover changes impact on land surface temperature, which impacts the velocity of ascending air. This model quantifies the volume of water transported by hot air into the atmosphere, and models the amount of sensible heat released. These impacts relate to natural water storage in the landscape, and also to atmospheric dynamics. Such issues are important for this case study, and hence is modelled in some considerable detail. In addition, the investments in different land use types, the water loss rate from different land use types (influenced by land use and the climate, which is influenced by the climate, forming an intimate feedback process), and the influence on economic production are modelled. The model is broken down into four parts, all described below.

The first part of the climate submodel (Figure 3.10.19) models for upward velocity of air from different land use types. Following this, and using data about the absolute humidity, the volume of hot air is modelled. The next part of the submodel (Figure 3.10.20), uses the main output from part 1 (i.e. the hot air volume), together with the area of each land use class, to derive the volume of water transported upwards from the land surface, thus representing a loss of water from the landscape. In addition, the second part of the model accounts for the implementation of water retention measures within different land use classes to model how much water volume can effectively be stored in the landscape for utilisation. The investment cost of such retention measures is also modelled in this part of the model. The third part of the model (Figure 3.10.21) estimates the intensity of new water resources made available (in l s^{-1}) as a result of changing water resource management (WRM) practices on the ground in different land use classes. In addition, such WRM practices may also contribute to increasing the water available for near-surface climate cooling effects in the landscape, which is also modelled. Part four (Figure 3.10.22) of the model estimates the increase in economic production of different crop types due to land use changes. In addition, the sensible heat reduction and consequent decrease in local near-surface temperature resulting from land use and landscape water content changes are assessed. Finally, to CO2 sequestration potential of different land use types is modelled.

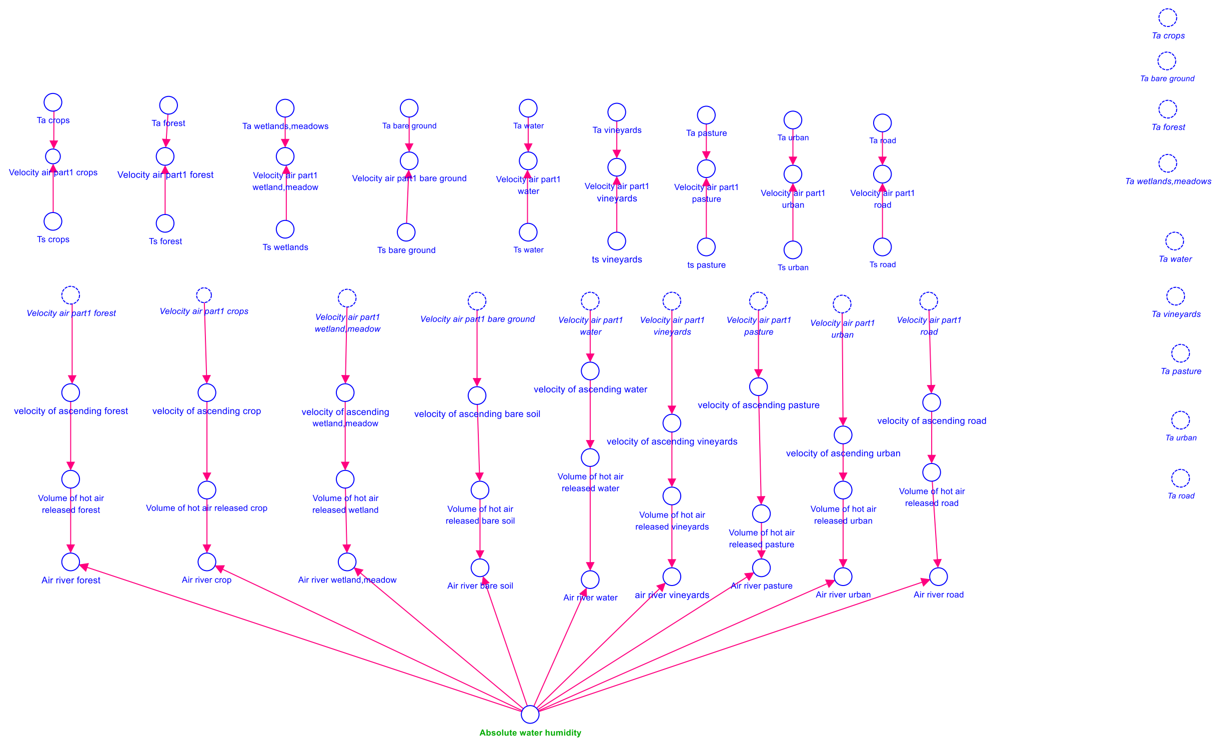


Figure 3.10.19: Part 1 of the climate sector submodel for the DE-CZ-SK case study.

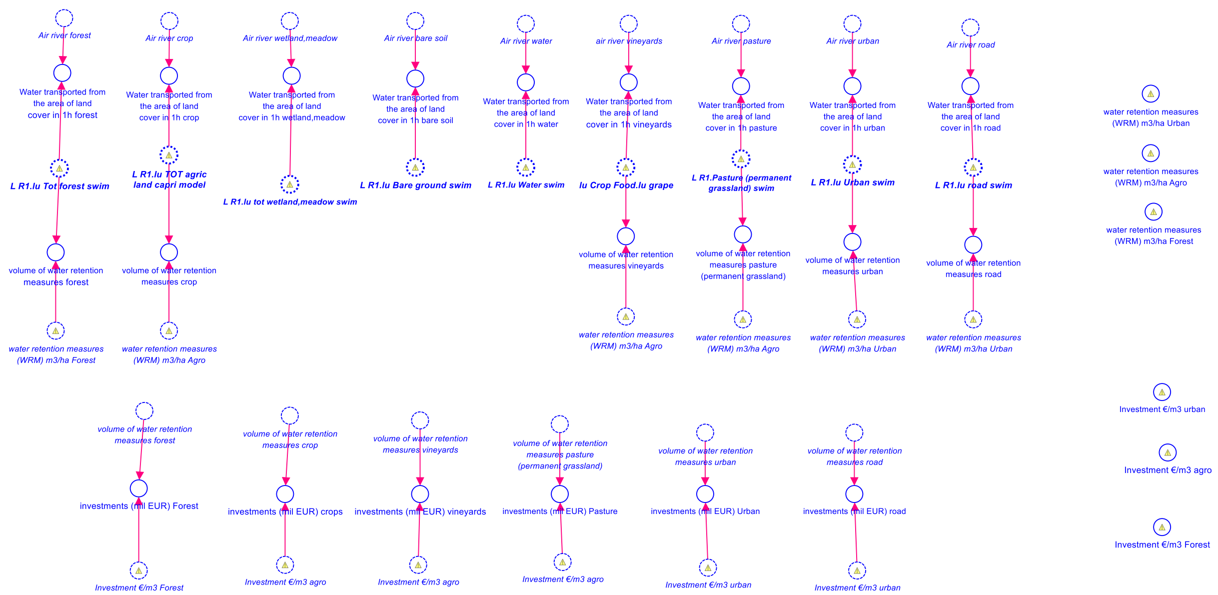


Figure 3.10.20: Part 2 of the climate sector submodel for the DE-CZ-SK case study.

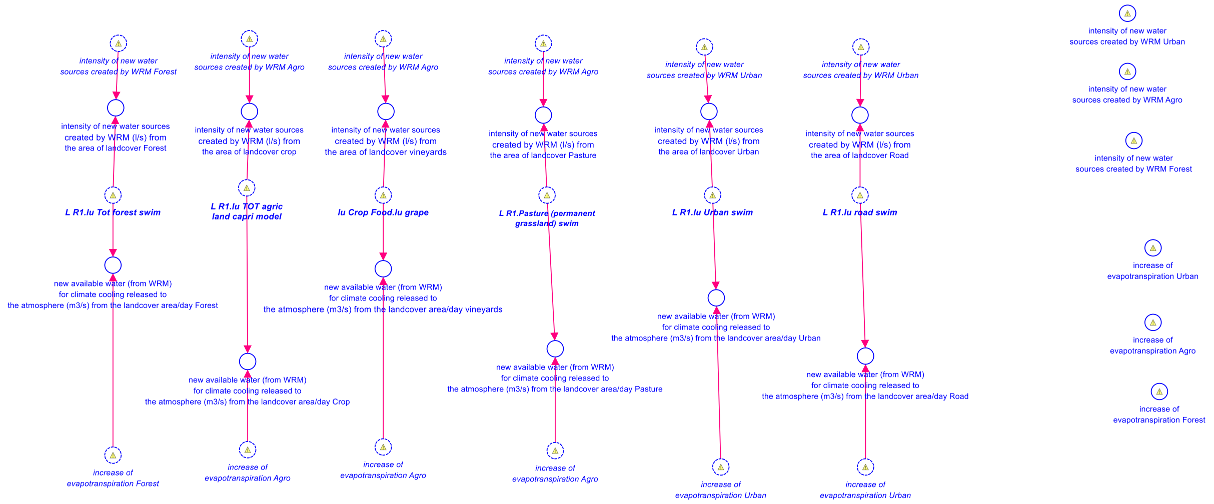


Figure 3.10.21: Part 3 of the climate sector submodel for the DE-CZ-SK case study.

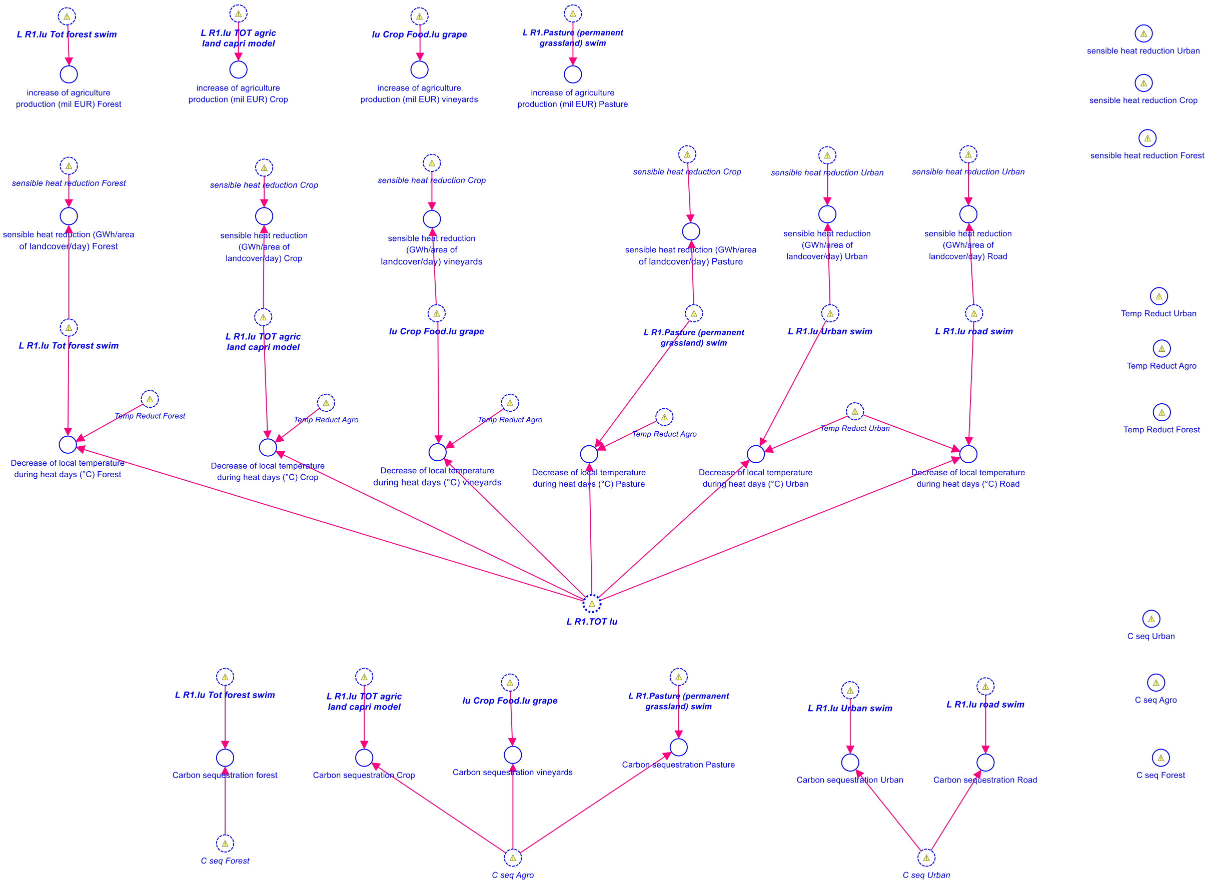


Figure 3.10.22: Part 4 of the climate sector submodel for the DE-CZ-SK cases study.

The difference with other case studies is apparent, with a focus on landscape water availability, and the relationship to atmospheric heat and water transfer, local near-surface air temperature modulation, and the economic impact on crop production. GHG sequestration is also modelled however.

3.11 European case study

3.11.1 Short description of the case study

The SIM4NEXUS European case study examines the impact of a transition to a low carbon economy in Europe across all five nexus sectors. The spatial scale is the entire European continent (Figure 3.11.1), however a division is made between the EU (European Union) and the rest of the European continent. The time frame for the analysis is until 2050, with future projections reported in 10 year periods. The case study will examine economic incentives, such as carbon prices and renewable energy subsidies, as well as regulatory policies on, for example, land use or transport emissions such as biofuel mandates, as possible pathways for the transition to a low carbon economy in Europe as a mitigation strategy to combat climate change. The case study will assess the impacts of this transition on water demand for hydro-power and for irrigation of bioenergy crops resulting from policies that stimulate these sectors, and how this change in water demand will affect environmental flows and biodiversity. Further, the impacts of the transition to a low carbon economy on European and global food security and nutrition will be examined as agricultural land could be used for growing energy crops and forests instead of food. Unlike the national and regional case studies the Continental European case study is initially driven by the thematic models (E3ME-FTT, MAGNET, CAPRI, IMAGE-GLOBIO, and MAgPIE) and will engage the stakeholders once the preliminary analysis of the energy transition pathways is completed. Organizations involved either directly or as anticipated end users of the analysis and results of the European case study include: various departments of the European commission including DG Energy, Agriculture, Climate and environment, the European parliament, the water supply and sanitation technology platform (WssTP) and Copa-Cogeca (an organization representing farmers and their cooperatives). The transition pathways developed in this case study would then help to inform the stakeholders in developing an integrated Europe wide energy, climate, water and agricultural policy as well as provide a framework of possible future scenarios for national level decision makers in these policy arenas.

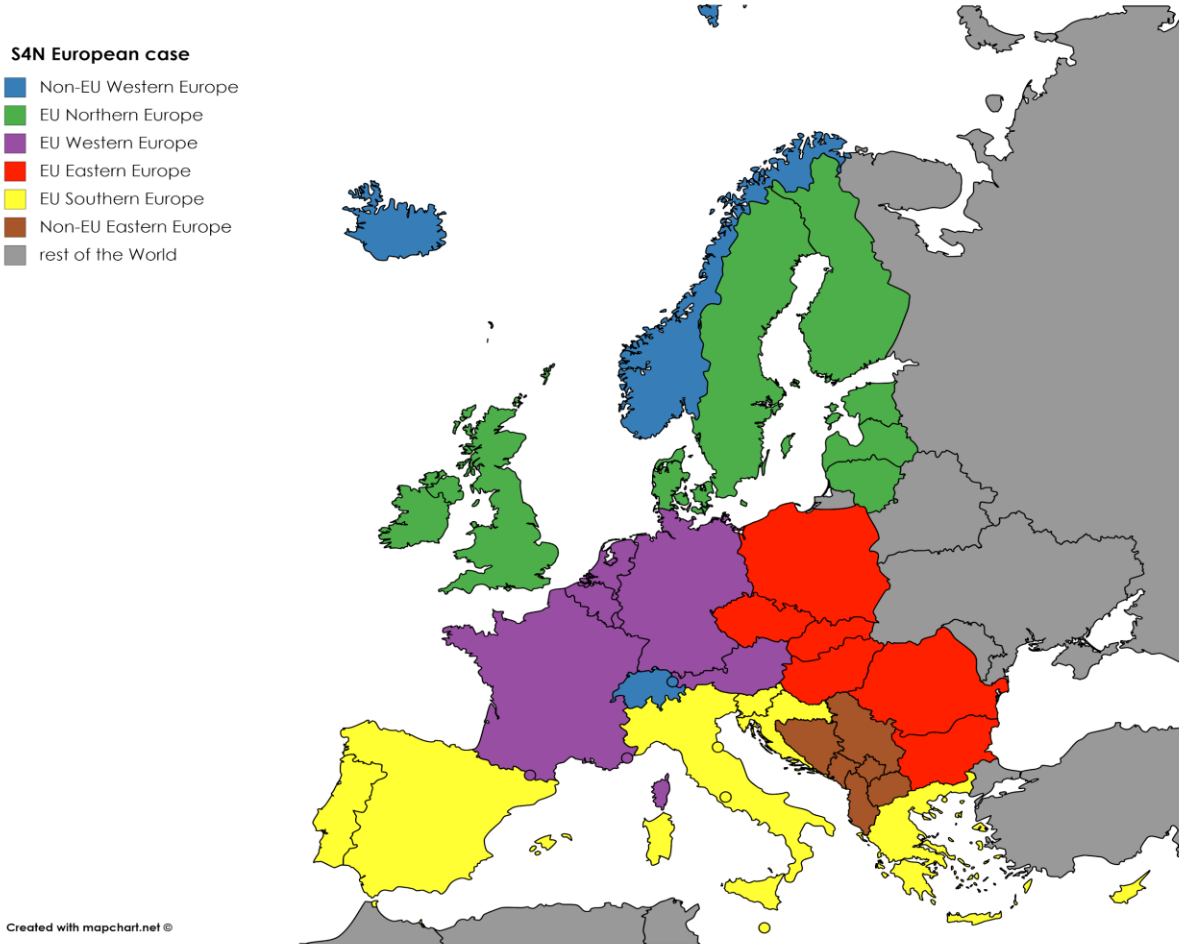
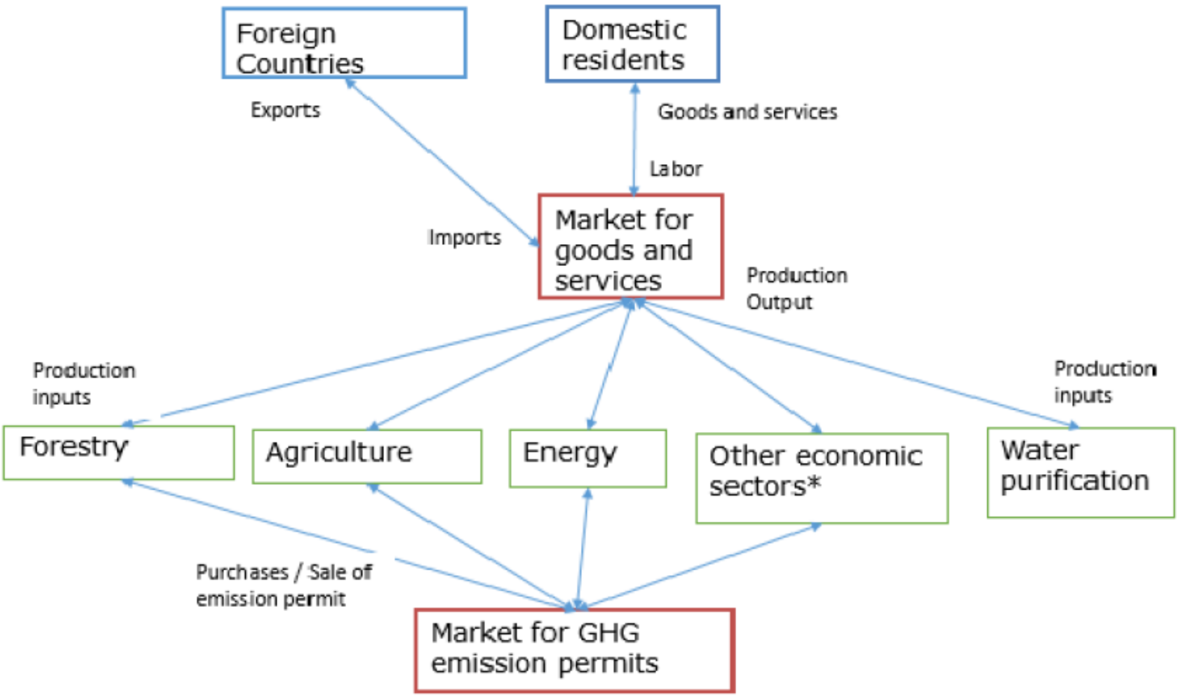


Figure 3.11.1: Spatial coverage of the European case, as well as the spatial (computational modelling) units being considered.

3.11.2 Evolution and description of the conceptual diagram

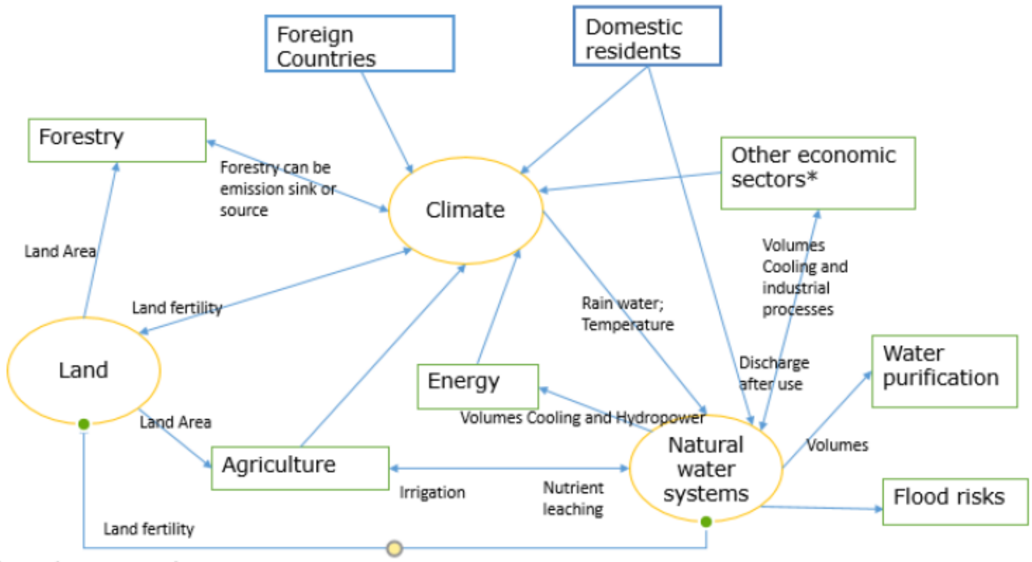
The initial conceptual model of the European case consisted of three sub-models (Figure 3.11.2). Figure 3.11.2a highlights only the economic relationships between sectors, for example import flows from outside to within the EU. Markets, food good and service and for GHG emissions and permits, drive production and demand for goods and services within the case study.

(a)



*E.g. Chemicals, Industry, Services, transport etc...

(b)



*E.g. Chemicals, Industry, Services etc...

Direction of physical element

All → into climate are emissions

(c)

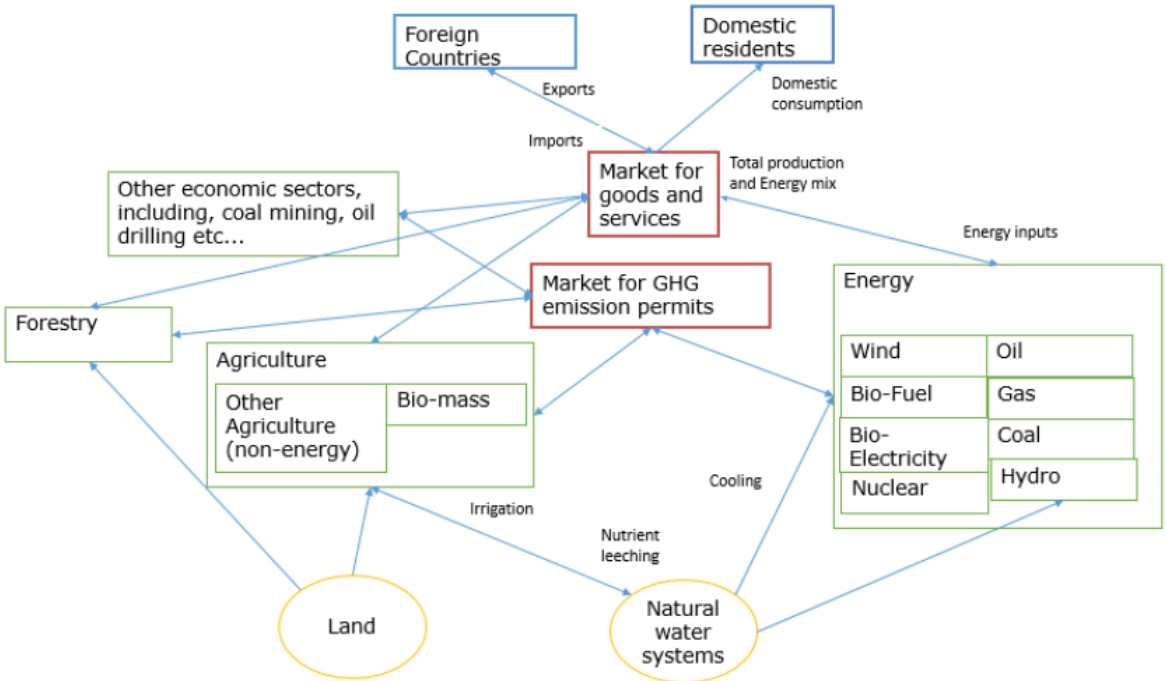
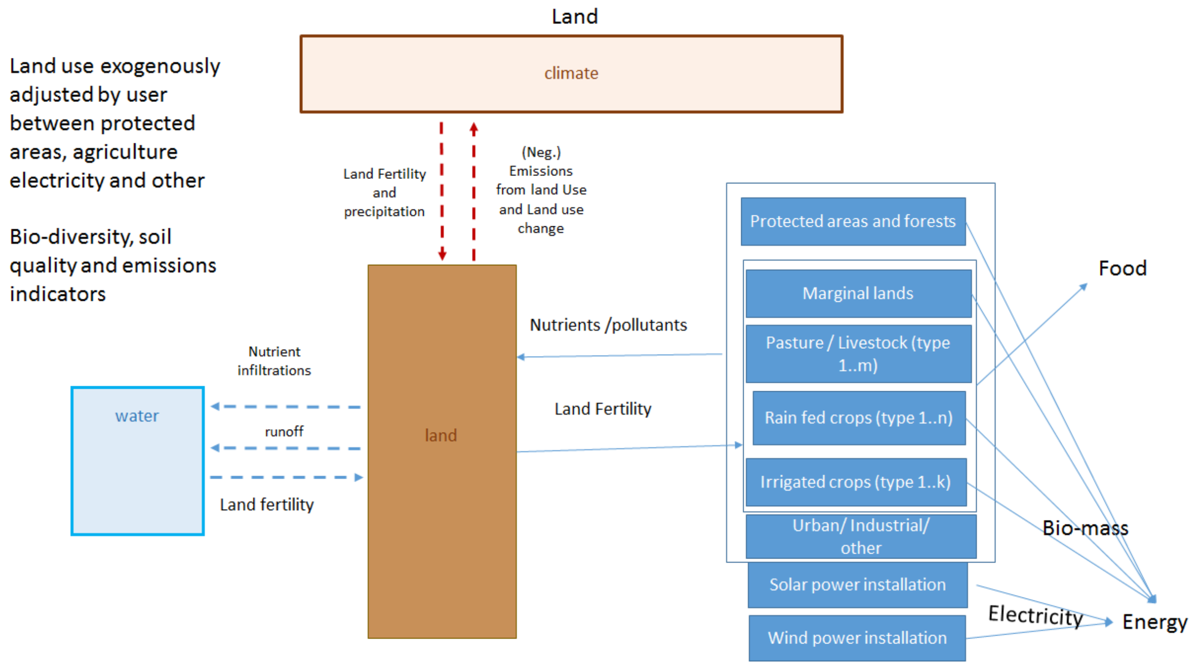


Figure 3.11.2: Initial conceptual model for the SIM4NEXUS European case, showing: (a) economic relations between entities; (b) physical flows and relationships between entities; and (c) economic and physical flows as they relate to energy and emissions.

Figure 3.11.2b shows the physical relationships between sectors. Climate is at the centre, as the focus of this case is the impacts of a transition to a low carbon economy. The links to and from the land sector, forestry, the agricultural sector, energy and the water sector are captured, along with the links between these sectors (e.g. the link between agriculture and water). Some of the high-level mechanisms between sectors are also mentioned (for example, climate will impact water systems through changes in temperature and precipitation, irrigation demand will affect the water system, forestry stocks will impact on GHG sequestration potentials). In addition, the impact of domestic (within case study domain) and foreign (outside the case study domain) residents is captured. Figure 3.11.2c brings out the economic and physical flows specifically in relation to energy and emissions – a focal area for this case study. The markets for goods, services and emissions are central here, affected by and affecting the forestry, agriculture (split into energy and non-energy crops), water and energy (split into renewables and non-renewables) sectors. Again, the impact of trade outside of the EU is important, and captured here.

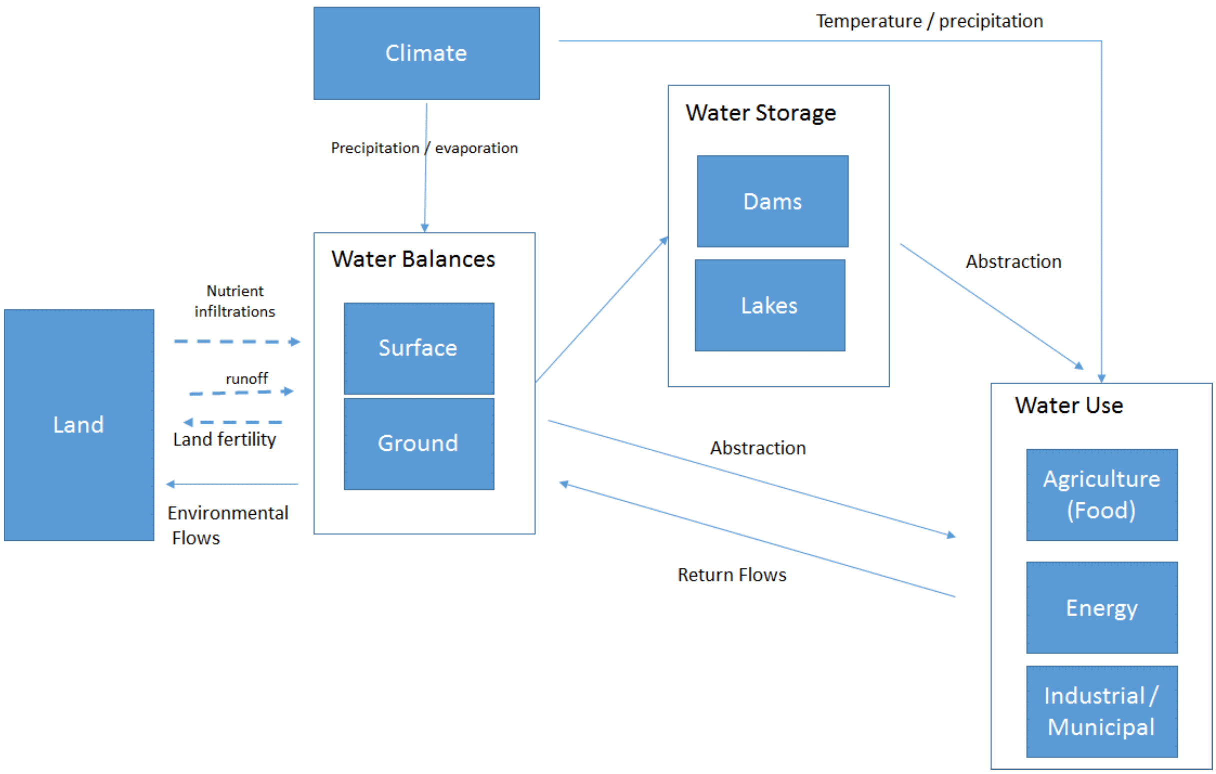
After several iterations, the initial version was amended to produce the final version of the European case study conceptual model (Figure 3.11.3). As with the De-CZ-SK case study, there is no overarching nexus diagram. Figure 3.11.3a details the land sector. Land use can be changed by the end user (serious game player). The land sector has impacts on the climate (GHG sequestration) and water (runoff, quality changes) sectors. Land is divided into many categories, including land used for forestry, pasture, livestock and agriculture, urban areas and renewable energy installations.

(a)



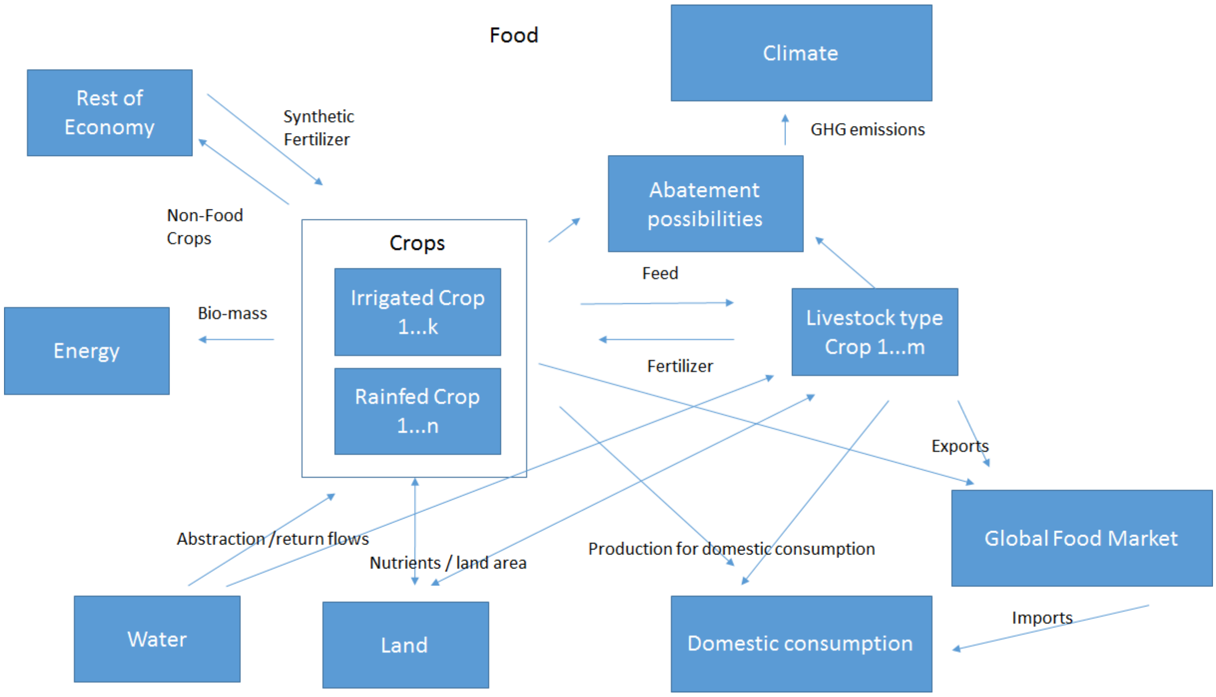
Land use exogenously adjusted by user between protected areas, agriculture electricity and other
Bio-diversity, soil quality and emissions indicators
Land
climate
Land Fertility and precipitation
(Neg.) Emissions from land Use and Land use change
land
water
Nutrient infiltrations
runoff
Land fertility
Nutrients /pollutants
Land Fertility
Protected areas and forests
Marginal lands
Pasture / Livestock (type 1..m)
Rain fed crops (type 1..n)
Irrigated crops (type 1..k)
Urban/ Industrial/ other
Solar power installation
Wind power installation
Food
Bio-mass
Electricity
Energy

(b)

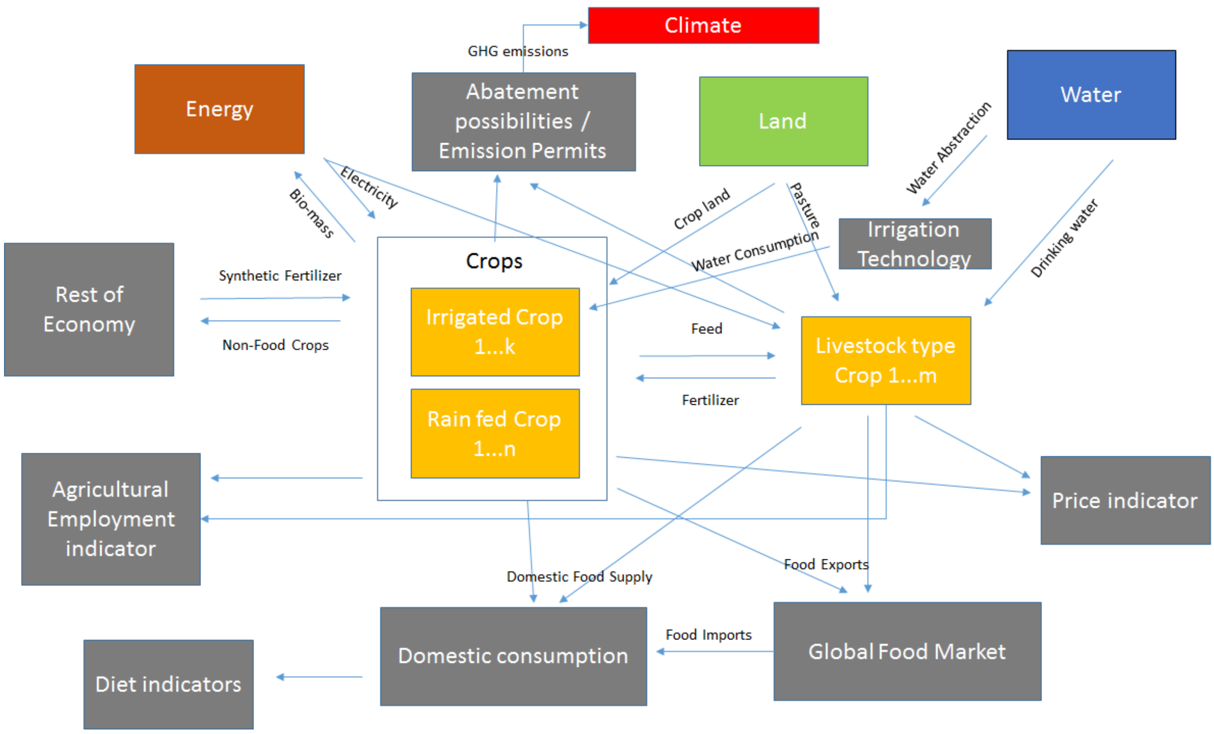


Climate
Temperature / precipitation
Precipitation / evaporation
Water Storage
Dams
Lakes
Abstraction
Water Balances
Surface
Ground
Land
Nutrient infiltrations
runoff
Land fertility
Environmental Flows
Abstraction
Return Flows
Water Use
Agriculture (Food)
Energy
Industrial / Municipal

(c)


Food
Climate
Rest of Economy
Synthetic Fertilizer
GHG emissions
Abatement possibilities
Non-Food Crops
Crops
Irrigated Crop 1…k
Feed
Livestock type Crop 1…m
Energy
Bio-mass
Fertilizer
Rainfed Crop 1…n
Exports
Global Food Market
Abstraction /return flows
Nutrients / land area
Production for domestic consumption
Imports
Water
Land
Domestic consumption

(d)


Climate
GHG emissions
Energy
Abatement possibilities / Emission Permits
Land
Water
Water Abstraction
Electricity
Bio-mass
Crop land
Pasture
Irrigation Technology
Water Consumption
Drinking water
Rest of Economy
Synthetic Fertilizer
Non-Food Crops
Crops
Irrigated Crop 1…k
Feed
Livestock type Crop 1…m
Fertilizer
Rain fed Crop 1…n
Agricultural Employment indicator
Price indicator
Food Exports
Domestic Food Supply
Diet indicators
Domestic consumption
Food Imports
Global Food Market

(e)

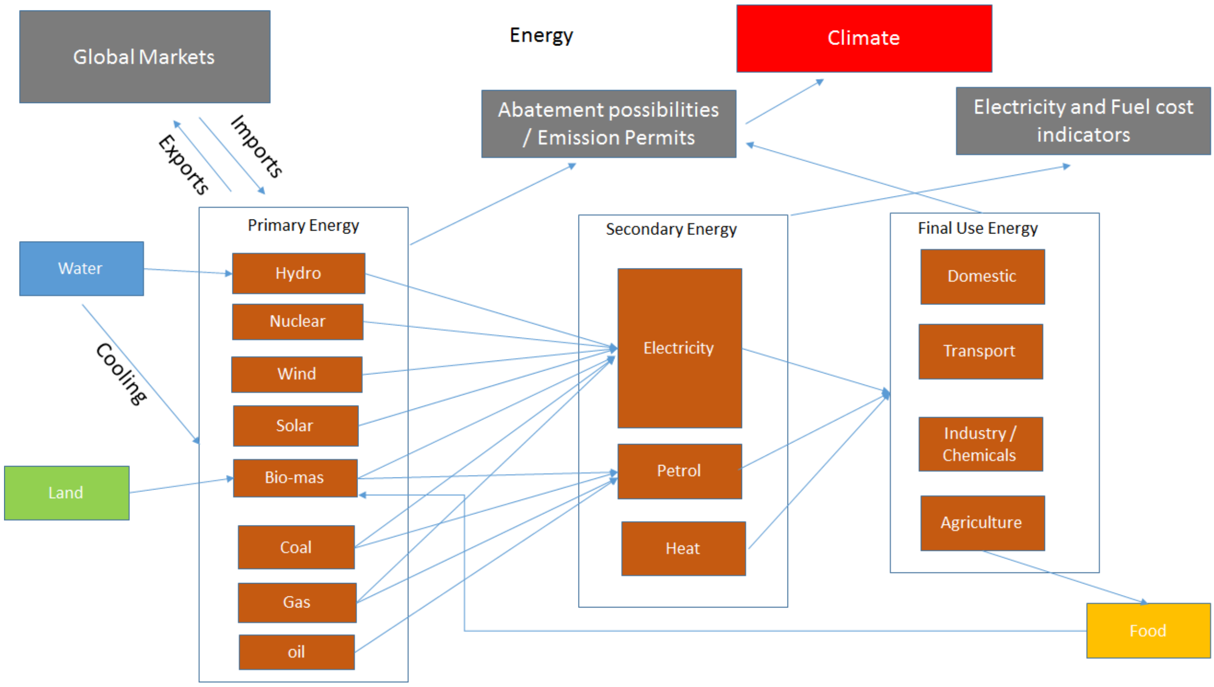


Figure 3.11.3: Conceptual model for the SIM4NEXUS European case, showing: (a) the land sector; (b) the water sector; (c) the food sector linked physically to other sectors; (d) the food sector linked economically to other sectors; and (e) the energy sector.

The water sector (Figure 3.11.3b) distinguishes high-level water availability and demand in order to produce policy-relevant water-related metrics. In addition, water stored in lakes and reservoirs is highlighted, in specific relation to human water supply and ecosystem service provision. The links to the land, food, energy and climate sectors are noted. The food sector is represented twice, once in terms of physical connections (Figure 3.11.3c) and again in terms of market and economic connections (Figure 3.11.3d). In terms of physical flows, the food sector is connected to energy via biomass, water for irrigation, land, and climate though emissions and abatement potentials. Consumption helps determine production, and levels of imports and exports. In terms of markets, diets, economic development, technology and global food markets also determine production – what types of crops and over what areas? Such changes in turn influence the water, land, energy and climate sectors. The energy sector (Figure 3.11.3e) specifies primary energy sources, and the water and land implications. It then specifies secondary energy generated from the primary sources (electricity, fuels, heat), and the final energy consumption of these secondary energy types. Thus, the climate impact of production and consumption can be assessed. Global markets and permits impact on primary energy production and on final energy consumption patterns.

3.11.3 Description of the developed system dynamics model

The top-level nexus model for the European case study is shown in Figure 3.11.4. Each sector is developed in further detail, as described here.

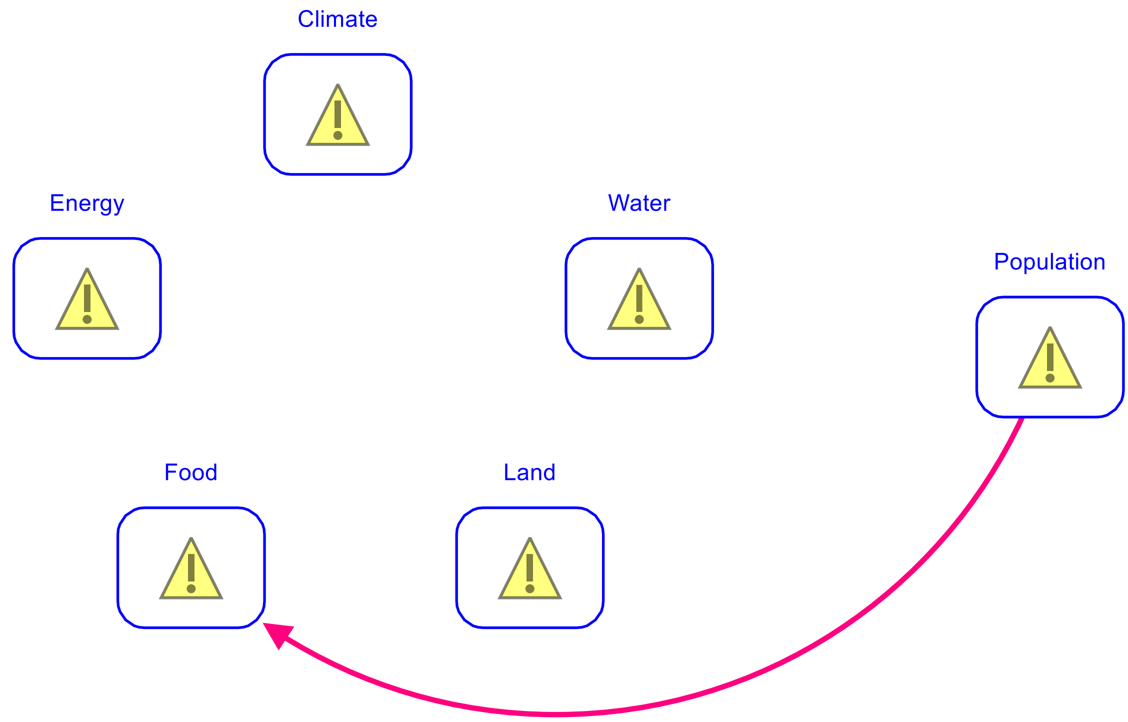


Figure 3.11.4: Top level nexus model for the European case study.

The water sector (Figure 3.11.5) in the European case is concerned with water withdrawals, nitrogen (N) and phosphorus (P) loading to water bodies, and indicators in aquatic ecosystems. Water withdrawals are accounted for by the following sectors: municipal water demand, industrial water demand, water for irrigation, and the water demand for electricity production using hydropower, solar, biomass, fossil fuels and nuclear sources. Nitrogen loading form urban areas, and P loading from urban and agricultural areas is quantified. The indicators of aquatic ecosystems comprise of biodiversity intactness, the percentage of algal blooms (related to N and P loads), and biodiversity loss in rivers due to habitat disturbance.

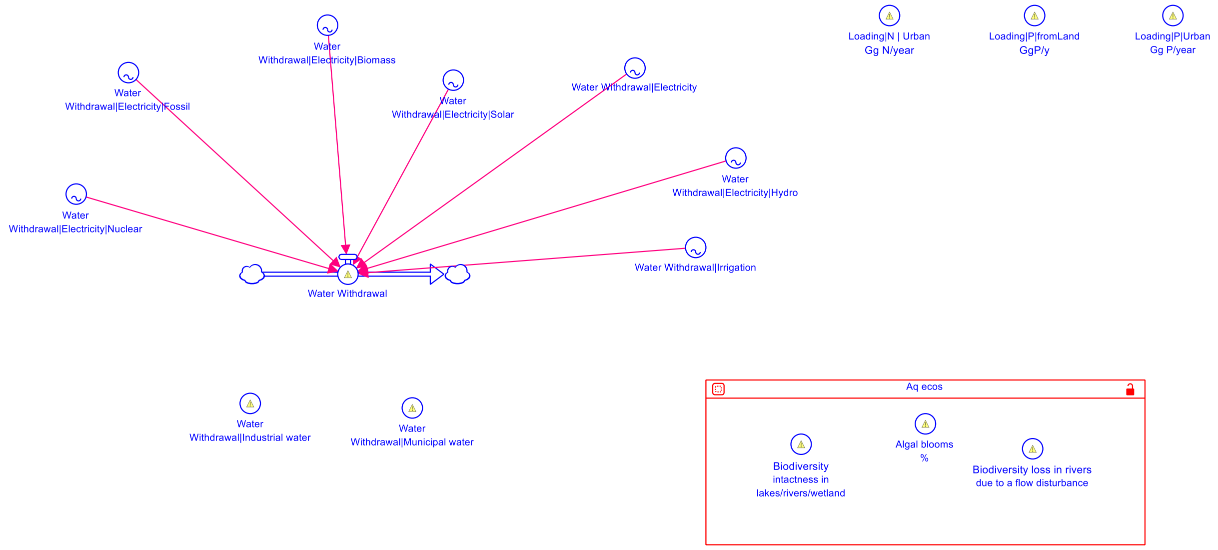


Figure 3.11.5: The water sector submodel for the European case study.

The land sector (Figure 3.11.6) tracks the area of land dedicated for rain-fed and irrigated agriculture, pasture, energy crops, protected areas and other unprotected areas. In addition, an indicator of terrestrial habitat intactness is also tracked by the model.

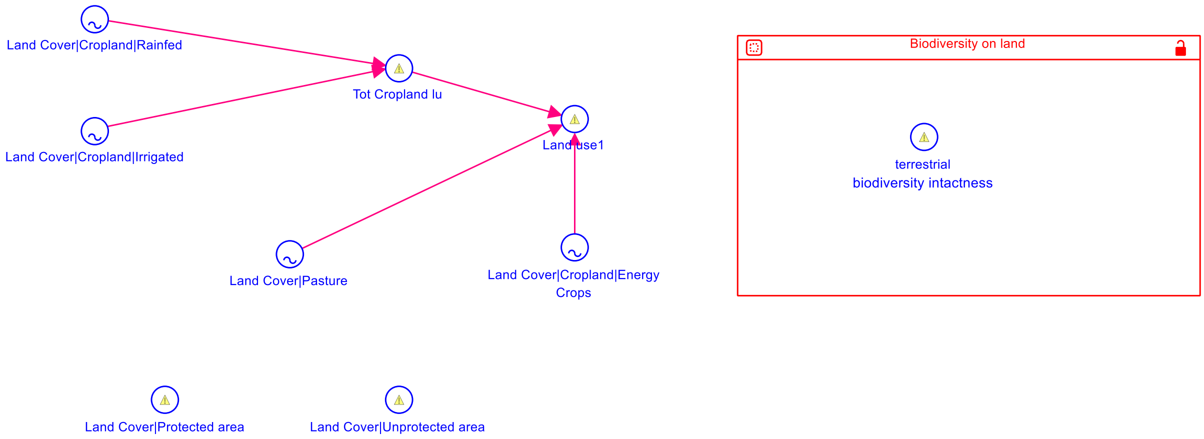


Figure 3.11.6: The land sector submodel for the European case study.

The food submodel (Figure 3.11.7) considers both food production and food consumption in the different European regions. Trade (imports and exports) between regions is also tracked in the model. On food availability, both livestock and crop production, as well as the production of fodder, is modelled, as well as the trade of all these products. On the consumption side, the food and livestock product demand per capita is multiplied by the population within each European region to estimate the total food demand. Because food demand is split by livestock and crops, the water, energy and climate impacts of dietary changes will be able to be modelled.

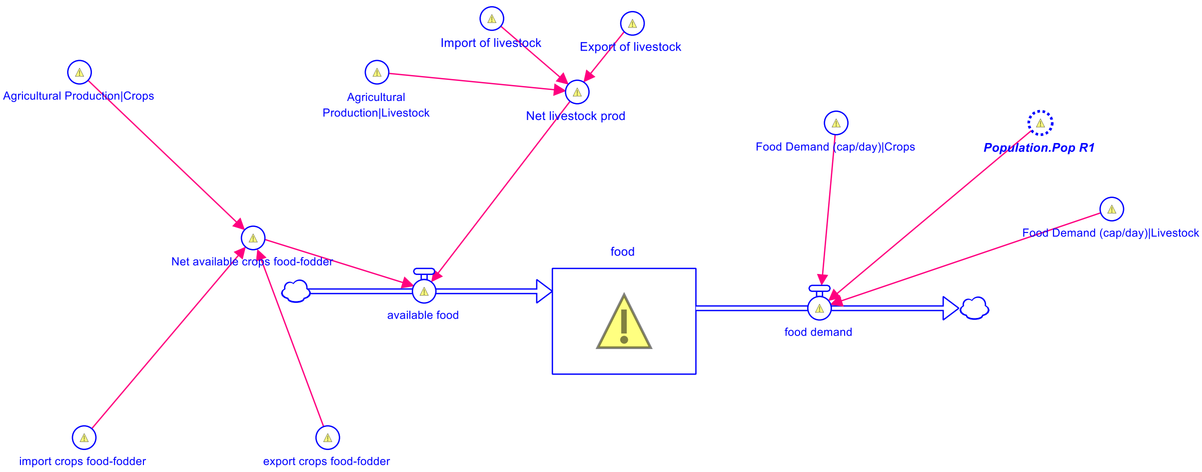


Figure 3.11.7: The food sector submodel for the European case.

The energy submodel (Figure 3.11.8 up to Figure 3.11.13) has been developed in considerable detail. The top-level (Figure 3.11.8) shows the balance between supply from three main sources, and demand from five sources. Each supply and demand source is further developed with its own submodel.

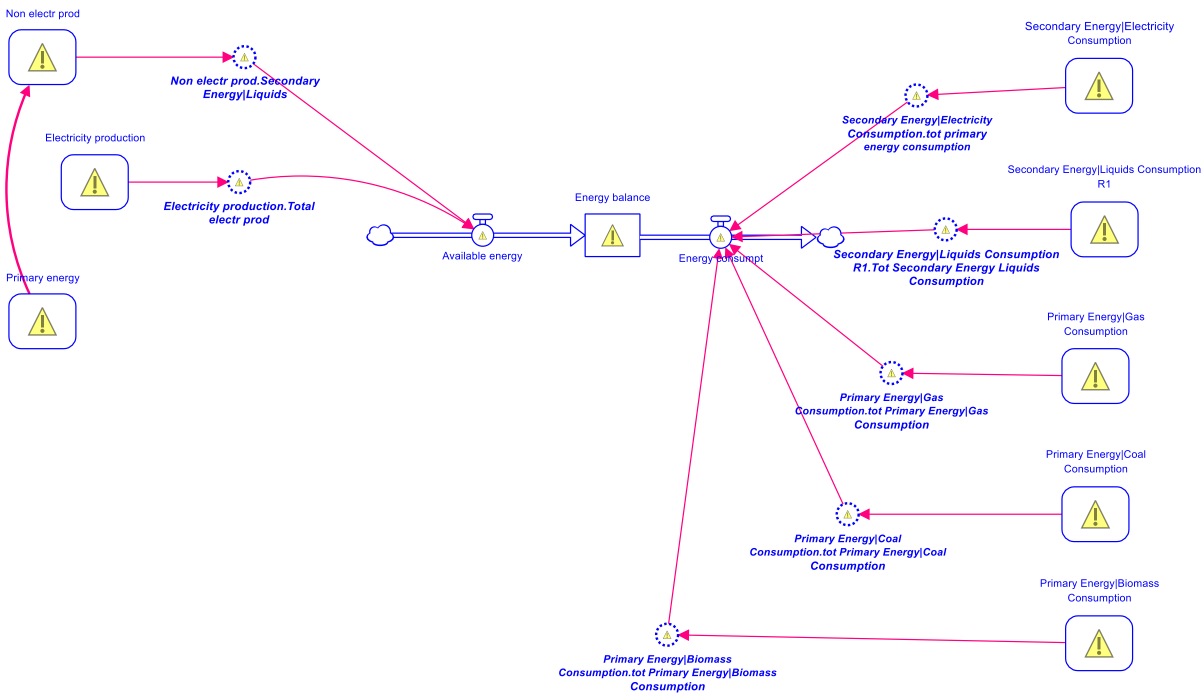


Figure 3.11.8: Top-level energy sector submodel for the European case. Each supply and demand sector is subsequently developed further.

Primary energy (Figure 3.11.9) in each European region is comprised of biomass, coal, oil, gas, plus the balance between import and export of these products. In addition to primary energy sources, electric and non-electric energy is modelled. Electric energy (Figure 3.11.10) comes from gas and coal (fossil fuel) sources, nuclear power, hydropower, biomass, and wind and solar sources. Non-electric power (Figure 3.11.11) comes from biofuels, and oil-fuel sources, both representing liquid fuels. Again, imports and exports are accounted for in the model.

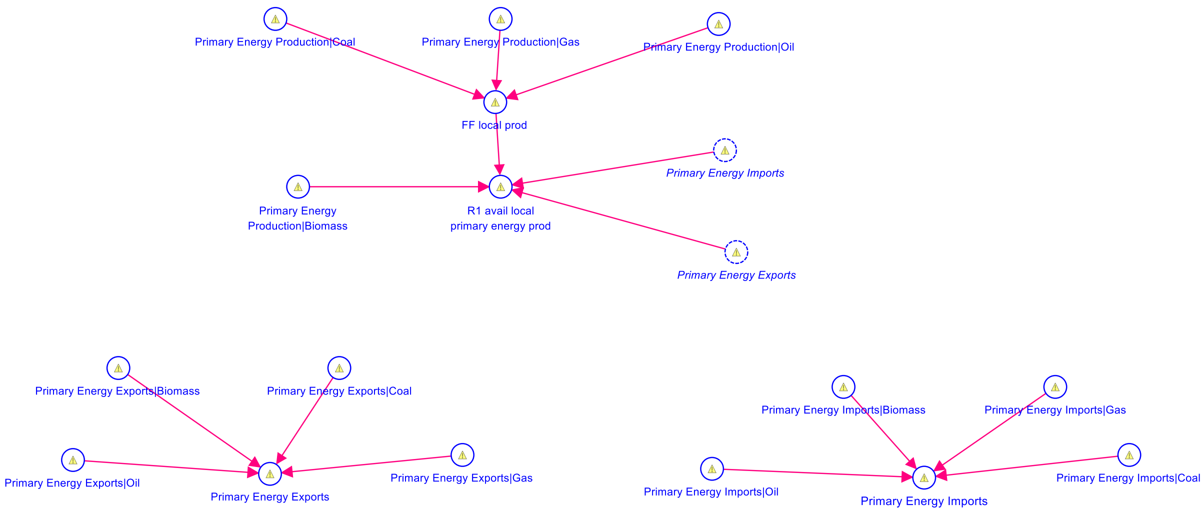


Figure 3.11.9: Primary energy sources submodel for the European case study.

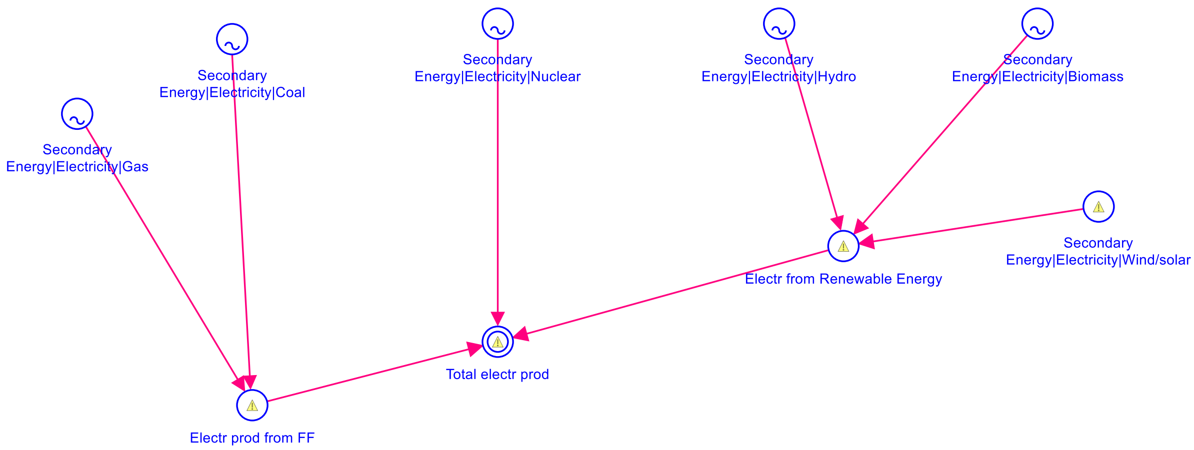


Figure 3.11.10: Electric energy production submodel for the European case study.

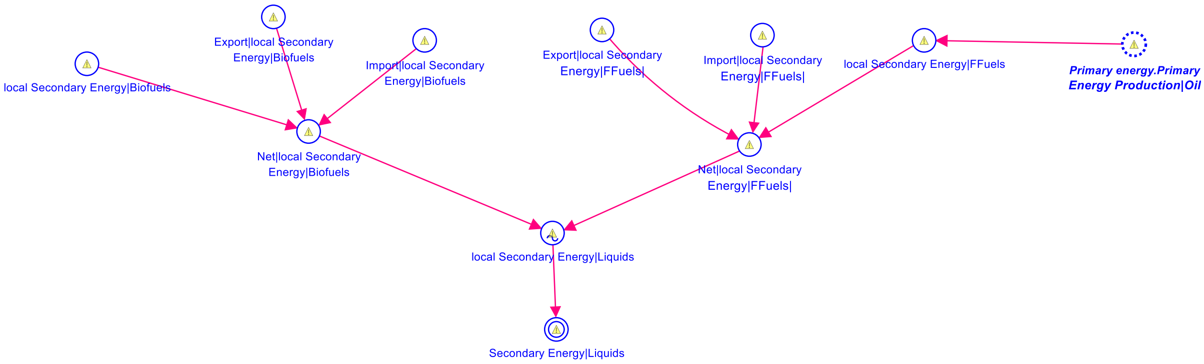


Figure 3.11.11: Non-electric energy production submodel for the European case study.

In terms of demand, consumption is divided by energy type, and consists of electric, liquid, gas, coal and biomass fuel consumption. Demand for each fuel type comes from the same five sectors for each fuel type mentioned: industry, services, transport, agriculture, and domestic. Figure 3.11.12 shows the submodel for the demand of electric energy. The submodels for liquids, gas, and coal are identical in terms of structure and sectors. Only the fuel type differs, and therefore these other sector submodels are not shown here. The demand for biomass energy differs (Figure 3.11.13), accounting for consumption of biomass for production of biofuels and electricity from biomass sources.

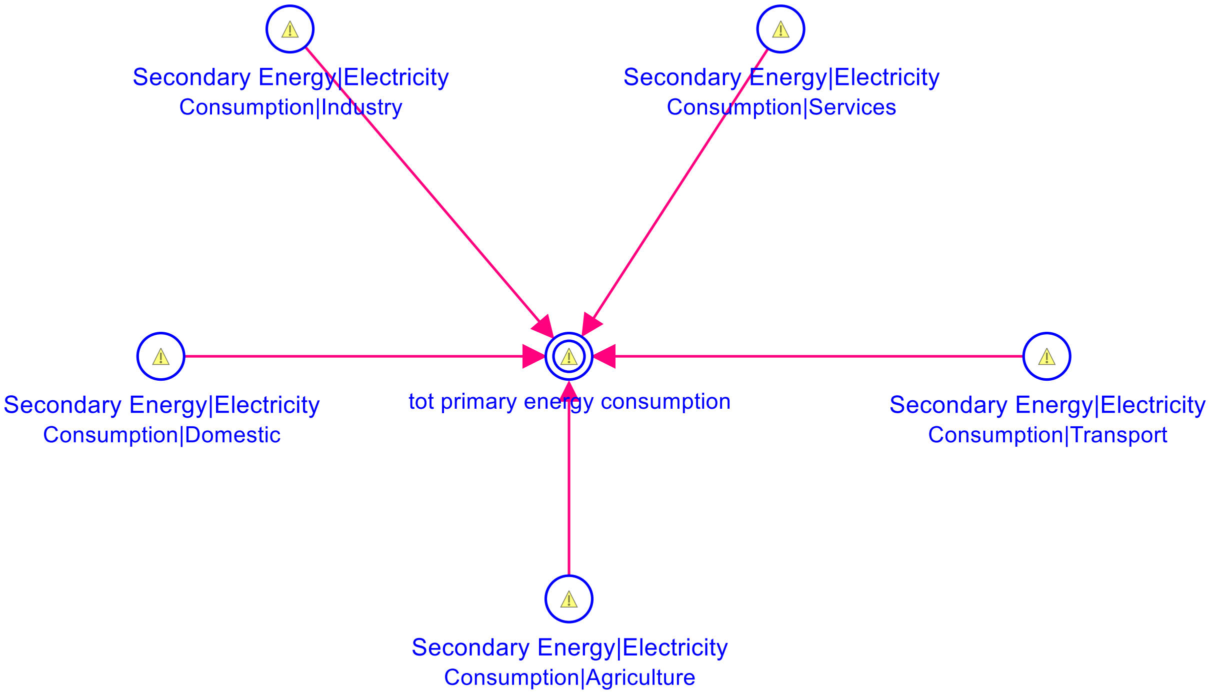


Figure 3.11.12: Submodel for the demand of electric energy for the European case study. The demand submodels for the liquids, gas, and coal energy sources are identical in structure.

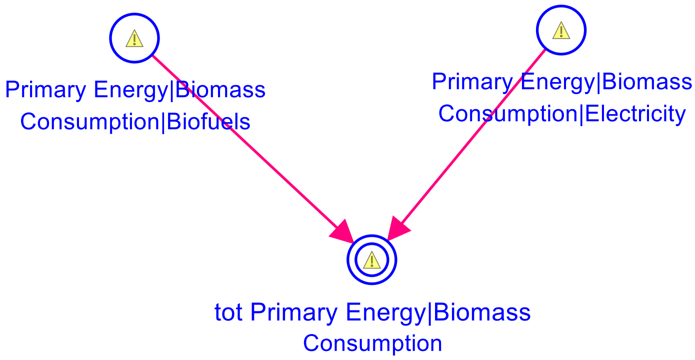


Figure 3.11.13: The biomass energy consumption submodel for the European case study.

The climate sector submodel (Figure 3.11.14) models the total emissions from gas, coal and liquid energy consumption, as well as production in six sectors (domestic, services, transport, industry, agriculture, and other) in units of CO_2-e. In the gas, liquid, and coal energy sectors, emissions come from the services, domestic, transport, industry, agricultural, electricity generation, and other sectors. In terms of emissions from production (of products), production in the industry, transport, domestic, other, and service sectors are accounted for, as well as within the agricultural sector, which itself is divided into crops and livestock, and accounts individually for N_2O, CH_4 and CO_2 emissions from these products (Figure 3.11.14). As such, the climate change potential from different agricultural products (linked to diets) and from different climate forcing gases, and be modelled.

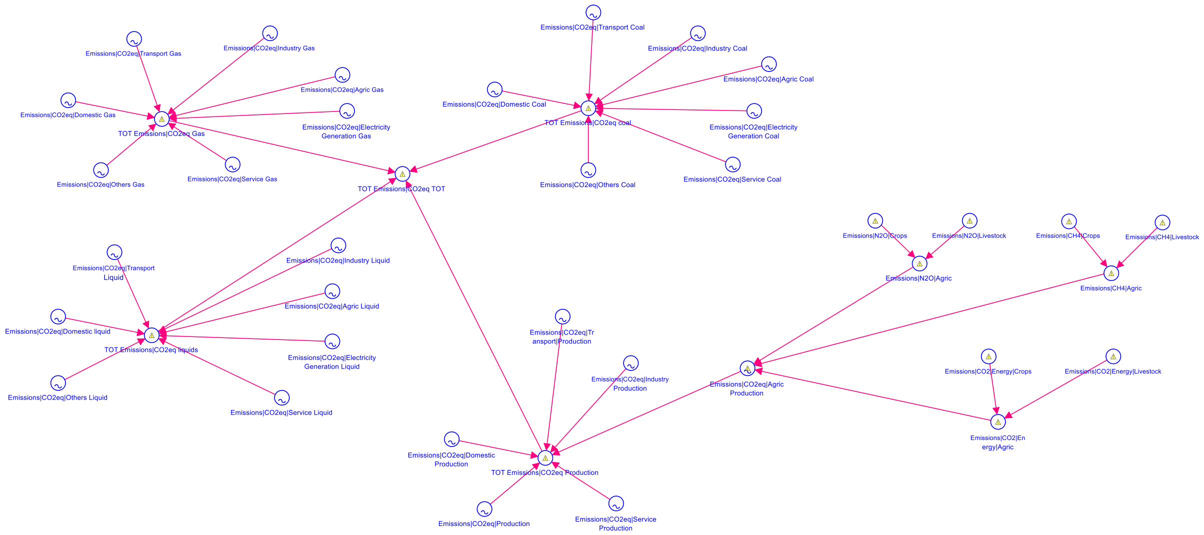


Figure 3.11.14: Climate sector submodel for the European case study.

3.12 Global case study

This deliverable presents the status of the Conceptual Model (CM) and System Dynamics Model (SDM) development as of May 2019. To reflect the further process after May, this section on the global case was updated, as described in some more detail in section 3.12.3.

3.12.1 Short description of the case study

The objective of the global case study is to identify and assess nexus issues at the global scale, without output indicators relevant for tracking global progress towards various SDGs. The main tool for these analyses are the six participating thematic models: E3ME-FTT, MAGNET, CAPRI, IMAGE-GLOBIO, OSeMOSYS and MAgPIE. Therefore, the focus of the global case lies on nexus issues that are represented by these models. Specifically, these are the interactions between the water, land, food, energy and climate systems. The global case is divided into seven IMAGE model regions (Figure 3.12.1) for analysis.

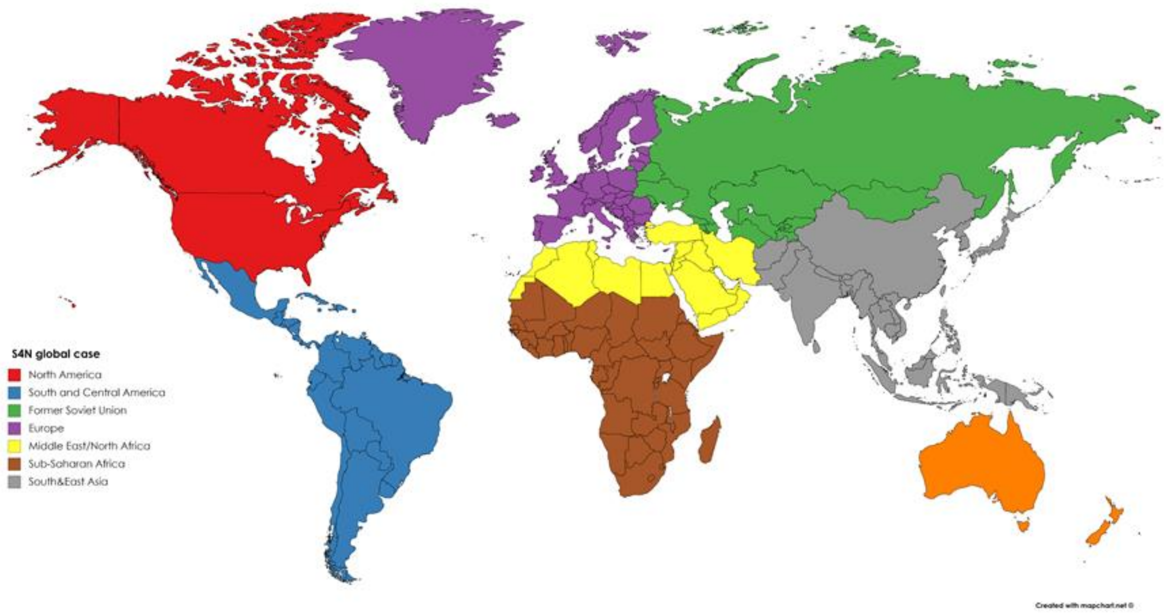


Figure 3.12.1: The global case study in SIM4NEXUS split into seven IMAGE regions.

3.12.2 Evolution and description of the conceptual diagram

Figure 3.12.2 shows the first draft conceptual model for the global case study. The five nexus sectors are clearly indicated, along with an indication of the processes acting between sectors. For example, water shortages may impact on food production, food production affects irrigation water requirements, and climate change can affect food production and water availability, while climate is impacted by the energy generation mix. In addition, the specific thematic model that can best represent and model the interactions between any two nexus sectors is indicated. For example, GLOBIO is best suited to modelling biodiversity changes, while IMAGE is suited to assessment of water shortages and the corresponding impacts. For the climate impacts on food production, IMAGE, MAgPIE, MAGNET and CAPRI can all be used to assess the impacts.

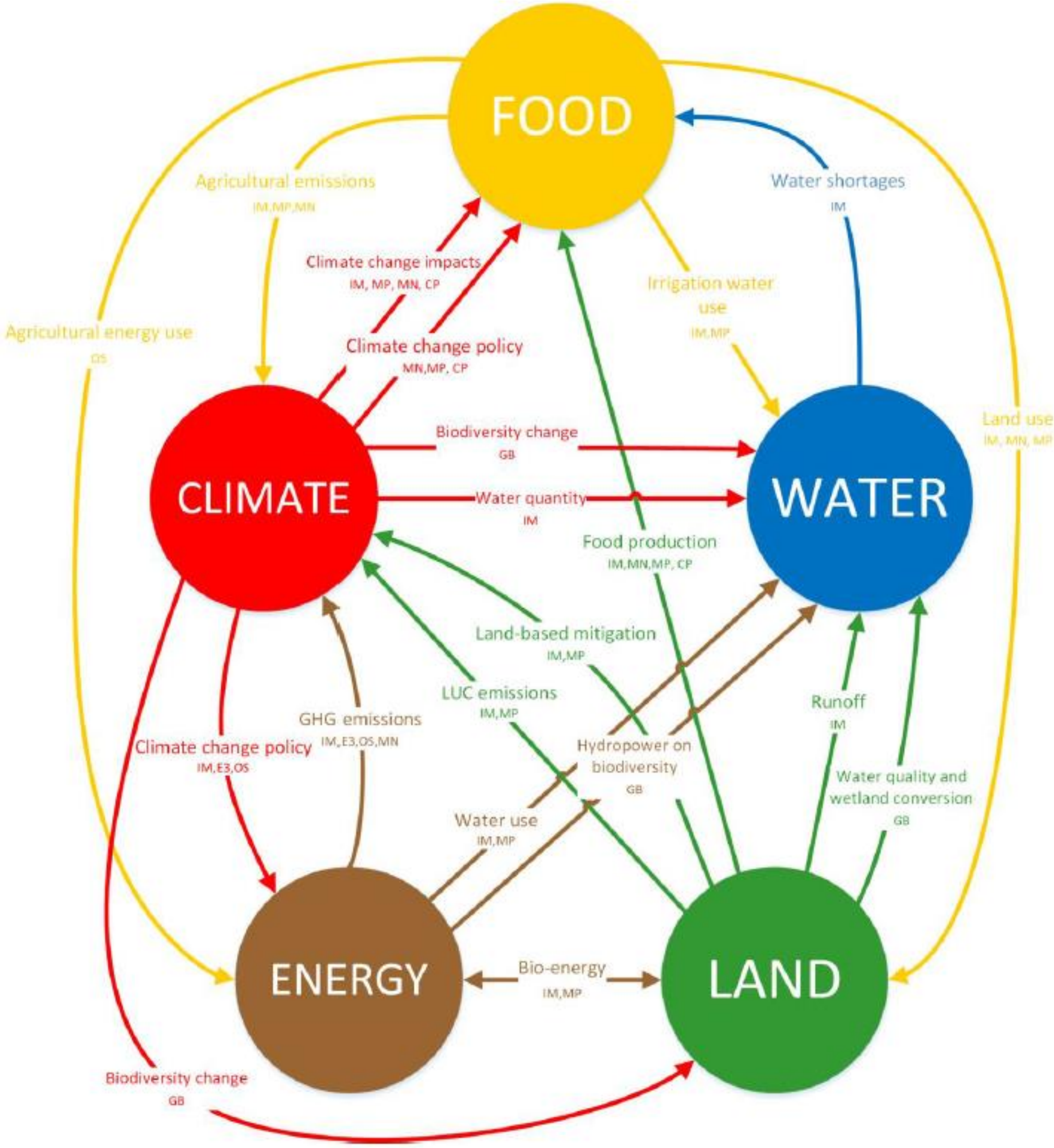


Figure 3.12.2: First draft conceptual model for the global case study, showing the main nexus linkages and the thematic models suited to modelling the links. IM = IMAGE; E3 = E3ME; OS = OSeMOSYS; MN = MAGNET; MP = MAgPIE; CP = CAPRI; GB = GLOBIO.

In addition, Figure 3.12.2 shows how (policy) changes in each nexus sector not only impacts on the other sectors, but can also affect global markets and prices. It shows the linkages coming from issues such as emissions pricing, land planning (and changes thereof), water certificates, and dietary education, both between the nexus sectors, but also on related issues such as crop production, processing and trade, and in turn, the relationship with global markets and prices, which ultimately underlay the scales and locations of production and consumption in our global economy.

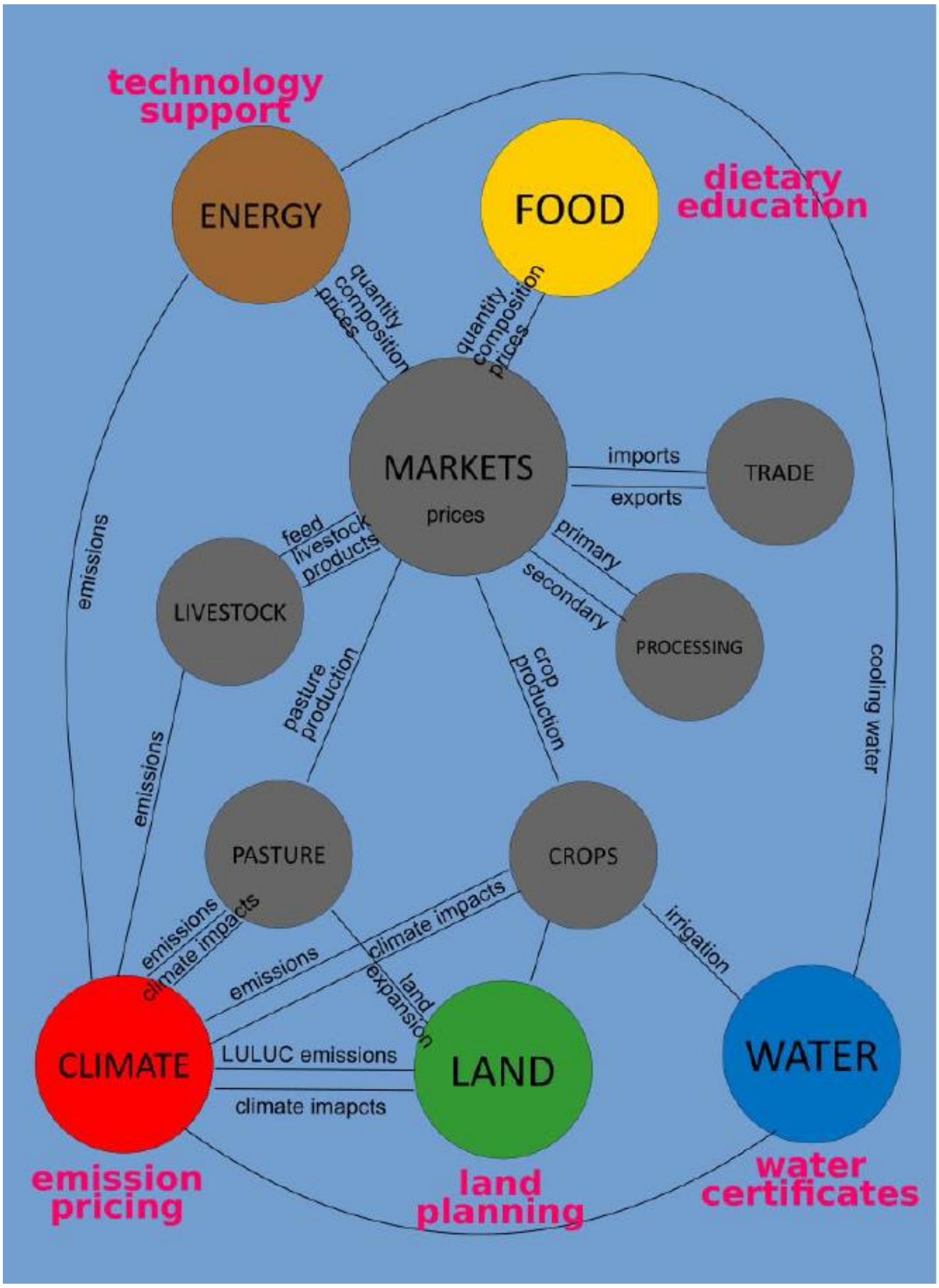
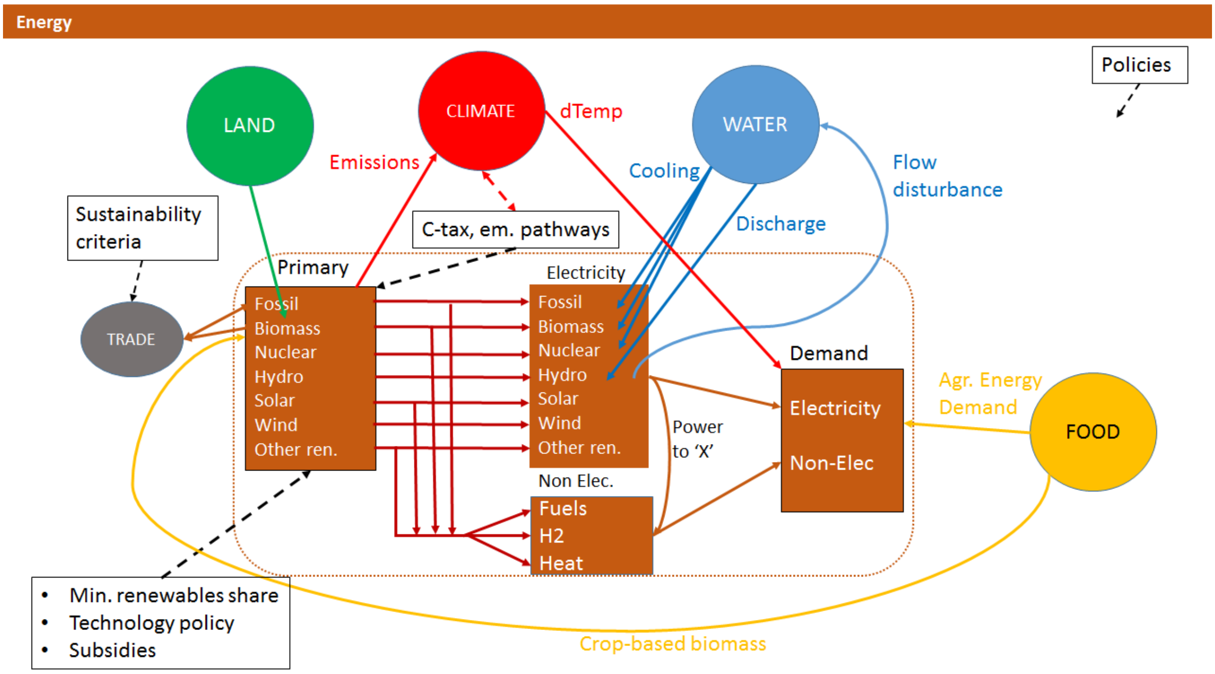


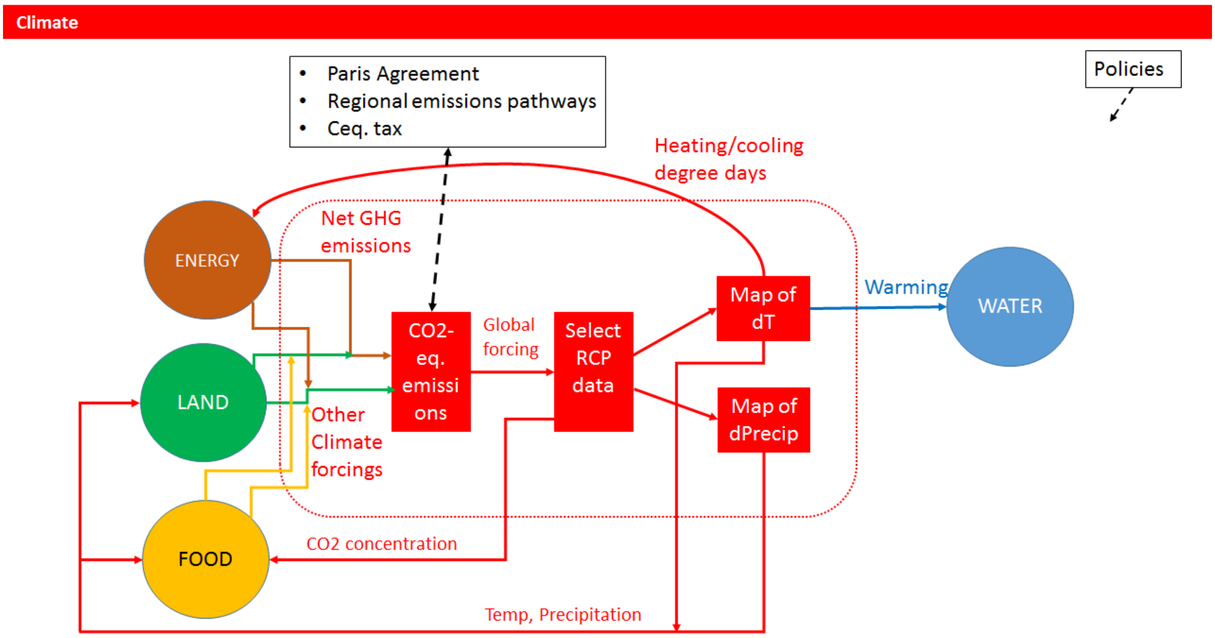
Figure 3.12.3: A different draft of the conceptual model showing how various (policy) interventions may act on each nexus sector and in consequence, on global markets.

For the final conceptual model, Figure 3.12.2 and Figure 3.12.3 above do not change, and now represent the high-level nexus model. The detailed sector models were completed (Figure 3.12.4) and are now described. It is noted that because the European and Global case studies have thematic models at their core, and seek to explore similar issues and deliver similar messages, the two conceptual models have considerable overlap. This will ultimately offer some consistency between these two case studies in SIM4NEXUS.

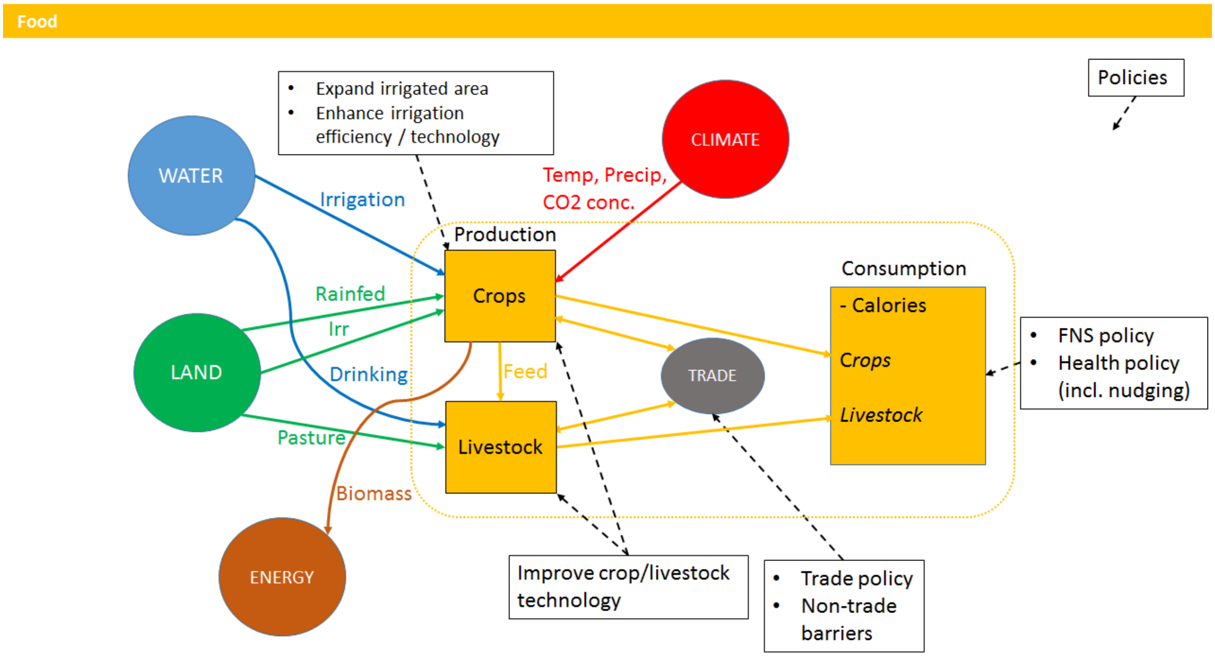
(a)


Energy
Policies
LAND
CLIMATE
dTemp
WATER
Emissions
Cooling
Flow
disturbance
Sustainability
criteria
C-tax, em. pathways
Discharge
Primary
Electricity
TRADE
Fossil
Biomass
Nuclear
Hydro
Solar
Wind
Other ren.
Fossil
Biomass
Nuclear
Hydro
Solar
Wind
Other ren.
Demand
Agr. Energy
Demand
Electricity
Non-Elec
FOOD
Power
to 'X'
Non Elec.
Fuels
H2
Heat
Min. renewables share
Technology policy
Subsidies
Crop-based biomass

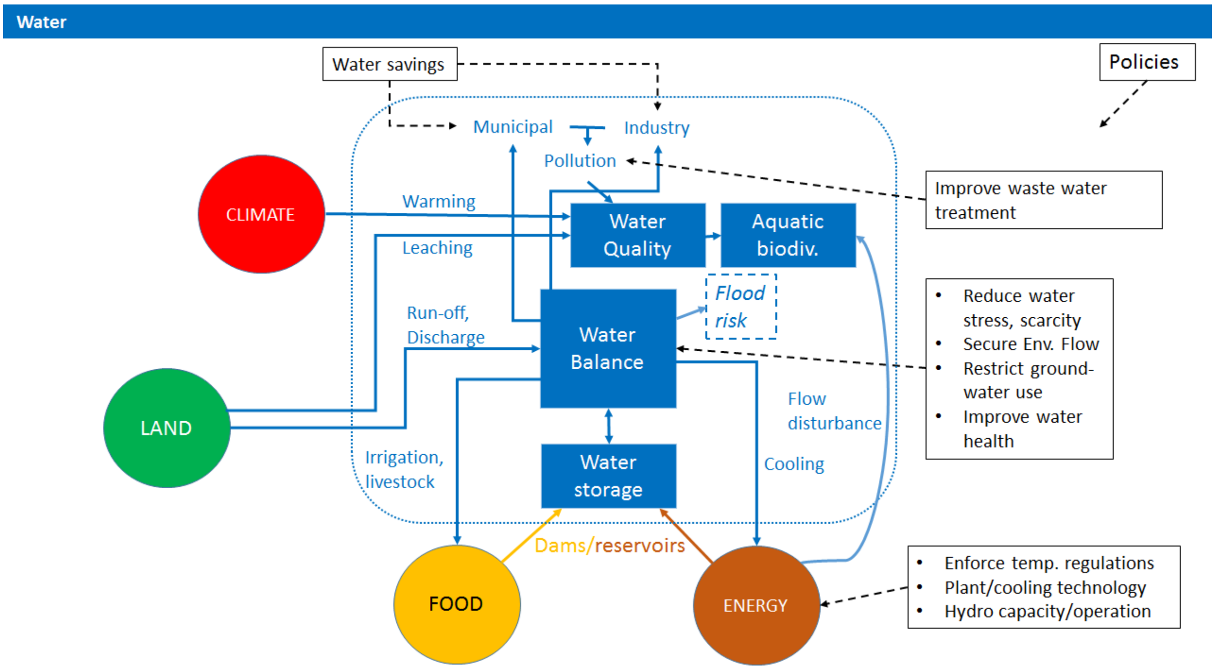
(b)


Climate
Paris Agreement
Regional emissions pathways
Ceq. tax
Policies
Heating/cooling
degree days
Net GHG
emissions
ENERGY
CO2-
eq.
emissi
ons
Global
forcing
Select
RCP
data
Map of
dT
Warming
WATER
LAND
Other
Climate
forcings
Map of
dPrecip
FOOD
CO2 concentration
Temp, Precipitation

(c)


Food
Policies
Expand irrigated area
Enhance irrigation efficiency / technology
CLIMATE
WATER
Irrigation
Temp, Precip, CO2 conc.
Production
Crops
Consumption
- Calories
Rainfed
Irr
LAND
Drinking
Feed
TRADE
Crops
Livestock
FNS policy
Health policy (incl. nudging)
Pasture
Livestock
Biomass
ENERGY
Improve crop/livestock technology
Trade policy
Non-trade barriers

(d)


Water
Water savings
Policies
Municipal
Industry
Pollution
CLIMATE
Warming
Leaching
Water Quality
Aquatic biodiv.
Improve waste water treatment
Flood risk
Run-off, Discharge
Water Balance
Reduce water stress, scarcity
Secure Env. Flow
Restrict ground-water use
Improve water health
LAND
Flow disturbance
Irrigation, livestock
Water storage
Cooling
Dams/reservoirs
FOOD
ENERGY
Enforce temp. regulations
Plant/cooling technology
Hydro capacity/operation

(e)

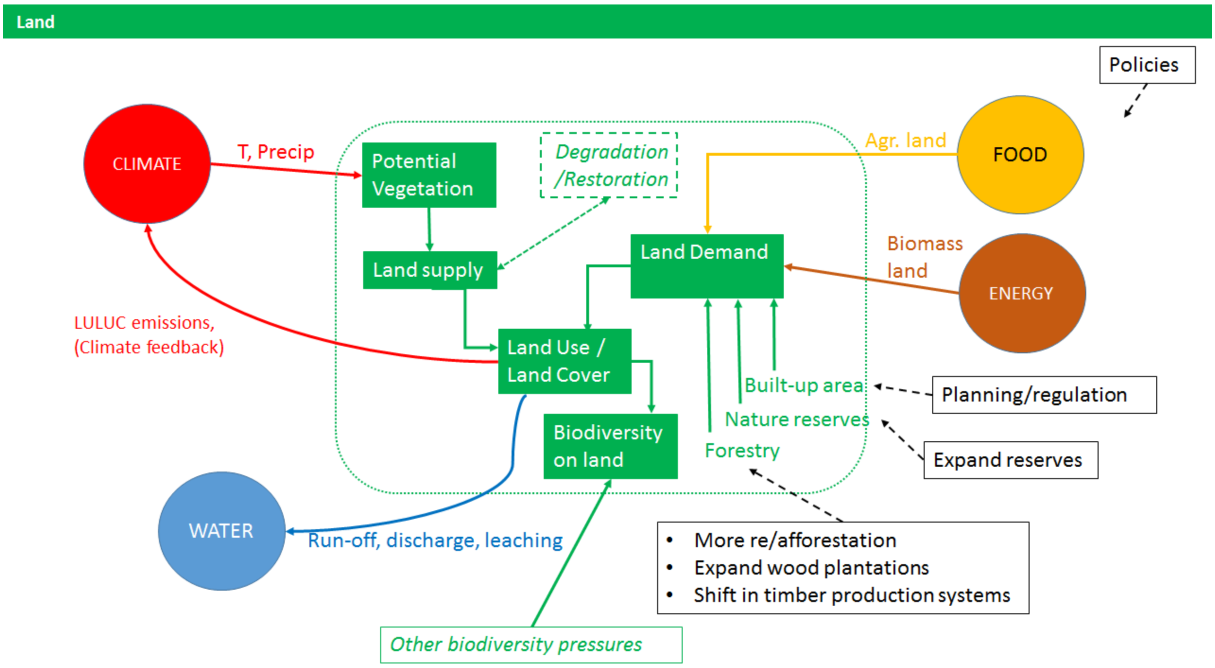


Figure 3.12.4: Final conceptual model for the Global case study in SIM4NEXUS, showing: (a) the energy sector; (b) the climate sector; (c) the food sector; (d) the water sector and; (e) the land sector.

The energy sector (Figure 3.12.4a) comprises primary energy production (fossil, biomass, nuclear, wind, solar), and subsequently electricity and non-electricity power generation. Demand is simply split by electric and non-electric demand. Climate impacts on energy demand and energy production changes the climate. Water impact particularly on electricity generation. Land contributes to primary bioenergy production and is in conflict with food production. Trade influences especially fossil and biomass. Carbon taxes and emissions pathways contribute to changes in the make-up of the energy-producing sources, with a move away from fossil sources being most desirable. In terms of the climate sector (Figure 3.12.4b) net CO_2-e emissions (therefore accounting for changes in sequestration due to land use and technological changes for example) come from the energy, land and food sectors, and changes therein. Emissions force changes in temperature and precipitation according to RCP projections. These changes feedback to influence land use and land cover, food production and energy generation (amount and sources), and also change water-related characteristics. Emissions pathways, taxes and the Paris Agreement may act to change emissions futures. In the food sector (Figure 3.12.4c), production is split into crops and livestock, and is forced by global trade and technology. Water and land influence production, and some of the production goes to the energy sector for biomass energy production. The climate impacts on crop production especially. Consumption is also measured, and is partly linked to production patterns and also influences by policy such as healthy eating initiatives and a shift (nudge) towards a lower meat-content diet. The water sector (Figure 3.12.4d) is based on a relatively simple water balance, and is affected by the land, food, climate and energy sectors. The water sector itself has an influence on the food and energy sectors, and influences on aquatic biodiversity. Water demand savings positively affect water balances. Increasing water supply efficiency, technological improvements in other sectors (e.g. the energy and irrigation sectors) and water savings measures contribute to improving water balances, while climate changes may positively or negatively affect balances depending on the location. Finally, the land sector (Figure 3.12.4e) has land use/land cover at its core. Land supply and demand cause changes in land use/cover, and thus impact biodiversity indicators. The land sector is influences by changes in the climate, agricultural expansion and bio-crop demand. It is also influenced by planning and regulatory policy, protection of natural areas and reforestation and/or afforestation efforts. The land sector in turn influences the water sector by altering runoff patterns and water quality and it can alter climatic variables through modulating emissions to the atmosphere.

3.12.3 Graphic representation of interlinkages towards an SDM

The Conceptual Model drawings of section 3.12.2 were used to get started with the development of a system dynamics model (SDM) for the global case. In May 2019, that status of the SDM of the global case was as reported in figures 3.12.5 to 3.12.17 (The top level nexus SDM for the global case is shown in Figure 3.12.5). In the further process, it emerged that building a SDM model for the global case could not be realized. Different from other case studies, there is no need to quantify expert knowledge, but very detailed explicit relations are already included in the complex models of the global case (IMAGE, MAgPIE, E3ME, ….), including complex multi-region relationships. In fact building a SDM would in fact mean to build a very sophisticated meta-model, and the endeavour to built such a meta-model was beyond capacities available in SIM4NEXUS. Therefore, in close discussion with the relevant project partners (IHE-Delft, UNEXE, WUR-LEI, PBL) it was decided not to follow the SDM at the global case further, but to develop other forms of interactive communication on the global case and it's nexus relations. These will be further described in Deliverable D3.6 (due for Month 48).

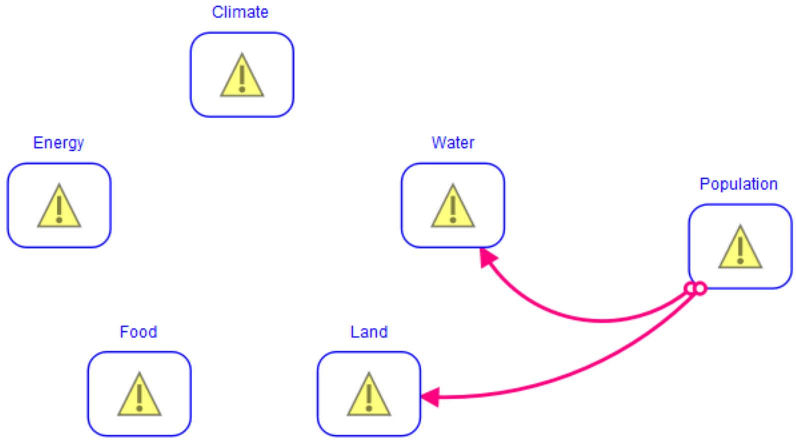


Figure 3.12.5: Top-level SDM for the global case study.

The water sector has two main components, water quantity and water quality, with both elaborated in detailed (Figure 3.12.6 and Figure 3.12.7).

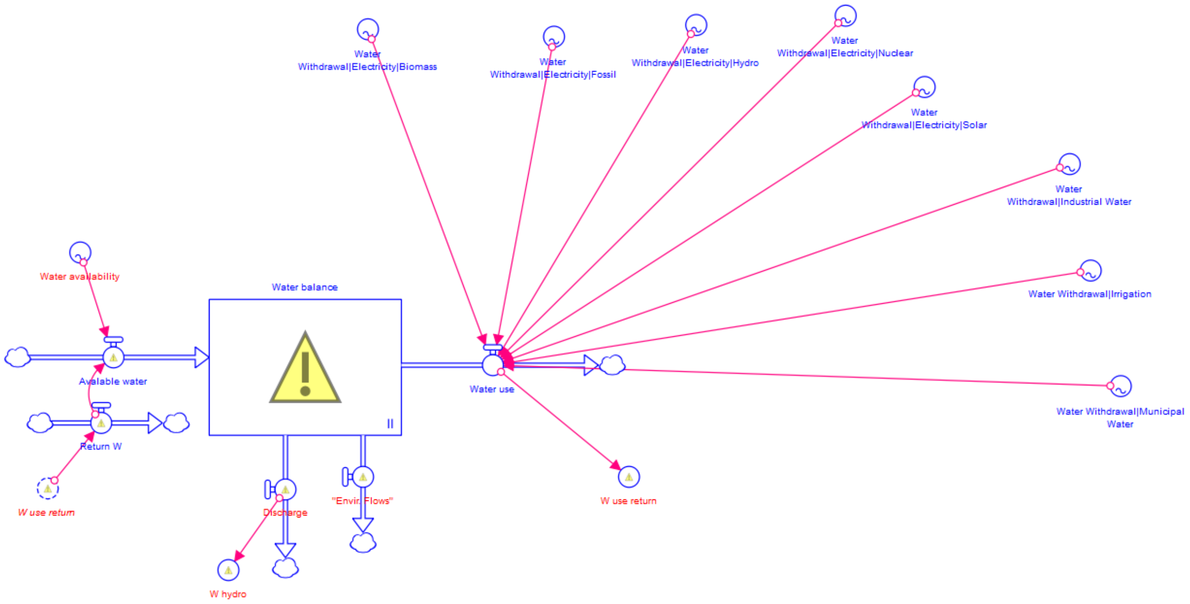


Figure 3.12.6: Water quantity part of the water sector in the global case study.

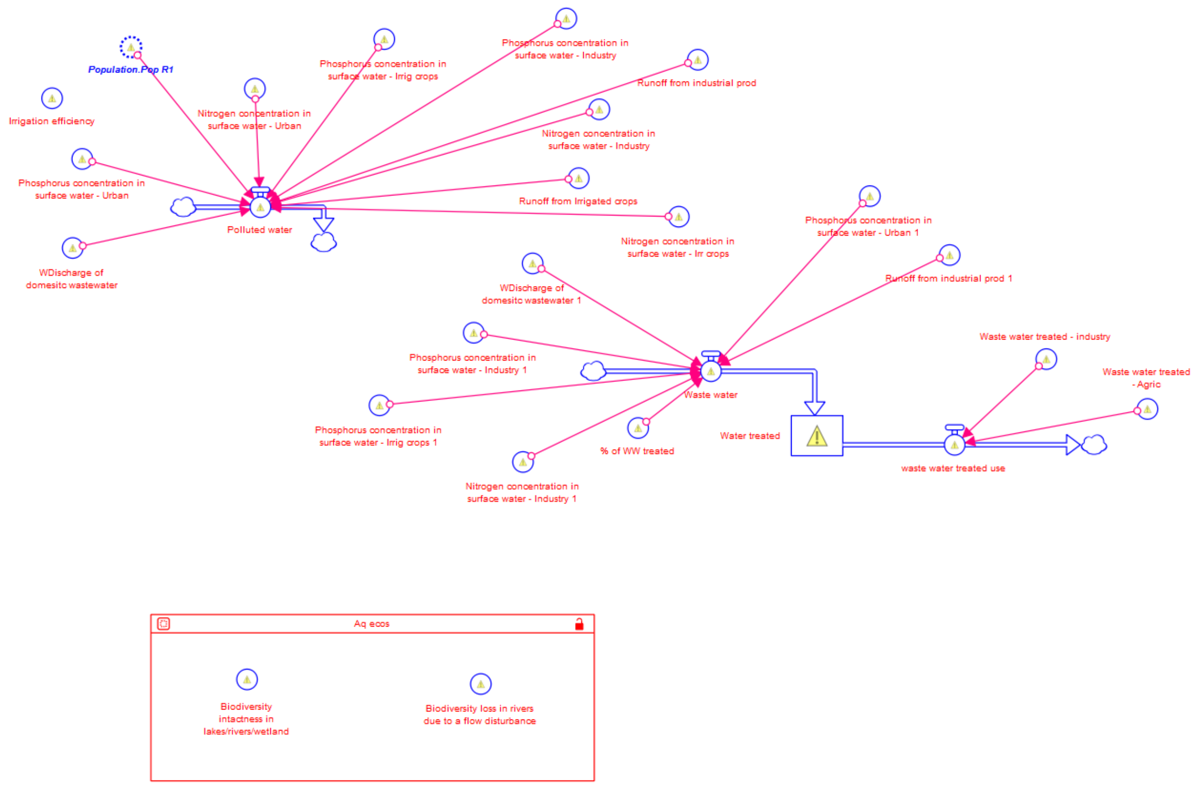


Figure 3.12.7: Water quality part of the water submodel in the global case study.

Water quantity concerns water availability within each IMAGE model region, and water demand for hydropower, environmental flows, and water demands from the power generation sector (and sub-sectors thereof), industry, irrigation and the municipal sector. Water quality considers nitrogen and phosphorus loads to water bodies from a number of sources, as well as waste water discharges and the proportion of waste water that is treated, potentially to be reused.

The land sub-model (Figure 3.12.8) accounts for land use in a number of sectors including cropland, built up areas, forests and energy crop cover. An indicator of terrestrial biodiversity intactness is included in this submodel.

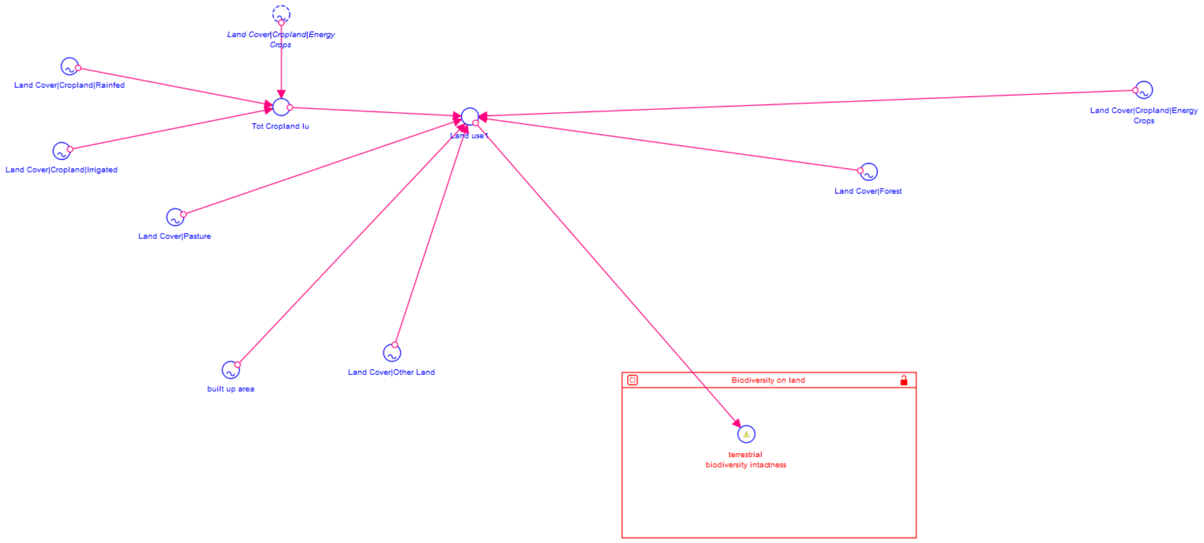


Figure 3.12.8: The land submodel of the global case study.

In the food submodel (Figure 3.12.9), food supply is accounted for from crop food production and from livestock production, while food demand for agricultural and livestock crops is modelled. All data are relative to the IMAGE model regions, and trade between regions is accounted for in this SDM.

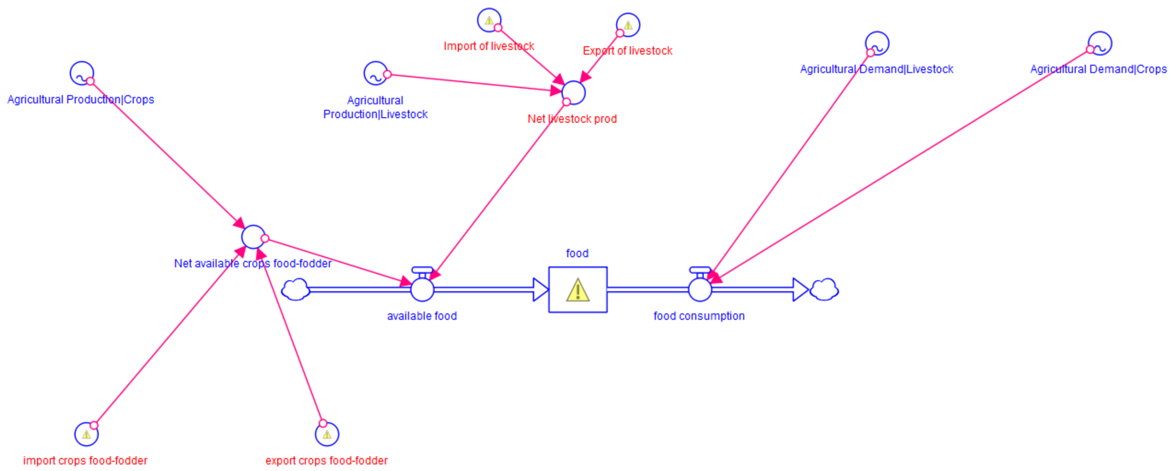


Figure 3.12.9: The food submodel of the global case study.

The energy sector is very detailed (Figure 3.12.10 up to Figure 3.12.16). The top level model (Figure 3.12.10) is an energy balance, with energy availability defined by electricity and non-electricity, and demand for primary and secondary energy sources. Each availability and demand sector is further developed in the model.

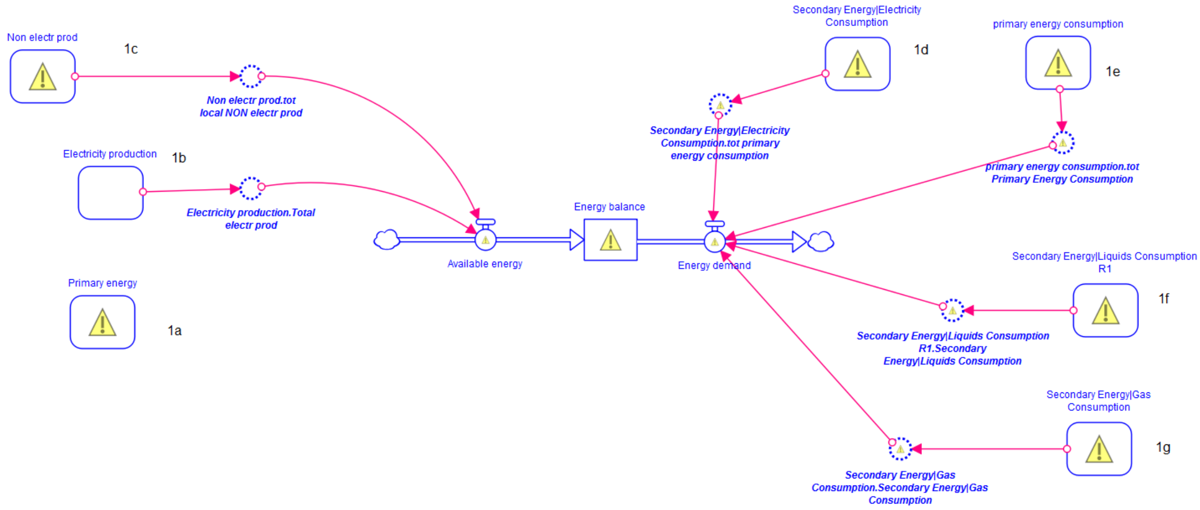


Figure 3.12.10: Top level energy submodel for the global case study.

Primary energy (Figure 3.12.11) consists of hydropower, wind, solar, biomass, coal, gas, oil, and nuclear sources. Electricity is generated from coal, gas, oil, nuclear, hydropower, wind, solar and biomass sources (Figure 3.12.12), while non-electric power consists of gas, hydrogen, heat, liquid and solid energy (Figure 3.12.13).

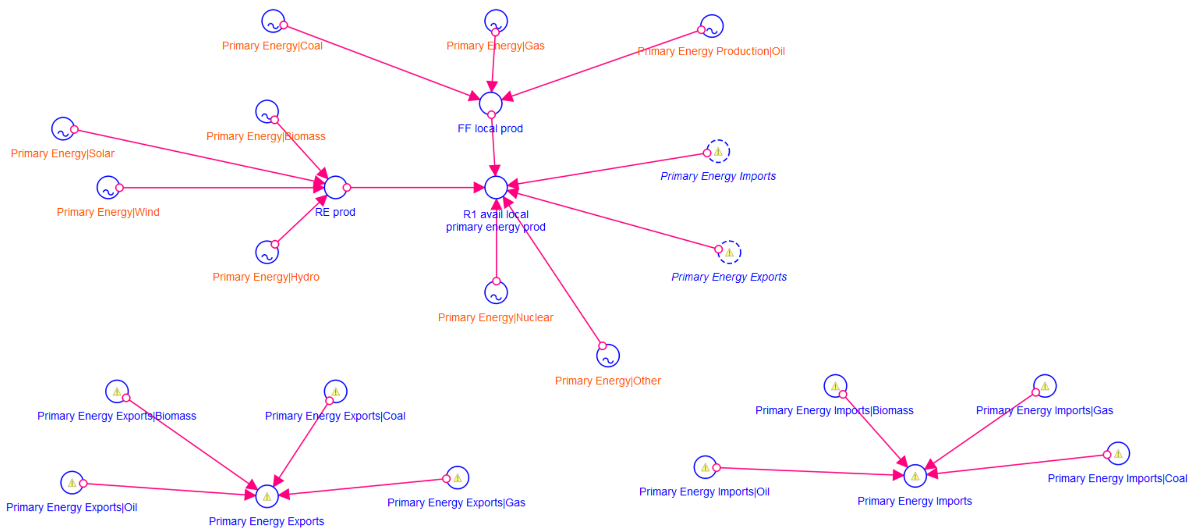


Figure 3.12.11: Primary energy submodel of the global case study.

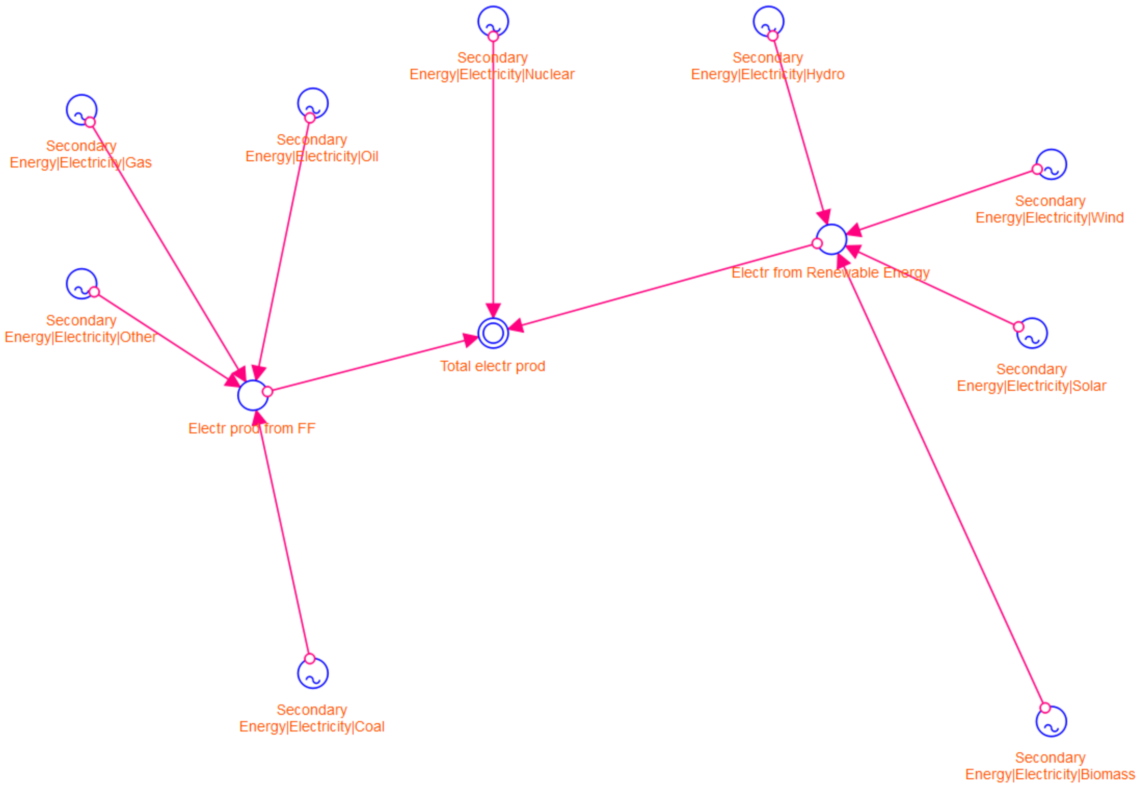


Figure 3.12.12: Electricity generation submodel of the global case study.

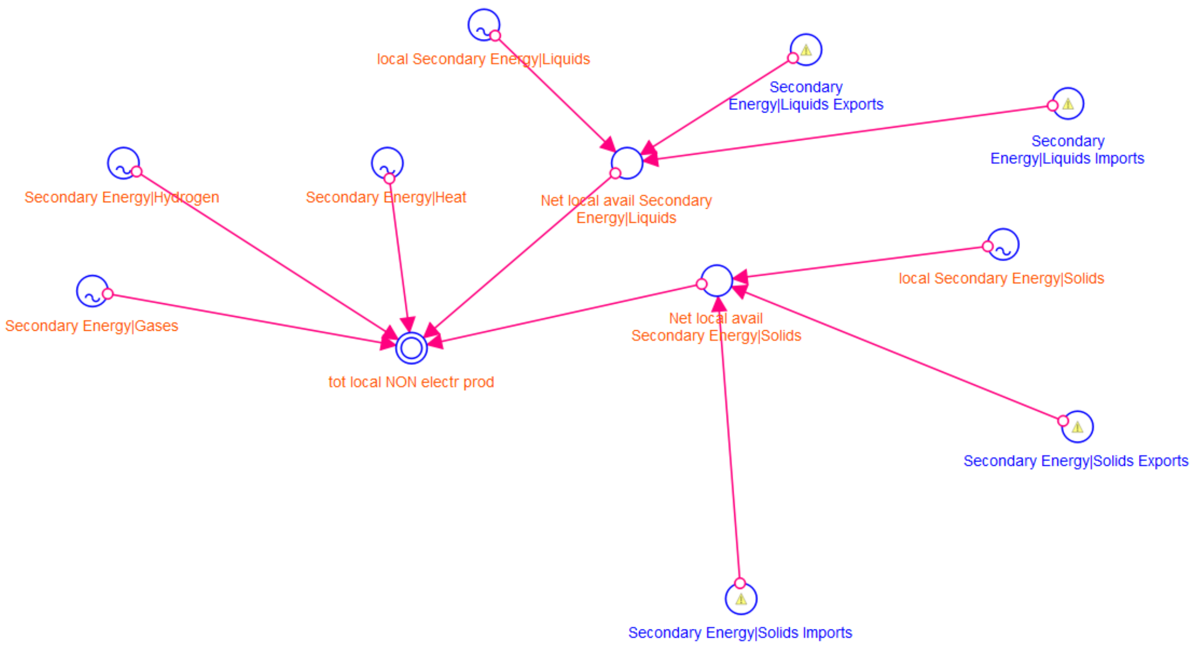


Figure 3.12.13: Non-electric generation submodel of the global case study.

On the demand side, the model accounts for consumption of all the primary energy sources mentioned above, electricity consumption from the domestic, industry, services, transport and agricultural sectors (Figure 3.12.14), liquid energy consumption in the transport, industry, services, domestic and agricultural sectors (Figure 3.12.15), and gas consumption in the agricultural, services, industry, domestic and transport sectors (Figure 3.12.16).

Figure 3.12.14: Sources of electricity consumption in the global model.

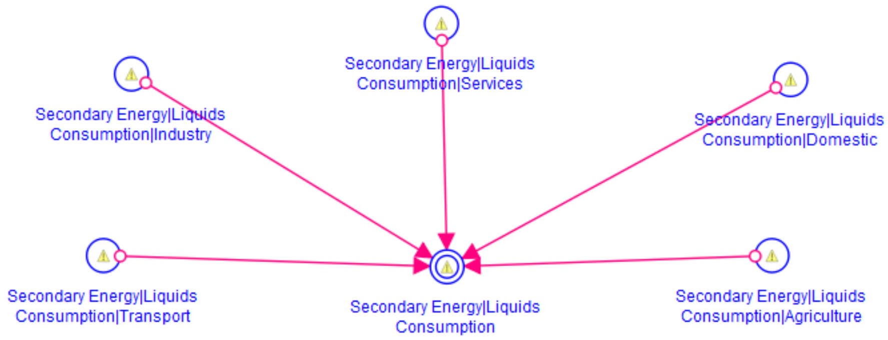
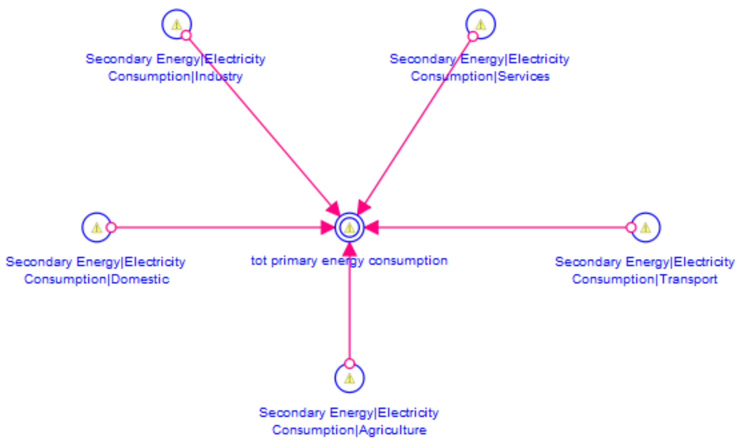


Figure 3.12.15: Source of liquid energy consumption in the global model.



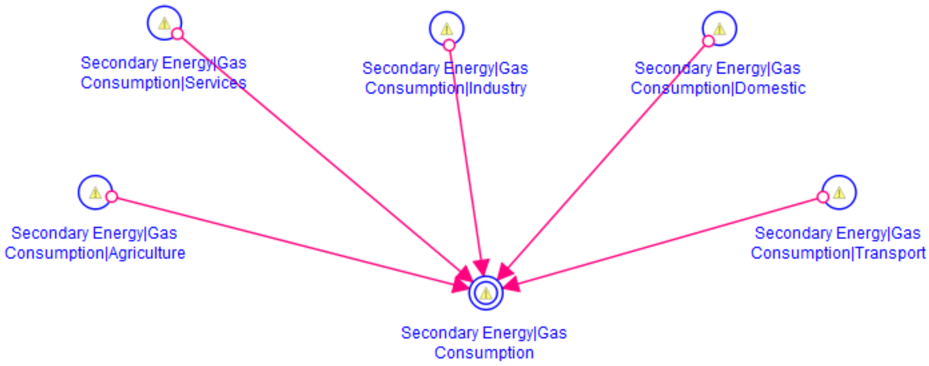


Figure 3.12.16: Gas consumption submodel for the global case study.

The climate sector accounts for CO_2-e emissions from a wide range of economic sectors (Figure 3.12.17). Greehouse gas emissions are modelled from the food production, services, land use, electricity generation, industrial, transport, and domestic sectors, as well as a category for other emissions.

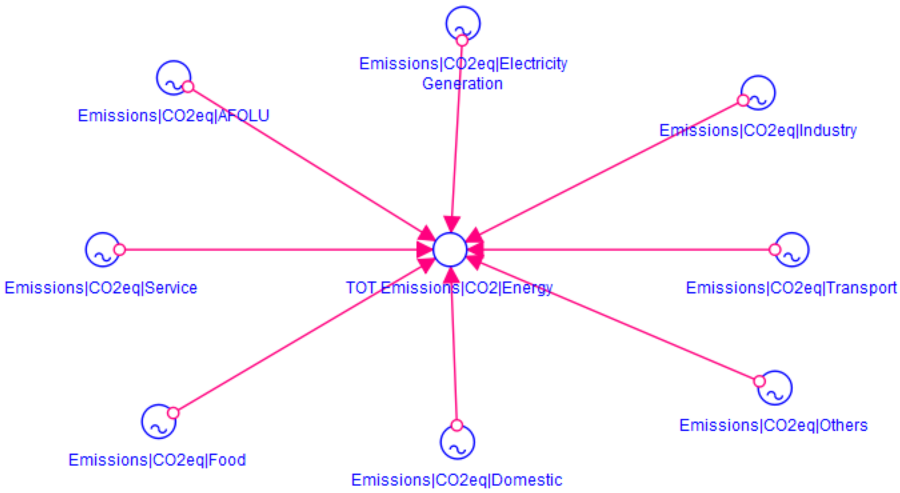


Figure 3.12.17: The climate submodel for the global case.

4 Conclusions

This Deliverable (3.4) is the main and final outcome from Task 3.4., a major Task in WP3. It presents the development of the Complexity Science integration models for the 12 Case Studies of the project.

System Dynamics Modelling (SDM) was selected as the most appropriate methodology for Complexity Science integration for SIM4NEXUS and has been applied to all the Case Studies, using the STELLA environment.

The development of complexity science model(s) for each case study started with the conceptual models, developed in Year 2 and continued with the SDMs in Year 3. Both the conceptual models and the SDMs have been presented in this report, with details for each Case Study. They have been developed in participatory process with the teams and the stakeholders at each Case Study, supported by experts from WP3 (mainly from IHE-Delft and also from UNEXE). Currently (M36) the SDMs are being populated with numerical data and the first results are reported in other Deliverables (MS26).

The uncertainty methodologies to be implemented are also under way, but will be reported in the next WP3 Deliverable (Deliverable 3.5).

At the same time, WP3 transfers the SDMs to WP4, to be implemented to the Serious Game developed for each Case Study, with the inclusion of policy cards (WP4).

During the last year of the project, we will finalise the SDMs, produce results for uncertainty analysis for each Case Study and consolidate the outcomes into a recommendation report for future similar projects and types of modelling.

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