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

D3.6 COMPLEXITY SCIENCE MODELS IMPLEMENTED FOR ALL THE CASE STUDIES

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ADDRESSING REVISION COMMENTS	
COMMENT	RESPONSE
THE EXECUTIVE SUMMARY IS A COPY OF THE DESCRIPTION OF THE TASK, AS INCLUDED IN THE DOW. IT MUST BE ADJUSTED AND BETTER REFLECT THE CONTENT OF THE DELIVERABLE (AND REMOVE THE USE OF FUTURE TENSE).	THE EXECUTIVE SUMMARY IS COMPLETELY REWRITTEN TO BETTER REFLECT THE CONTENTS OF THE DELIVERABLE
THE RESULTS FROM THE UK CASE STUDY SHOULD STILL BE INCLUDED – SECTION 3.1.2 NOW MENTIONS "NOTE: RESULTS FROM THE UK CASE STUDY WERE NOT PROVIDED BY THE CASE STUDY LEADER AT THE TIME OF REPORT WRITING." SINCE THE DELIVERABLE WAS DUE IN MAY 2020, IT WOULD BE EXPECTED THAT ALL THE RESULTS ARE AVAILABLE.	A LETTER FROM THE STAKEHOLDER AT SOUTH WEST WATER IN THE UK (PAGE 20) DEMONSTRATES THAT THIS SDM AND THE RESULTS HAVE INDEED BEEN SEEN AND VERIFIED BY THE LOCAL CASE STUDY OWNERS AND STAKEHOLDERS. RESULTS ARE INDEED READY, HOWEVER AS THEY FORM THE BASIS OF ACADEMIC PUBLICATIONS, ARE NOT INCLUDED TO PREVENT SELF-PLAGIARISM ISSUES
THE RESULTS FROM THE TWO TRANSBOUNDARY CASES ARE NOT YET VALIDATED. SINCE THE DELIVERABLE WAS DUE IN MAY 2020 IT WOULD BE EXPECTED THAT ALL THE RESULTS ARE AVAILABLE AND VALIDATED. CONCLUSIONS IN THESE CHAPTERS SHOULD BE REVISED BASED ON VALIDATED RESULTS.	BOTH ARE NOW VALIDATED. PLEASE SEE THE RESPONSES IMMEDIATELY BELOW
SECTION 3.9.2 DISCLAIMER: "AT THE TIME OF WRITING OF THIS DELIVERABLE, THE SDM RESULTS FOR THIS CASE STUDY COULD NOT BE VALIDATED BY CASE STUDY LEADERS DUE TO TIME LIMITATIONS. CONCLUSIONS IN THIS CHAPTER ARE SUBJECT TO UNCERTAINTIES AND ERRORS WHICH MAY BE ADDRESSED IN THE FUTURE."	THE RESULTS FOR THIS CASE STUDY ARE NOW VALIDATED BY THE CASE STUDY OWNERS. PLEASE SEE NEW TEXT ON PAGES 104-105
SECTION 3.10.2 MENTIONS "DISCLAIMER: THESE RESULTS HAVE NOT BEEN CHECKED OR VALIDATED BY THE CASE STUDY OWNERS."	THE RESULTS FOR THIS CASE STUDY ARE NOW VALIDATED BY THE CASE STUDY OWNERS. PLEASE SEE NEW TEXT ON PAGES 114-115 AND 117-118
EDITORIAL – PG 55 & 106 "ERROR! REFERENCE SOURCE NOT FOUND" SHOULD BE CORRECTED.	THESE ERRORS HAVE BEEN FIXED

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Executive summary

Task 3.6: Overall assessment of the complexity science models and integration approach in SIM4NEXUS (M37-M48)

Leader: UNEXE; Involved partners: UTH, IHE, UPM, EURECAT, EPSILON, UB, PIK

This Deliverable presents the final versions of the developed system dynamics models for all 12 SIM4NEXUS case studies. It also presents results for all the cases. These results have been validated by local case study owners. In general, the tight interconnectedness between the water-energy-food-land-climate sectors in demonstrated. The system wide impacts resulting for example from policy implementation will therefore be wide-ranging across the nexus, and will likely include unanticipated and detrimental impacts. Future modelling to assess the potential impacts of policies should be conducted. These models underlie the SIM4NEXUS Serious Games. It is noted that for some case studies, results are not shown here as they form the basis of academic publications. They are therefore excluded so as to avoid self-plagiarism.

Task duration: Task 3.6 started in Month 25 and is expected be completed by Month 48, with a duration of 24 months.

Changes with respect to the DoA

Not applicable.

Dissemination and uptake

This Deliverable report is for verification by the PCT of SIM4NEXUS and the reviewers of the Commission. The Deliverable is Public.

Short Summary of results (<250 words)

This Deliverable outlines the System Dynamics Model (SDM) structures and baseline scenario result set for each of the 12 SIM4NEXUS case studies. SDM structures show in detail how the five nexus sectors (water, energy, food, land, climate) are interconnected within each case study. Many cases show similar inter-sectoral connections (e.g. water for agriculture, emissions from energy), suggesting that a pseudo-universal nexus modelling template may be achievable. On the other hand, each case adds richness to modelling studies, bring its own unique nexus interpretations and requirements. For example, Latvia has a focus on nitrogen emissions to water bodies, and the transboundary Germany-Czechia-Slovakia case explores the role of 'atmospheric rivers' for local air cooling impacts, demonstrating a nexus between water retention, land use, and local climate impacts. Larger scale cases such as the EU case can show likely EU-wide nexus trends to 2050, and help to identify trade-offs and synergies. Baseline results demonstrate the evolution of nexus sector trends to 2050. In demand-driven sectors (water, energy) consumption is expected to generally increase, potentially conflicting with supply limitations. Climate impacts are largely linked to energy generation sources. In this report, starting dates of simulations differ between cases, but these are harmonised for the Serious Games. With the potential for policy implementation in the SDMs, SIM4NEXUS models are able to help policy makers and academics explore the multi-sectoral impacts of policy goals and targets, and may lead to more holistic, efficient and integrated policy making at a range of scales.

Evidence of accomplishment

This report, Deliverable 3.6.

1 Introduction

1.1 Structure of the document

This report is structured into three main chapters: this short introductory section describing the main system dynamics modelling (SDM) conventions used in the model structure descriptions, a short section explaining how this Work Package (WP) interacts with other WPs in SIM4NEXUS, and the third section which forms the main part of this Deliverable. In Section 3, the final developed SDM for each SIM4NEXUS each study is described, showing how each nexus sector (water, energy, food, land, climate) is built up and the constituent elements in each sector, and the links to the other nexus sectors are described. Following model descriptions, final results from the SDMs are presented, showing critical results from each nexus sector for each case study. The case studies are ordered from smallest to largest scale (i.e. sub-national → national → European → global).

1.2 System Dynamics Modelling conventions, and model simulations

The SD models described in this report were all developed and implemented in the STELLA Professional software[1], a specific SDM software, with the exceptions of the Sardinia case study and the Global case study (see Sections 3.3 and 3.12 respectively). As a result, the other 10 case study model descriptions all follow the same graphical 'nomenclature'. STELLA SDM models comprise three core elements: stocks, flows, and converters (Figure 1). Using a 'bathtub' analogy, stocks store material, such as water in a bath (e.g. in units of m^3). Flows move material (water) into or out of the stock at a rate per unit time (e.g. m^3 s^{-1}). Converters acts to change the flow rate (e.g. by altering evaporative loss rates from the water surface, or by hypothetically opening a tap so more water flows in).

Connectors (Figure 1) are used to link system elements, and essentially transfer information between system components. It is the links between system elements that allows for complex feedback structures to be formed in SDMs. In addition, because the academic field of study is not pre-defined, disparate disciplines can be mixed within the same model, so long as functional relationships (e.g. mathematical, logical, statistical) between elements are defined, and that units are properly converted between sectors (e.g. from GWh of electricity use to tons CO_2e emissions). In many SDMs described here, due to the complexity of the systems being modelled, nexus sectors and in many instances even different parts within a given sector (e.g. energy production, energy consumption) are split into their own sub-modules. This i) makes model building more straightforward and transparent, reducing the chance of mistakes; and ii) makes tracking model interactions much simpler. It also allows for easier graphing and recording of model outputs. Sub-models are contained within 'rounded boxes' in the STELLA environment (Figure 2).

[1] https://www.iseesystems.com/

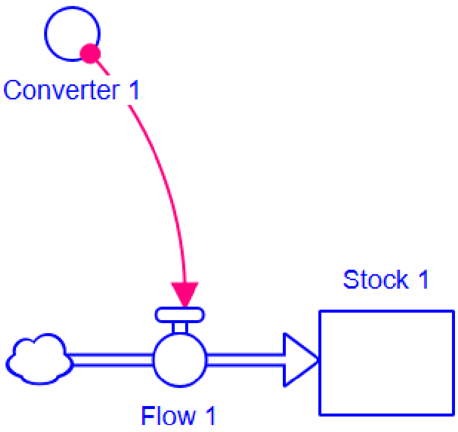

Figure 1: the three core modelling elements used in the STELLA SDMs, comprising stocks (square box), flows (large arrow with the 'valve' and 'cloud') and converters (small circle). Connectors (pink arrow) transmit information between model elements.

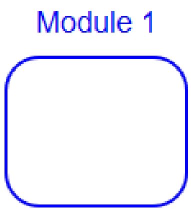

Figure 2: the 'rounded box' in STELLA within which entire nexus sector (e.g. water, energy) models are contained, or within which parts of nexus sectors (e.g. water supply, electricity consumption) are contained.

A final point to note is that in this Deliverable, all model results are presented for the Baseline Scenario to 2050, with no policy implementation. Policies implemented after 2020 remain unchanged. The models are able to simulate the impacts of policy decisions throughout the nexus, however here only Reference results are shown because they have less uncertainty and in order to demonstrate the successful development and implementation of the models for each case study.

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 SIM4NEXUS. These interactions are an iterative process within the project. Figure 3 summarizes the interconnections between WP3 tasks and efforts in other Work Packages of the project.

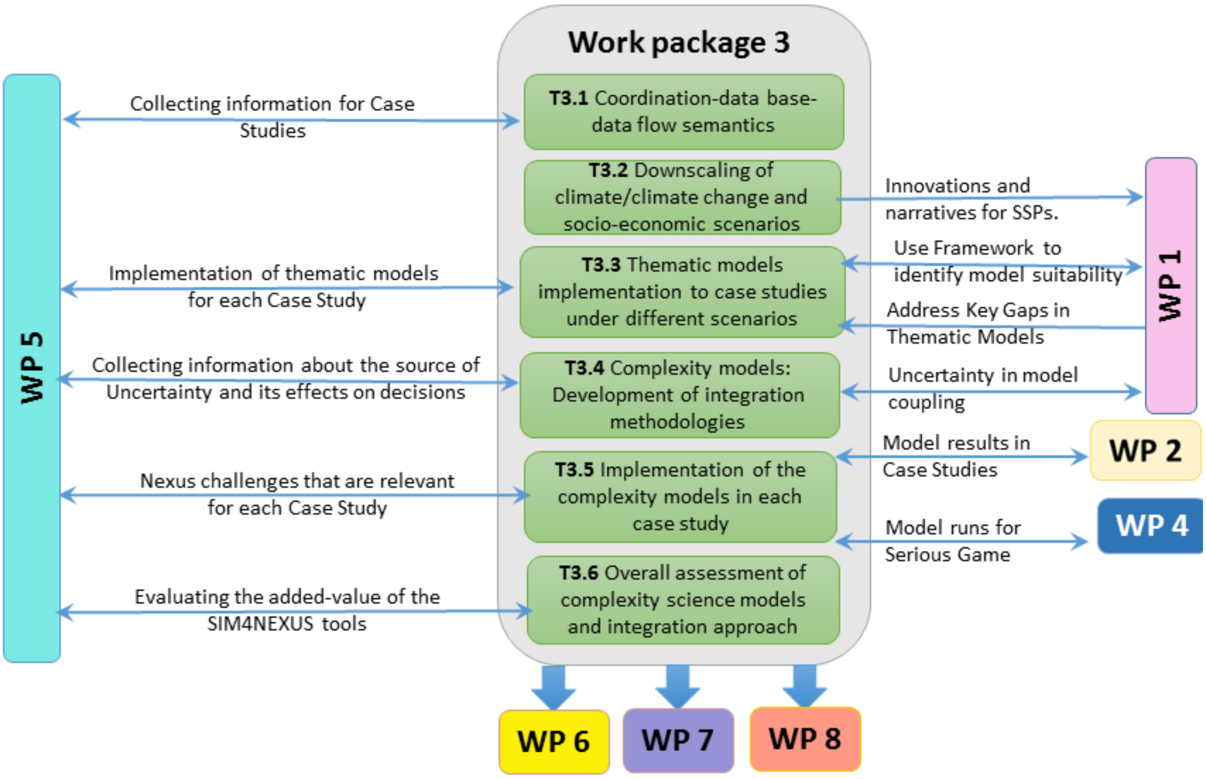

Figure 3: Task by Task diagram of Work Package 3 and interactions with other Work Packages in the project as established in the SIM4NEXUS Grant Agreement.

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. 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 Figure 1. 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.

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

This section is structured by increasing level of spatial scale. Therefore for sub-national cases are at the beginning, followed by the national, transboundary, European and finally the Global case study. Short descriptions of each case study are to be found in Milestone Report M26, and will not be repeated here to save space. SIM4NEXUS Deliverable 5.5 also provides detailed report on the work in the 12 case studies.

3.1 UK case study

3.1.1 Description of the final complexity science 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 and land use.

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.

In the context of the nexus existing to meet societal demand, resource flows between sectors are analogous to system losses, i.e. they are resources which are consumed by the system but not made available to meet society's demand. Therefore, an efficient nexus seeks to minimise the cross-sector supply and demand flow, while maximising the availability of resources to society.

The SDM is structured to comprise six modules, which describe the interactions between society and the nexus sectors, and one module which is used to track metrics.

3.1.1.1 Water sector

The water sector module focuses on the demands for drinking water arising from society and the other nexus sectors, which are consider against the treatment and distribution capacity of the local supply system. The model forecasts the supply-demand relationship with respect to the stresses of seasonal variation, climate change and population growth via monthly time steps.

The water sector module is subdivided into drinking-water and wastewater supply chains which when linked via raw water resources describe the urban water cycle. The water module has been developed to suit SWW's planning objectives, and to mirror activities undertaken by SWW under the following obligations; Water Resource Management Plan (WRMP), and Drainage and Waste Management Plan (DWMP).

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 across the home. This is further exaggerated in the southwest due to an influx of tourists who place additional demand on the system. 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 consumer demand, allowances for system leakage and operational losses are variables influenced by policy decisions.

Water availability is considered by evaluating the complex relationship between demand and the ability of the system to utilise and supply drinking water. Three conventional water sources and two additional sources are modelled:

Conventional sources:
1. River abstraction, 2. Reservoir storage, and 3. Borehole supply,
Additional sources:
1. Extra regional import and 2. desalination.

The model abstraction priorities follow the order;
1. River Abstraction>2. Reservoir Abstraction>3. Borehole Abstraction >4. Extra regional import >5. Desalination.

The wastewater module assumes that for every unit of drinking water consumed, one unit of foul water is generated. This approach is deemed valid due to the lack of foul flow data and the assumed relationship between drinking water and foul water that is used by all UK water companies for sewage billing (SWW, 2019). The other flows into the wastewater process are primarily due to external environmental factors. These are represented as a surface water drainage volume, impacted by rainfall, and intrusion rates ("inward leakage") resulting from either saline or ground water.

3.1.1.2 Land sector

The land sector module has been developed to investigate the environmental impacts to water quality and climate associated with active land use and changes to land use. The model is divided into three primary processes; 1. land use, 2. run-off water quality, and 3. waste management.

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

1. Residential and Urban Area: describes all land that is used for residential housing and the immediately associated activities.
a. Urban Green space; is a subcategory parallel to residential and urban area 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.

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. Utilised 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 Common Agriculture Policy Regional Impact Model (CAPRI) thematic model.
a. Land for dedicated energy crops, is a subcategory parallel to both Agriculture Area and Forestry Area, which describes land area utilised for dedicated energy crops
b. Land for solar, is a subcategory 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 land, which is categorised as: 'managed', 'unmanaged', 'broad leaf' and 'coniferous'.
7. Natural habitat: describes all remaining unutilised land which has not been included in the other categories.
a. Restored peatland: is a subcategory of natural habitat which describes moorland which has been restored by SWW up-stream thinking project.

Using these categories, the module simulates the transition from one state to another based on policy decisions or forecast data. To account for the different drivers for change applicable to each type of land use, the module is subdivided in three distinct sub process; 1. Residential and urban area, 2. Commercial and Industrial, and 3. Primary land resource.

The land use module is a highly simplified model and intentionally excludes from the analysis 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 - The residential and urban area process utilises a demand-led philosophy that is heavily constrained by the availability of land supplied from the green field and brown field sources.
The demand to expand the residential and urban area 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 also an underlying driver. The SDM therefore takes a highly simplified approach to this complex situation by relying on a policy defined housing density. The housing density policy acts such that when it is high, less land is used per capita thus reducing demand to expand the residential area, and vice versa. In situations when the actual housing density is different from the specified desired density two mechanism facilitate the adjustment. 1. Population growth, which drives density up, and 2. Demolition of existing housing stock, which increases the supply of brownfield land ready for redevelopment at the desired density and is driven by a housing renewal policy.

Commercial and industrial -The commercial and industrial area process and its relationships to the brownfield area and greenfield area 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.

Primary land resource - 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, then 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 cards for forestry and natural habitat that increase or decrease these rates, and where negative values are used, they allow for the transition of forestry and natural habitat into agricultural land.

Greenfield land - Greenfield land made available for development is highly sort after by land developers of all types and is tightly controlled, because this is practically an irreversible transition. The Greenfield development policy card acts as the main driving force enabling the flow of land resource into the greenfield area. The flows of forestry and natural habitat land into the greenfield stock are further constrained by those forestry and natural habitat policy cards.

Utilised agricultural area - 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 utilised agricultural area from within the SDM. Data extracted from CAPRI is used to drive the trends of agricultural activities based on percentages of the whole area of utilisation. This enables the SDM to control the gross volume of agriculture land, and for CAPRI to forecast the specific more detailed agricultural land uses.

Forestry & woodland - The forestry area describes the total combined area of forest and woodland. 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 (NFI, 2018).

Water quality - The surface run-off water quality process uses a mass balance principle 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.

3.1.1.3 Energy sector

The energy sector module seeks to examine the balance of supply and demand for electricity at the macro scale across the region. All major forms of renewable electricity generation are included as well as fossil fuel and grid electricity import. The demands for electricity arising from society and the other nexus sectors are consider against the generation and transmission capacity of the local supply system.

The model forecasts the supply-demand relationship with respect to the stresses of seasonal variation, climate change and population growth via monthly time steps.

The energy module is an example of a supply lead philosophy, which is deemed to be appropriate due to the nature of renewable energy generation, which is utilised as the resource becomes available. In its current state, the Distribution Network Operator (DNO) has limited ability to limit 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 role whereby they become responsible for balancing arrangements within the network (WPD, 2017). The SDM, therefore, provides an opportunity to examine strategies for enhancing the utilisation of renewable energy generation including the curtailment (limiting) of generation for new generating capacity.

As with the water sector, demand is a core component of the Energy sector, and it is a summation of the electricity demand from domestic, agricultural, industrial and commercial sectors, and crucially also the water sector. 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 also 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 (Elexon, 2019) which peaks in the winter months.

At the centre of the energy sector module is the local distribution network process which models the basic activities of the distribution network operator (DNO). The distribution network receives locally generated electricity, as well as imported electricity from the transmission network which it distributes to all end-users. The primary function of this process is to balance input and output, ensuring that demand arising from across the nexus is met through a combination of available electricity sources. 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. The import and export to and from the transmission network is a major influencing factor to the effective utilisation of renewable energy and the carbon intensity of the electricity consumed.

The import and export of electricity is constrained by the available capacity of the interconnection between the two networks. In order to model this relationship a check process monitors the volume of import/export against the effective transmission network capacity. When a network capacity is exceeded a "curtailment signal" throttles output from certain electricity sources.

The renewable electricity generated in the region is managed under two distinct control philosophies; unconstrained and constrained. The unconstrained modality is the archetypal supply-led philosophy applied to pre-existing solar, wind and hydro installations. The constrained modality is applied to new installations and technologies with inherent storage functionality or dispatchability, such as biomass or energy from waste. Constrained generators are the only ones to respond to curtailment signals from the transmission or distribution network.

All generating technologies and transmission routes within the SDM are described in terms of installed capacity (maximum megawatt hours supplied per month) and capacity factor (ratio of energy supplied to theoretical maximum supply). The installed capacities and capacity factors are the main control variables driven by policy cards in the energy module.

The operational status of the planned nuclear plant Hinkley point and the proposed enhancement to network capacity are major influencing factors in the energy module.

The operational status of the planned nuclear plant Hinkley point and the proposed enhancement to network capacity are major influencing factors in the energy module.

Acting as a decision support tool, the module provides the opportunity to investigate:
- Supply/demand headroom Forecasting
- Strategic timing of capacity expansion of generation technologies and transmission
- Land use impacts for energy sources, i.e. renewables
- Regional Carbon emissions from energy and potential benefits of new renewable energy
- Potential impact of non-expansion, i.e. not meeting future energy demand and causing periods of energy outage.

A detailed economic analysis layer has been integrated into the policy card implantation processes for key variables within the water and energy sectors. When a policy card is played that increases a system capacity a discounted cashflow forecast (DCF) is generated based on the calculated assumptions in the time step. The DCF enables the user to evaluate the feasibility of the policy by considering the following financial metrics;
1. Time weighted value of money,
2. Net present value
3. Payback period.

The analysis is conducted at two levels: The first which considers the feasibility of the policy card in isolation, i.e. with no other active polices, and the second which is an aggregated analysis that includes the effect of the policy alongside all other past and current policies.

3.1.2 Description of the final results

A letter from South West Water demonstrating that the SDM has been assessed and validated is on the following page. Results figures are not included as they will form the basis of academic publications.

South West Water

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05 November 2020

To Whom it May Concern

With this letter I confirm that I have examined the results of the UK regional SDM developed as part of SIM4NEXUS. The results are a good reflection of the WEFLC trends in the operational area of SWW.

In addition, the specific nature of the model, including financial aspects and issues relating to detailed company water operations and their wider environmental impact, will be useful in the future as a decision and policy guiding aid for SWW company operational aspects. The ability to examine scenarios and to develop the model in the future are particularly useful.

Yours faithfully

Dr Ben Ward

Drinking Water Asset Manager, South West Water

3.2 Andalusia case study

3.2.1 Description of the final complexity science model

The SDM model has been developed in Stella and integrates the three sectoral models of the nexus: water, energy, and food/agriculture. It allows a joint analysis of the three of them and to simulate selected future scenarios. As a base year, the year 2010 has been selected, and simulations have been carried out for the time horizons 2020, 2030, 2040 and 2050. Additionally, the software uses an annual time step that allows viewing results for intermediate years.

3.2.1.1 Water sector

The water sector (Figure 4) shows the relations between the availability of water and the water consumption in Andalusia. To this end, five water stocks (Surface water, Groundwater, Desalination water, Urban water supply and Wastewater) and their corresponding flows are modelled. The relevant inflows of the whole system are runoff, groundwater recharge and desalinated water. The relevant outflows are irrigation water use, environmental flow, hydropower consumption, industrial and domestic consumption, and wastewater discharge.

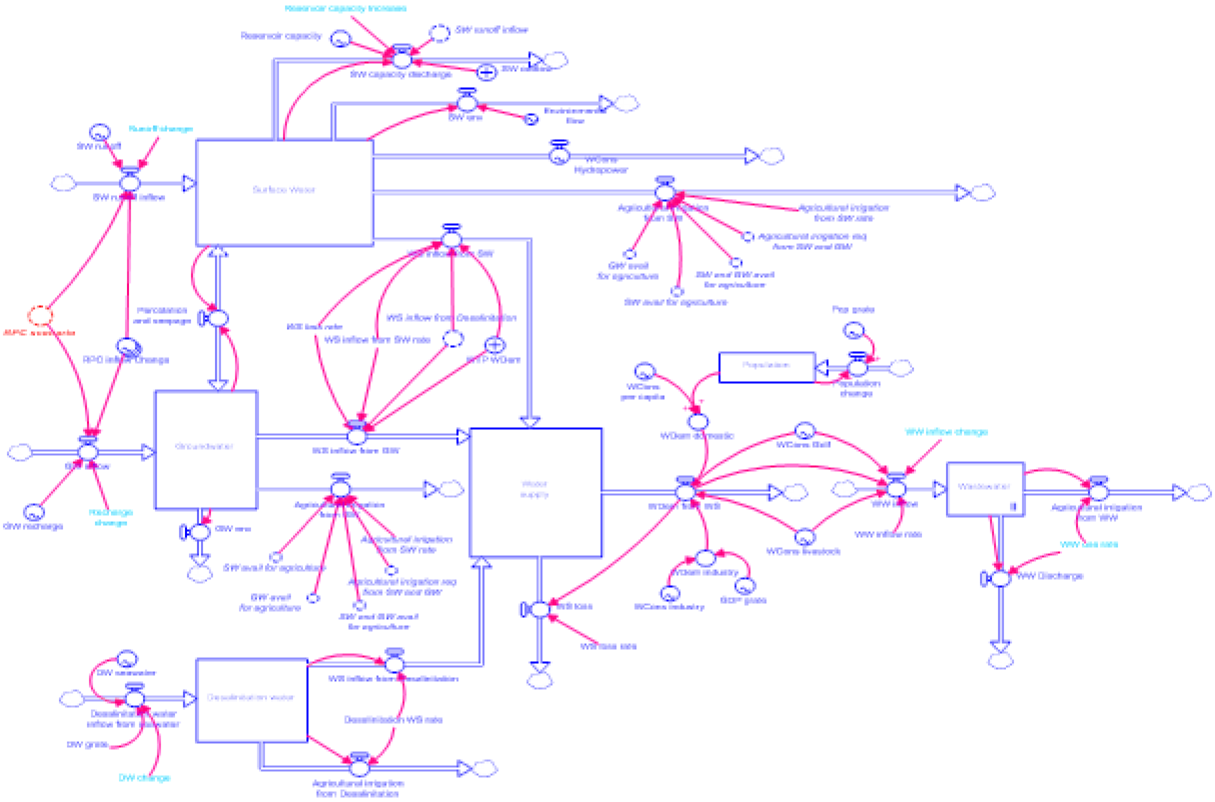


Figure 4: water sector module in the Andalucía case study.

3.2.1.2 Food sector

It is the core of the model as it combines different agricultural aspects and is most interrelated with the rest of the modules, for example, agricultural energy consumption with the energy model and the use of water in irrigation with the water model. It focuses on the economic aspects of the agricultural sector such as costs, revenues and incomes and technology variants. In this module two kind of activities are represented crops (Figure 5) and livestock (Figure 6). The activities to be modeled have been selected according to the EUROSTAT classification and the productivity importance for the region in 2010. They make up a total of 22 crops and 14 livestock. The crops represented are as follows:

- ✓ Olives for oil
- ✓ Other Vegetables
- ✓ Tomatoes
- ✓ Other Fruits
- ✓ Citrus Fruits
- ✓ Apples Pears and Peaches
- ✓ Durum wheat
- ✓ Sunflower
- ✓ Paddy rice
- ✓ Other crops
- ✓ Soft wheat
- ✓ Table Olives
- ✓ Grain Maize
- ✓ Barley
- ✓ Flax and hemp
- ✓ Wine
- ✓ Oats
- ✓ Table Grapes
- ✓ Potatoes
- ✓ Pulses
- ✓ Sugar Beet
- ✓ Rye and Meslin

Livestock are represented as:

- ✓ Dairy Cows
- ✓ Fattening calves
- ✓ Heifers breeding
- ✓ Heifers fattening
- ✓ Laying hens
- ✓ Male adult cattle
- ✓ Milk Ewes and Goat
- ✓ Other animals
- ✓ Other Cows
- ✓ Pig Breeding
- ✓ Pig fattening
- ✓ Poultry fattening
- ✓ Raising calves
- ✓ Sheep and Goat fattening

Each of these activities has its own sub-model in order to better represent production conditions, such as productivity function or water consumption. In addition, in each sub-model, each crop has two productions, one irrigated and the other rainfed. Thus, the main parameters obtained with this model are income (€/ha) and water consumption (m3/ha). These parameters will vary mainly if the crop is irrigated or dry. Additionally, in this module there is also a segment where the land use is calculated, which is composed of agricultural surface, constructed areas, forests and natural areas, and water surface.

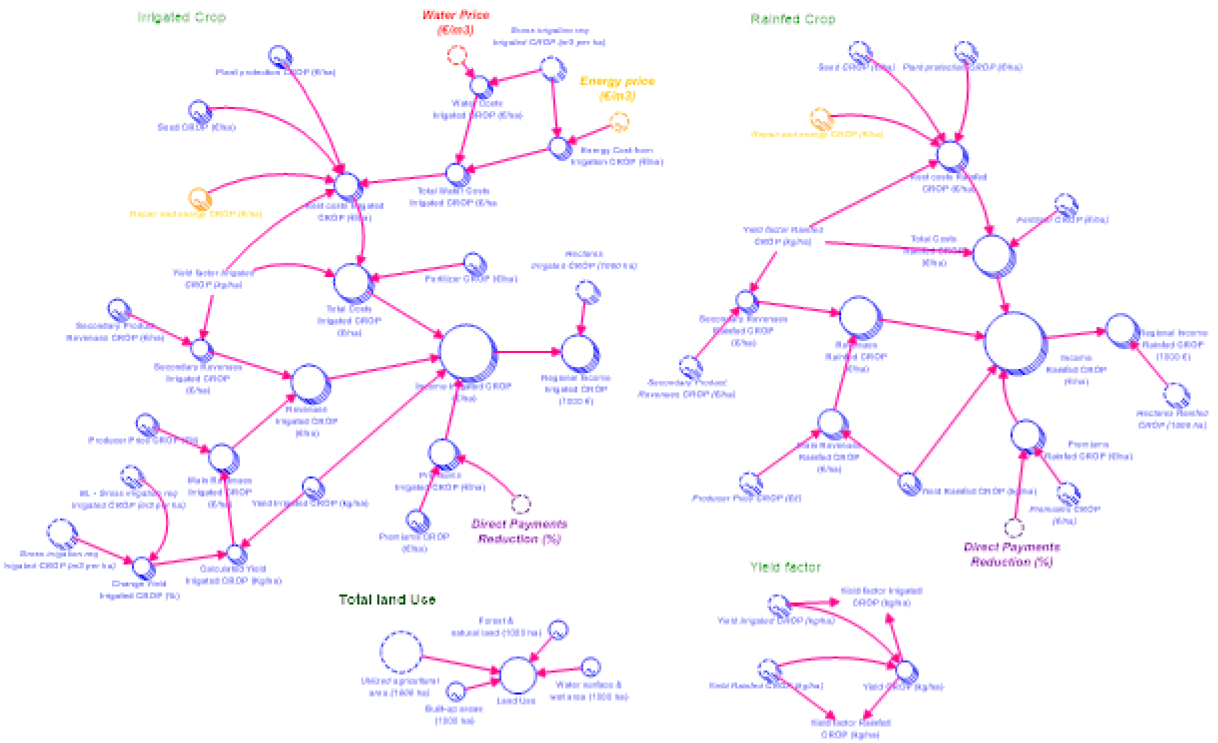


Figure 5: food crop representation in the Andalucía case study.

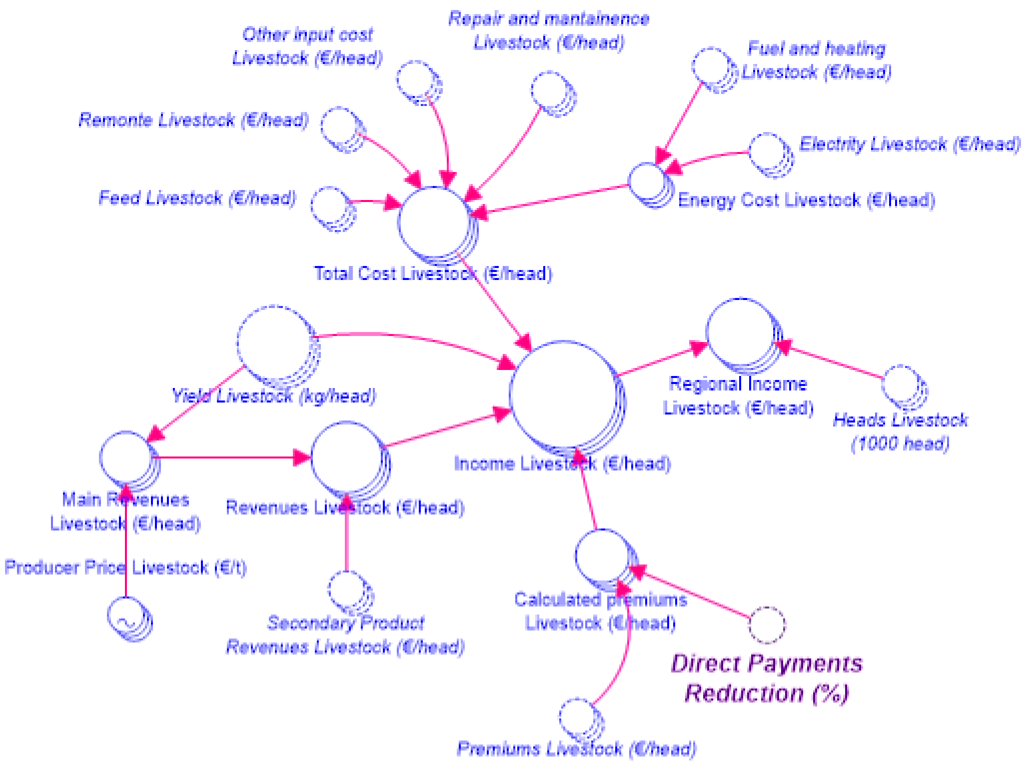


Figure 6: livestock module in the Andalucía case study.

3.2.1.3 Linking the water and agricultural modules

Figure 7 shows how water and agriculture are related in the Andalucía SDM. Irrigation needs from different crops are summed and used as a water demand. This is coupled with information on the water sources for irrigation (surface or ground). Increases in irrigation water demand will be reflected in the water module, and changes to supply could act as constraints in the agricultural sector.

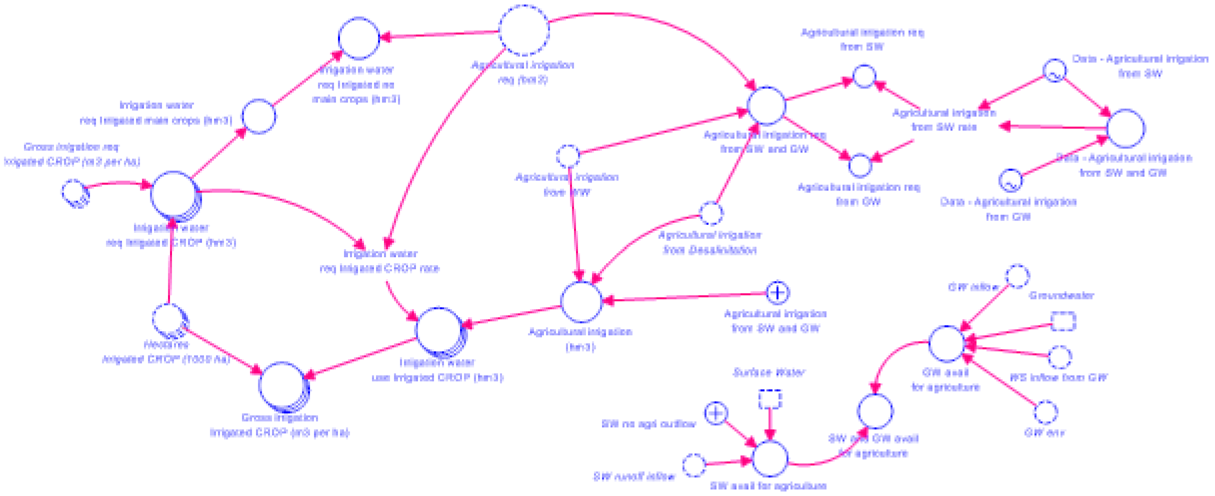


Figure 7: representation of the water-agriculture links in the SDM.

3.2.1.4 Energy sector

In this case, the energy inputs and outputs come respectively from energy production at primary level by source and energy consumption by sector (Figure 8). Within energy consumption, the model shows in more detail the consumption of the agricultural sector and especially the consumption of irrigation, related to the water and agricultural model.

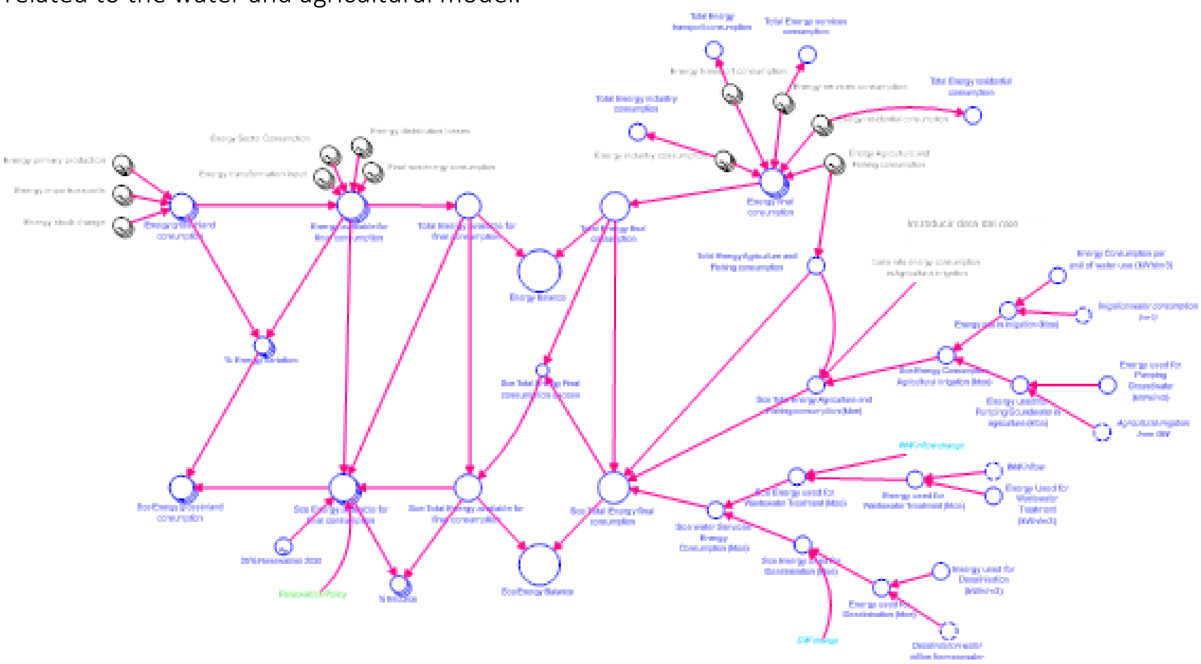


Figure 8: energy sector module in the Andalucía case study.

3.2.2 Description of the final results

The SDM has been applied to the analysis of water pricing scenarios, compared to a baseline situation. More specifically, we analyse the impacts of an increased water price by 0.04 and 0.10 euros (WP04 and WP10 scenarios) on four relevant regional level variables (Figure 9). In one hand, agricultural income (million euros, M€) is evaluated, as an output that measures the agricultural economic profit of the region. In the other hand, irrigation water use (cubic hectometres, hm3), energy consumption by irrigation (thousand tonnes oil equivalent, ktoe) and irrigated agricultural area (thousand hectares, kha), are evaluated as inputs that measures the utilized resources.

In the baseline scenario, as shown in Figure 9, agricultural income (M€) overall grows over time, except for the 2020-2030 period, when it will slightly decrease. In 2010, agricultural income was 5652 M€, by 2050, it is expected to increase by 18.7% to 6712 M€. Agricultural income per hectare is expected to increase by 19.1% during the same period. Focusing on irrigation water use, results show a negative trend, from 3976 hm3 until 3318 hm3 between 2010 and 2050. As a result, the share of irrigation water in total water consumption decreases from 79.4% in 2010 to 57.8% in 2050. Regarding energy results, energy consumption for irrigation decreases from 25.2 ktoe to 21.1 ktoe between 2010 and 2050. This is mainly due to the decrease in water consumption by the agricultural sector. Finally yet importantly, the curve of land use shows that irrigated agricultural area increases slightly from 921 kha to 968 kha between the analysed periods. From the total utilized agricultural area, irrigated area represents 18.8% in 2010 and it increases to 19.8% in 2050.

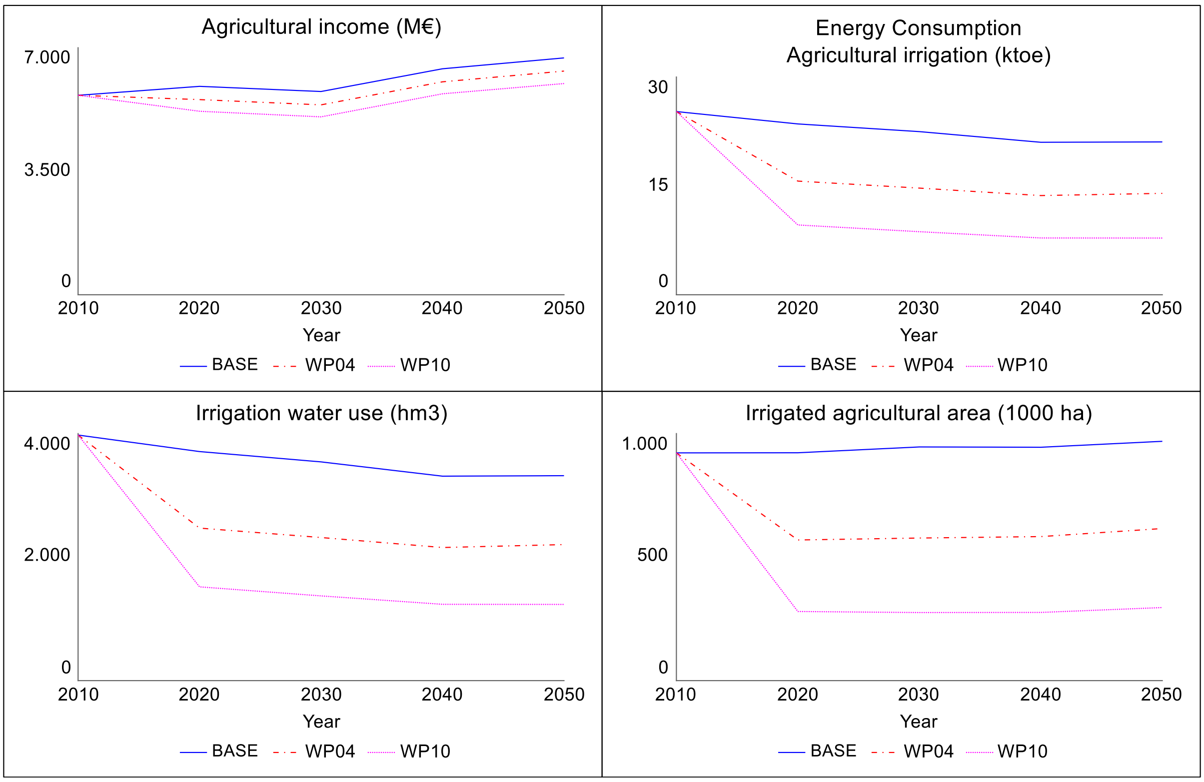


Figure 9: key Andalucía model results.

Figure 9 represents the trends of each of the four variables comparing the scenarios to the baseline. From this, we can notice that the trends are similar to the baseline and the water price affects directly each variable. The application of WP04 scenario will affect negatively the total regional income and it will decrease by 6.4% in 2020. In 2050, it will decrease only by 5.6% from the baseline. For WP10 scenario, the difference between the total regional incomes starting from the baseline is 11.9% lower in 2020 and 10.8% lower in 2050. For irrigation water use, an important impact of those scenarios in comparison to the regional income. The irrigation water use will decrease by 38.3% between the WP04 scenario and the baseline in 2020 and it will decrease by 36.4% in 2050. The impact of the implementation of WP10 scenario is more relevant than the first scenario since the irrigation water use will decrease by 69.7% in 2020 and 69.5% in 2050. The curves of energy consumption in irrigation water use shows that the difference between the WP04 scenario and the baseline is 36.6% in 2020 and 33.6% in 2050. Comparing the WP10 scenario with the baseline the difference is 59.1% for 2020 and 62.9% for 2050. According to irrigated agriculture area, the number of hectares between the WP04 scenario and the baseline will decrease 33.4% in 2020 and 33.6% in 2050. Comparing with the WP10 scenario it will decrease 59.1% in 2020 and 62.8% in 2050.

3.3 Sardinia case study

3.3.1 Description of the final complexity science model

Following the Water Framework Directive issued by the European Commission, the Sardinia region introduces the concept of Regional Multisectoral Water System (SIMR) with the aim of achieving a sustainable integrated water resource 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. Each district represents unique subsets with specific interactions between water supplies and demands for agriculture, domestic, industrial, hydropower, and touristic sectors, climate conditions and GHG emission/sinking, land use dynamics and agricultural food production systems. The Sardinia system dynamic model is then simulated for each district with a consistent replication of the analytical scheme for interaction between resources and demands and across nexus sectors. All the results (variables and output) from the simulation at districts level are aggregated at regional level when pertinent. The energy sector (energy production, energy demand, emission from energy sector, etc.) alone is simulated as integrated for the whole Sardinia island, since the distribution network is consolidated throughout the island and can not be accounted relatively to each district. Thus, the model representation below indicates the structure as simulated for each district, and replicated for all the districts and aggregated at regional level, while the described energy system structure is represented uniquely at regional level. The developed model for Sardinia identifies a total of 256 variables in total replicated at district and regional level, with a great and complex system of interactions across the Nexus sectors. The model runs at monthly timestep, starting in January 2006 and ending in December 2099 (i.e. 1128 timesteps in total). Nexus sectors are interlinked via multiple relations and feedbacks. Climate is impacted by emissions from the land, food, and energy sectors, while water is impacted by climate, population and tourism, land and food production. The energy sector is impacted by both population, changes in land-use and climate. In addition, food production is driven by water and climate, together with land use.

The SDM structure for Sardinia, and its districts, has been developed for analytical assessments in r. Such development allows to use GIS libraries to automatize extraction of input information from several spatialized raster variables (e.g. netcdf data format for climate data) and automatized computation for many different scenarios (GCM models, RCP emission scenario SSP scenarios) to facilitate uncertainty assessment.

3.3.1.1 Population and socio-economics

The socio-economic module retrieves and organizes information available from Computable general equilibrium thematic models and regional statistics characterizing distribution and trends of population/tourism and GDP, derived from the GTAP macro-economic model, and their outcomes on demand for different sectors. Trends in agricultural sectors are also defined from thematic models driven also at larger scale by Computable general equilibrium principles.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement NO 689150 SIM4NEXUS

3.3.1.2 Water sector

For the water sector module, the central focus was the representation of freshwater supplies through reservoirs water balance for the districts and the island and the fulfilment of water demand from different sectors. On the water supply side, the model accounts for inflows to the reservoirs based on a simplified hydrological model linked to precipitation, evapotranspiration, intercepted precipitation, soil depths and land-use and yields runoff as simulated by a soil water budget on the catchment areas upstream the reservoirs. This catchment hydrological model is linked to land use and slope to define the degrees of water consumption by vegetation and water partitioning to runoff. 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. The water demand for domestic use by resident population is calculated as function of resident per-capita water demand multiplied by resident population. Tourist water demand is calculated as function of tourist per-capita water demand multiplied by touristic fluxes, the latter modelled based as function of climate conditions with Touristic Climate Index (TCI) and socio-economic tourism development scenarios. The budgeting between water supplies and water demands defines the available water level in the reservoirs (both as absolute value and fraction of the reservoir allowed capacity). When water supplies in the reservoirs reach critical levels (fraction of the reservoir allowed capacity), then water distribution for the different sectors is proportionally diminished based on water management rules.

Monthly Minimum Environmental Flow (MEF) is calculated as fraction (20%) of long term (2000-2010) runoff and its purpose is to satisfy water demand of aquatic ecosystems. Spillways in time of overflow and river discharges during dry seasons contribute to its demand. In the baseline scenario, when water supplies in reservoirs undergo critical levels, environmental flows are reduced below the required levels. Water consumption for the different sectors is associated to specific energy consumption rates (Mw per cubic meter). Discharge levels that occur when water levels are higher than a specific threshold are accounted to modulate hydropower generation.

3.3.1.3 Land sector

The land sector module computes the area of different land uses in Sardinia and few ecosystem services generated by these. Sardinia’s land-uses are split into different categories based on their relevance and functioning within the nexus. Agricultural land is subdivided in 13 main crop types (Rice, Potato, Vegetable, Mais, Wheat, Barley, Oat, Fruit trees, Citrus, Olive and Grape, pasture and intensive pastureland), the most relevant in Sardinia, which are grown and accounted by their area distribution either as rainfed or irrigated. Irrigation requirements for these different crops are calculated by the SIMETAW model, which is coupled in r with the SDM for Sardinia to work accordingly under the same climate projections and modelling time-steps with analyses broken down at district level. SIMETAW model analyses crop specific irrigation requirements as function of several climate variables, crop development and irrigation management. These irrigation requirements are coupled with crop distribution of irrigated area of different crops to generate a seasonal and inter-annual variability of water demand from the agricultural sectors, which is dependent on climate inter-annual variability in the short-term and climate change and future trends of irrigated area in the long term.

As water availability in the reservoir may fall below critical level, water supplies may also be limited to satisfy agricultural water demand: the ratio between water supplies to agriculture water demand and the agricultural water demand defines a critical impact of the land sector to satisfy food security. Moreover pastureland areas are also accounted as either rainfed and irrigated conditions, together with their irrigation requirements as simulated by SIMETAW, and their relevance to sustain livestock (mostly sheeps and goats). Trends of agricultural area by crop type and irrigation/rainfed status, as output of the CAPRI model, predict a decreasing area toward 2050 for several crop types and in particular for pastureland. Abandoned pastureland, together with other fallow areas, can be subject to reconversion to natural vegetation (e.g. forest), especially if facilitated by proper policies. Land use changes between agriculture and natural vegetation are accounted in the model, and have a clear link to climate mitigation via ecosystem carbon sinking. When agriculture is converted to forest land uses carbon sinking is accounted, together with other areas where natural vegetation is growing into older stands. Thus for each land use a carbon stock and carbon sinking rate specific to each land use is calculated for an ecosystem carbon accounting by land use areas and aggregated for all land uses together. Furthermore, the level of environmental flows from the reservoirs compared to the MEF provides a measure of health for aquatic ecosystems.

3.3.1.4 Food sector

The food sector module in the Sardinia case also calculates a balance between supply and demand, where production and supply from different crop types and livestock are differentiated. Typical crop production levels for Sardinia decline proportionally if the water supplies to the agricultural sector do not satisfy agricultural irrigation requirement, when water level in the reservoirs are becoming scarce.

3.3.1.5 Energy sector

In the energy sector module the most relevant assessment was a balance between the energy production from the different mode of generation and consumption for the different sectors. Energy production is modelled from sources including oil, coal and methane (or natural gasses), solar, wind and hydropower, while energy demand comes from the agricultural, domestic, industrial and service sectors (including transportation). The production of energy, especially related to non renewable energy sources, have a direct implication on land uses both because energy farms imply land appropriation and also because the use of hydropower "limit" water availability that can indirectly sustain hydrological and physiological processes of ecosystem and reduce land degradation.

The use of energy from the different sectors and using different energy sources, either renewable and not renewable, have different implication and loading to emission of GreenHouse Gasses with specific impacts on climate change. The global warming potential (carbon dioxide equivalent) per unit of electrical energy (kilowatt hour) generated is multiplied by the energy production per source type to calculate the loading to emission for energy source: 820 gCO2 eq/kWh per coal, 480 gCO2 eq/kWh per methane, 48 gCO2 eq/kWh per solar, 24 gCO2 eq/kWh per hydropower, 11 gCO2 eq/kWh per wind.

Future energy production trends from sources directly linked to climate factors (i.e. wind and solar) were calculated by adjusting their installation capacity on the ground to wind speed or solar radiation using a non-linear equation calibrated with historical data of energy production, installation capacity and climate factors. Likewise energy production from hydropower was linked to water levels stored in the reservoir system.

For primary energy production the sources are split into those used for heat and energy production, where heating was related to particular domestic measures that could enhance energy savings in private and public buildings.

3.3.1.6 Climate sector

The climate sector module structures several climate variables and link their direct analytical influence on several processes throughout the Nexus. These include hydrological processes and vegetation functioning at catchment areas (Precipitation and EvapoTranspiration) generating runoff and inflow to reservoirs, Open Evaporation from reservoir water surface, Tourist fluxes and their demand of resources with a Tourist Climate Index, energy production from wind and solar power, evapo-transpiration and crop water requirements for several relevant crops with the SIMETAW model. These direct functional links to climate variables bring a high degree of variability following inter-annual climate variability and long-term climate change.

A net GHG emissions balance, including emission from different energy sources and sequestration from land use types, is evaluated to define path towards climate change mitigation and carbon neutrality.

3.3.2 Description of the final results

3.3.2.1 Population

According to actual demographic trends and population age structure already observed in the Sardinia region, a strong decrease in population from ~1,600,000 to ~ 1,400,000 is projected for the future due to slow economy and emigration to other regions and countries. The largest share of the resident population lives in the Flumendosa-Campidano and the Coghinas-Mannu-Temo districts, which refer to the two largest cities in Sardinia (Cagliari and Sassari).

Unlike population, touristic fluxes are expect to undergo strong increasing patterns in Sardinia and almost double by 2050. It is important to stress that a large share of touristic fluxes are targeting coastal areas and few proportionally smaller districts (Liscia and Posada-Cedrino), which witness an extremely high number of tourist arrivals posing strong demand on available resources.

3.3.2.2 Water sector

The resilience of the reservoir systems is expected to be roughly constant. However, higher variability of climate conditions and more prolonged droughts projected for the future may lead to critical periods with diminished water levels in the reservoir cutting supplies mostly to agricultural irrigation requirements and Environmental flow. More extreme lower levels in the reservoir systems are predicted before 2050.

Agriculture water demand is the predominant sector at regional level, accounting for more than half of the total freshwater demand. Water for domestic and tourist uses account for an additional 30% of total water withdrawal, but with higher priorities compared to water demand in agriculture. Thus, in case of water scarcity, agriculture water demand may undergo the significant reductions, rather than for the domestic/touristic sector. Industrial water demand in turn is very limited, due to decreasing relevance of the industrial sector, and expansion of self-supply water resources, including industrial use of seawater. Total agricultural demand is expected to remain roughly constant over time, since expected increases in irrigation requirements over unit areas due to climate change are compensated by decreases in irrigated cropping area. Domestic water demand is expected to slowly decline due to decrease in population, although the expansion of tourism sector can partially compensate such reduction for domestic.

For Minimum Environmental Flow, the pattern reflects that of water supply. Just as with water supply, after initial large seasonal and intra-annual variability, the total level for Minimum environmental flow for aquatic ecosystems is expected to decrease over the latter half of the simulation to 2050.

3.3.2.3 Land sector

Maquis shrubland (Macchia Mediterranea)is the largest land use and account for about 20% of the whole regional land, followed by crops and forested land each accounting for additional 17%. Agroforestry and pastureland are also very relevant with respectively 11 and 13% of regional area. Fallow area, i.e. agriculture land at rest, is also very abundant with about 9% and very interestingly areas under recolonization, namely under conversion to natural systems, account for another 4%. All of these specific land uses imply different carbon stocks and services to mitigation and ecosystem functioning. Additionally a relevant share of land under recolonization brings in a substantial extra carbon sinking that can be effective to offset other anthropogenic emissions from energy production.

Projections to 2050 indicate a strong drop of pastureland (-35%), following declining activities related to livestock, and crop area (-20%). Drivers of land use conversions see consequently increases in area under agroforestry (or silvo-pastural systems), and recolonization into natural systems or addition to fallow land, in first few decades. Subsequently, abandoned land use systems “migrate” to more natural and mature ecosystems, such as forest, while there is still a continuous but slower decline of cropland and pastureland. These conversions, although not positive for rural economic activities following a decline of GDP in the agricultural sector, on the other side bring a very consistent and positive effect on ecosystem services. In the SDM, these are clearly evident by an enhanced carbon sequestration with natural systems, but can also be linked to better hydrological functioning in terms of water provisions during drier periods (baseflow).

3.3.2.4 Food sector

For irrigated agricultural areas, pastureland, vegetables, grapes and olives are the most relevant agricultural types in Sardinia. Future simulations will see dynamics in the changes of irrigated land with a consistent decrease of the overall area by 2050. The area of pastureland will be 40% lower compared to its actual extent, due to associated and ongoing decline of livestock production on the island. Irrigated barley and maize will also see their extent reduced by half in the same period, while Potato and Rice extent will slightly diminish. On the other hand, the area of irrigated grape will rise by 50%. Other irrigated crop types (Vegetables, Olive, Fruit Trees and Citrus) are expected to remain roughly the same in terms of distribution. These patterns are here represented for the whole island, but do not see particular differences among the districts.

Food production from the agriculture sector will foresee a gradual but steady reduction due to decreasing irrigated and rainfed areas (5 and 10%). However, this reduction is counterbalanced by a comparable reduction in population (10%), and thus food demand. Gradually over the long term food security will not be much affected by changes in crop area distribution, as much as it may be affected over short terms due to interannual climate variability and prolonged droughts which may be more likely and severe in the last decades of the 2010-2050 period. Water shortages, when freshwater in reservoir reaches some critical level, will reduce supplies provided to satisfy agricultural demand. Thus the ratio over time between water distributed for irrigation in agriculture and effective water demand distributed for agriculture needs will indicate the potential yield reduction and food security risk for the different districts.

3.3.2.5 Energy sector

Results for the energy sector are computed in the SDM at regional level, since the energy distribution system guarantee quite a cohesive and integrated system throughout the island.
In terms of primary energy production, coal production is currently extremely relevant and has a dominant but rapidly decreasing importance for the future. Production from renewable energy sources, and in particular production from energy wind farms, will become dominant across renewable energy sources, in line with Sardinia policy goals of aiming at carbon neutrality. With time, methane will also acquire a large relevance by partially replacing coals in thermal energy production. Methane will provide a primary source energy that, according to Sardinia policy plans, can guarantee cheap energy prices and lower emissions than coal. It is noted that some following figures run only until 2030 due to thematic model inputs. However the full SDM implementation does run until 2050.

Energy demand by sector will foresee a decrease in demand from the industry, whose GDP and production levels are foreseen to follow a decline as in the last few decades. Demand for the domestic sector will see the most relevant increase as households are expanding the use of electrical appliances and heating/cooling systems. Agricultural demand will also follow a slight decline over the future.

Energy demand by source, as the energy demand by sector, will decrease for all sources mainly as a consequence of population decline and contraction of the industry sector.

3.3.2.6 Climate sector

Both carbon (equivalent) emissions from the energy sector and carbon sequestration from ecosystem, due to land use changes and recolonization with natural vegetation, are accounted together to estimate net carbon emissions towards carbon neutrality and climate change mitigation efforts. Emissions from energy sources can be reduced by an extreme and aggressive change of the energy portfolio including a large share of renewable energy sources integrated with additional use of natural gas to finally set off the use of coal on the island. Such reduction would be extremely far greater than emission savings from land use changes. In this sense it is clear than the far and most prompt action to reduce carbon emission requires rapid action and innovative shift towards renewable energy sources. If such an aggressive reduction from energy sector is put in place, then the emission saving by carbon sequestration in the land use factor would be extremely relevant to counterbalance energy emissions with aim for carbon neutrality.

3.4 Latvia Case study

3.4.1 Description of the final complexity science model

The Latvia system dynamics model describes the entire country split into five (5) sub-regions within the country. These regions are: R1 – Pieriga; R2 – Vidzeme; R3 – Kurzeme; R4 – Zemgale; R5 – Latgale. In each nexus sector, the same (sub-)model structure is used in each geographical region. This allows replicability and consistency of data and result across the regions (allowing for comparable assessment), and also allows for easy scaling up to national totals. As a result of this feature, in the model presentation below, the structure from only one region will be shown, as all other regions are identical in structure, only differing in their data input. The final model consists of 3049 variables in total. The model runs at monthly timestep, starting in January 2000 and ending in December 2050 (i.e. 612 timesteps in total).

Climate is impacted by the land, food, and energy sectors, while water is impacted by changes in the land sector. The energy sector is impacted by changes to the food sector, which itself is affected by the land sector. In addition, population estimates are also used to drive demand in the food sector (e.g. food consumption per capita.

3.4.1.1 Population

The population module (Figure 10) simply tracks the historical and projected future in each of the five regions, summing up to the national level. Population is used in the food sector regarding demand forecasting.

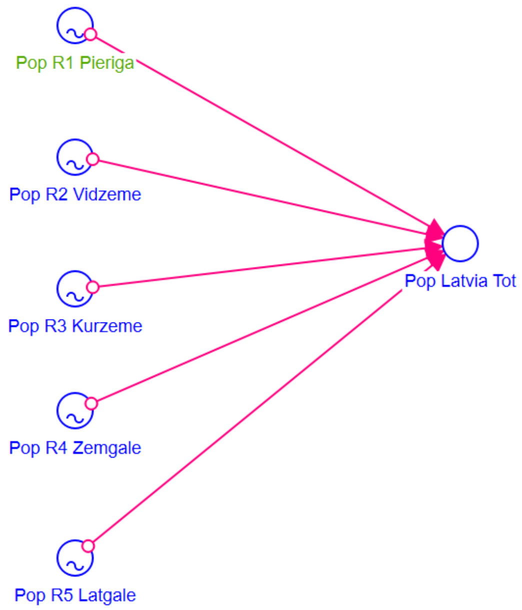


Figure 10: the population module in the Latvian case study.

3.4.1.2 Water sector

The water sector modules are primarily focussed on nitrogen (N) runoff to waterbodies in Latvia and are built up on three sub-modules (Figure 11). Water quantity was not considered an important aspect to track, and so in contrast to other SIM4NEXUS case studies, a quantitative water balance is not assessed for Latvia. The three sub-modules, explained below, track N runoff from agricultural fields, from fields used to grow energy crops, and from forest areas.

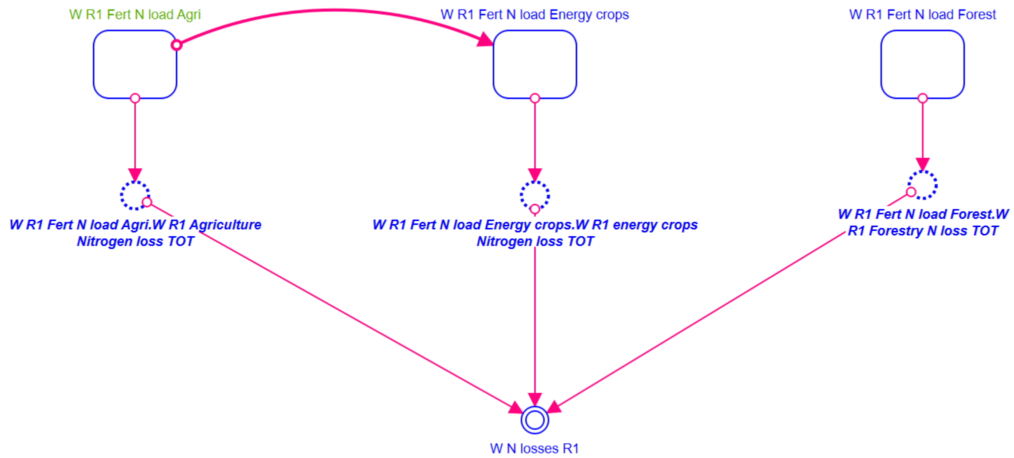


Figure 11: the top level of the water sector modules, showing how N runoff is tracked for agricultural, energy crop, and forest lands.

In the agricultural N runoff sub-module, the areas of perennial grasslands and cereals are multiplied with a N loss runoff rate to derive tot N runoff from these land types. The two classes are summed to give total N runoff from agricultural land. As mentioned previously, the N runoff from agricultural land can be summed across each of the five regions to arrive at a national total.

The energy crop N runoff sub-module only considers rape crops, which is again multiplied by an N runoff rate per hectare. Forest N losses (Figure 12), are estimated by considering felling areas, areas of restricted activity in forests (i.e. protected forest lands), and younger forests under management. Each is multiplied by a forest N runoff rate to derive a forest N loss total.

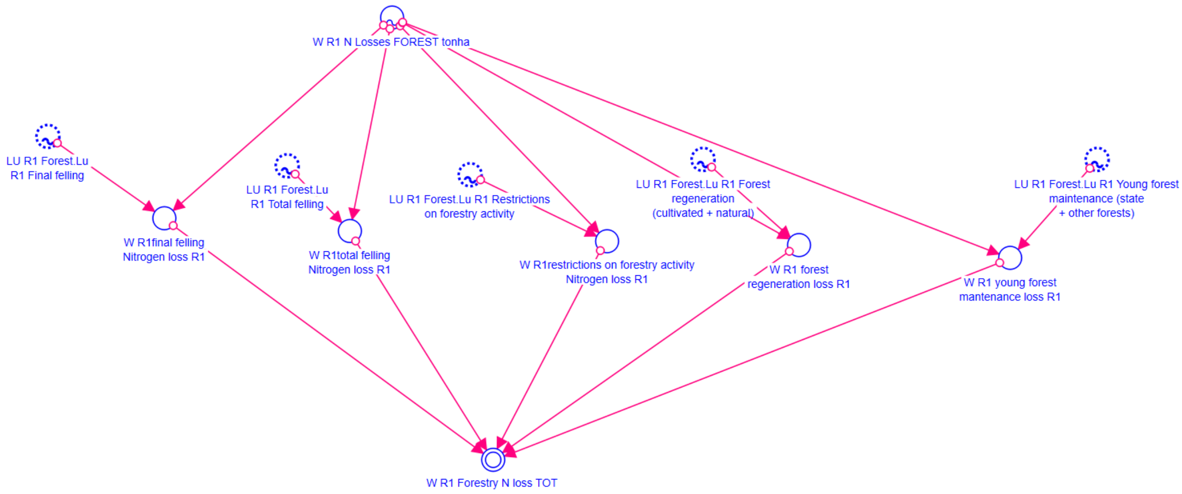


Figure 12: the forest N loss sub-model in the Latvia case study.

3.4.1.3 Land sector

In the land sector, apart from simply tracking land use in Latvia, income derived from different land use classes is also simulated (Figure 13).

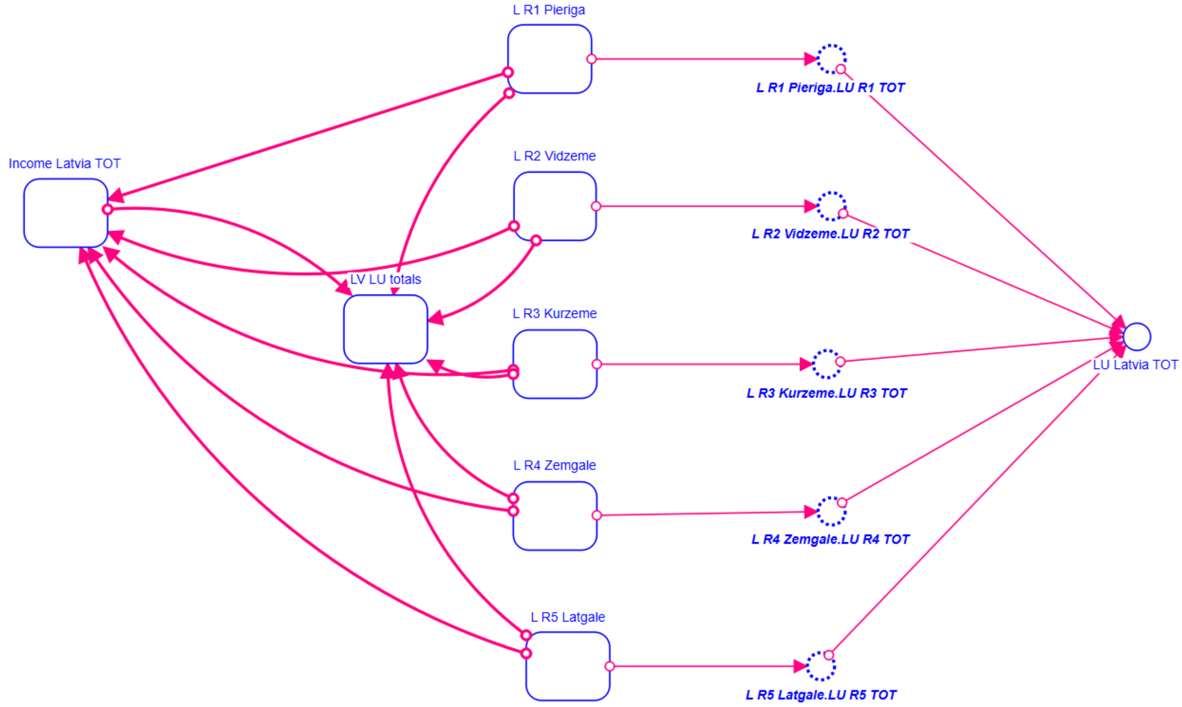


Figure 13: top level of the land sector in the Latvian SDM. Land use modules for each Latvian region can be seen in the middle. On the right, the regions are summed to give a national total, and on the left income from different land uses is simulated.

The land use estimates are split into four land classes: energy crops, agriculture, livestock, and forests (Figure 14). In energy crops, only rape is considered as it is the only energy crop in Latvia. For agricultural land, cereals, arable lands, and wheat are considered, with the model splitting the land into other arable land, arable land, utilised agricultural area, and non-utilised area. For livestock, perennial grasslands and meadows and pastures are tracked, while for forests, the total area is comprised of felling areas, areas of restricted activities, young forests under maintenance, and forests undergoing regeneration.

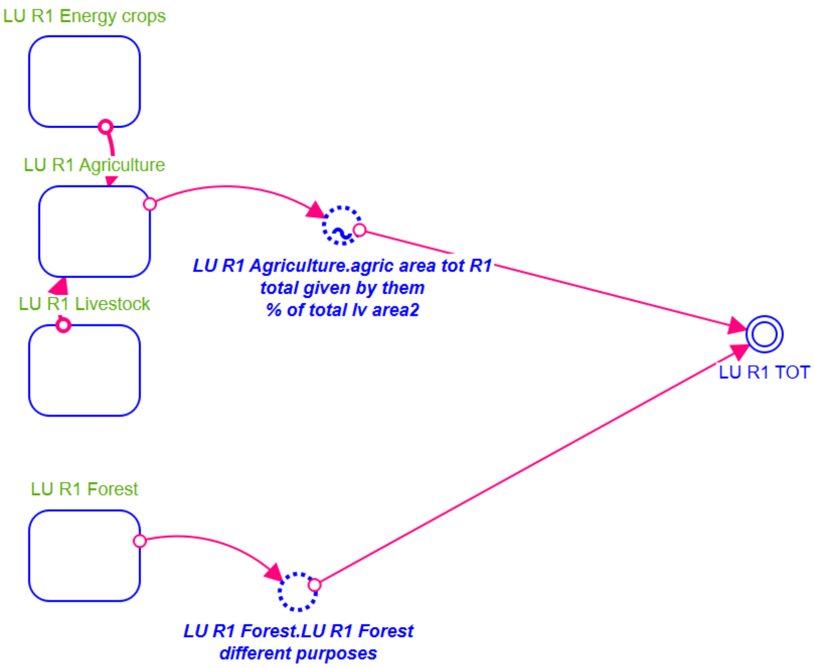


Figure 14: top level of the land sector modules in the Latvian case study.

In terms of estimating income, Figure 15 shows the model structure used to estimate income from arable land. The total area of arable land in each Latvian region is multiplied with an income per hectare of arable land. Therefore the total arable land income in each region can be estimated, and when summed, a national income arrived at. A similar structure is also used to compute income from utilised agricultural land, energy crop lands, cereals, perennial grasslands, and meadows and pastures, each with their own income rate per hectare.

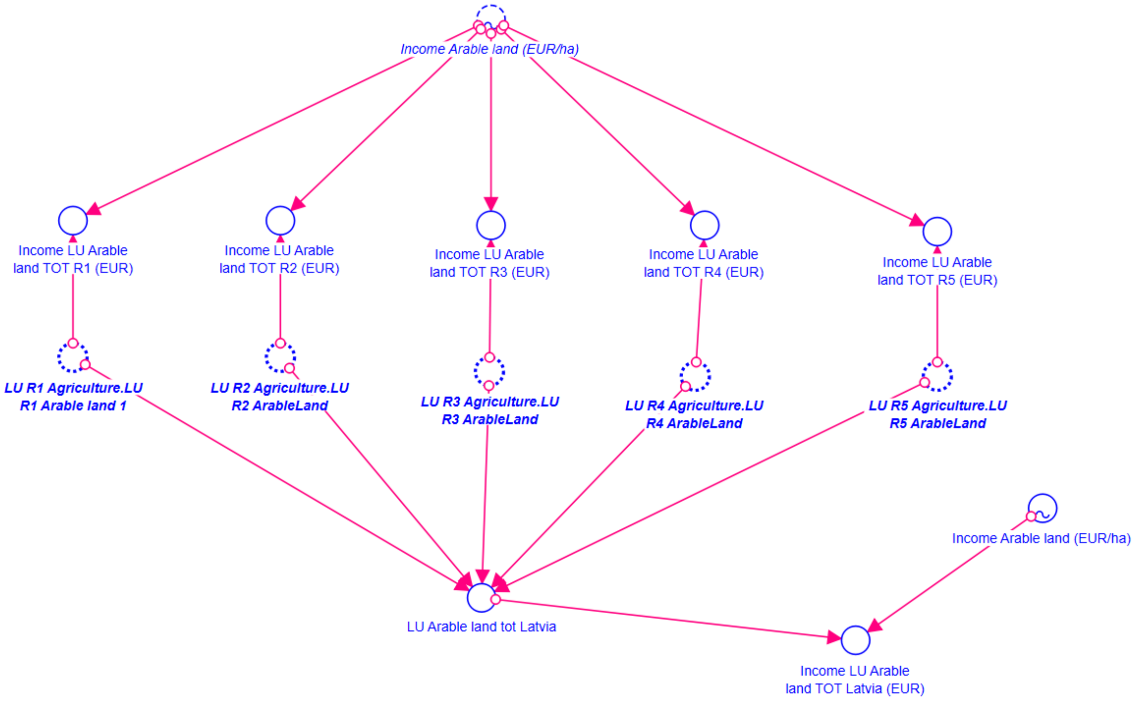


Figure 15: sub-module simulating income from arable land in the Latvian case study.

3.4.1.4 Food sector

The food sector module simulates the food production and consumption, along with a food supply balance, for each Latvian region, as well as aggregating to the national level. Each region has its own sub-module for simulating supply and demand. These are described in more detail below.

In terms of food production, crop food, livestock, and livestock products are quantified (Figure 16). For crops, only cereals are considered due to date restrictions. For livestock, dairy cows, other cattle, pigs and sheep are quantified, while in livestock products, milk, and meat products are differentiated. As show in Figure 50, each category is summed to give regional production totals, and each region is summed to give national totals. It is noted that some food production such as fruits and vegetables is not quantified due to a lack of data, and also due to a stakeholder desire to focus primarily on cereal crop production as it relates to national food security issues.

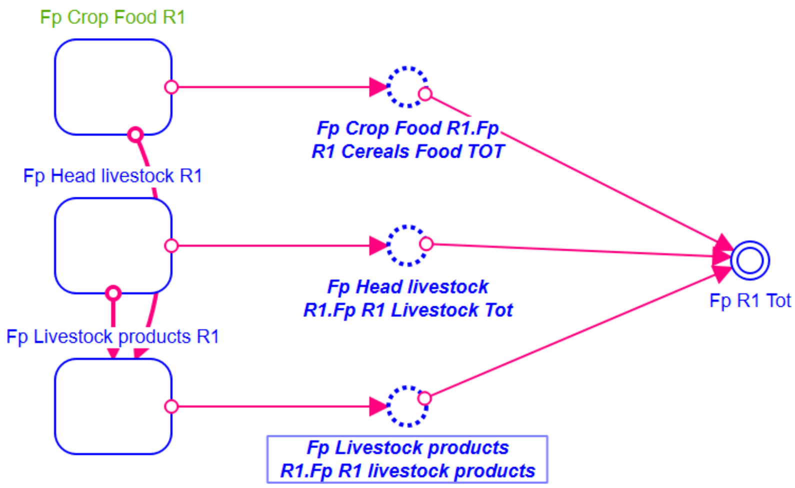


Figure 16: food production sub-module for the Pieriga region in Latvia.

On the food consumption side, the per-capita consumption of cereals, milk, meat and 'other' is multiplied by the population to arrive at estimates of the consumption of these products (Figure 17). These are summed to regional totals, and again to arrive at national estimates.

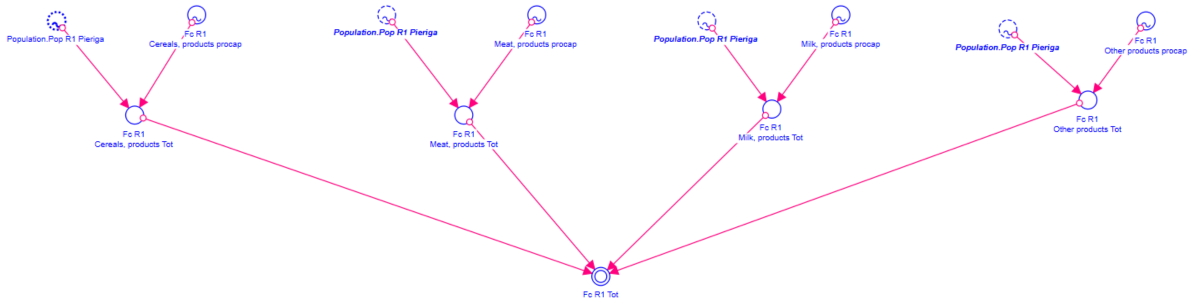


Figure 17: structure of the food consumption module in the Latvian SDMs. Note that food consumption in modulated by population and per-capita consumption rates of different products.

3.4.1.5 Energy sector

The energy sector module considers primary energy production, secondary energy generation, and energy demand in the Latvian regions. Nationally, the values for primary energy, secondary energy, imports, exports, and total demand are calculated (Figure 18). For each energy type, a balance is also calculated between the production and consumption on that energy source (Figure 19).

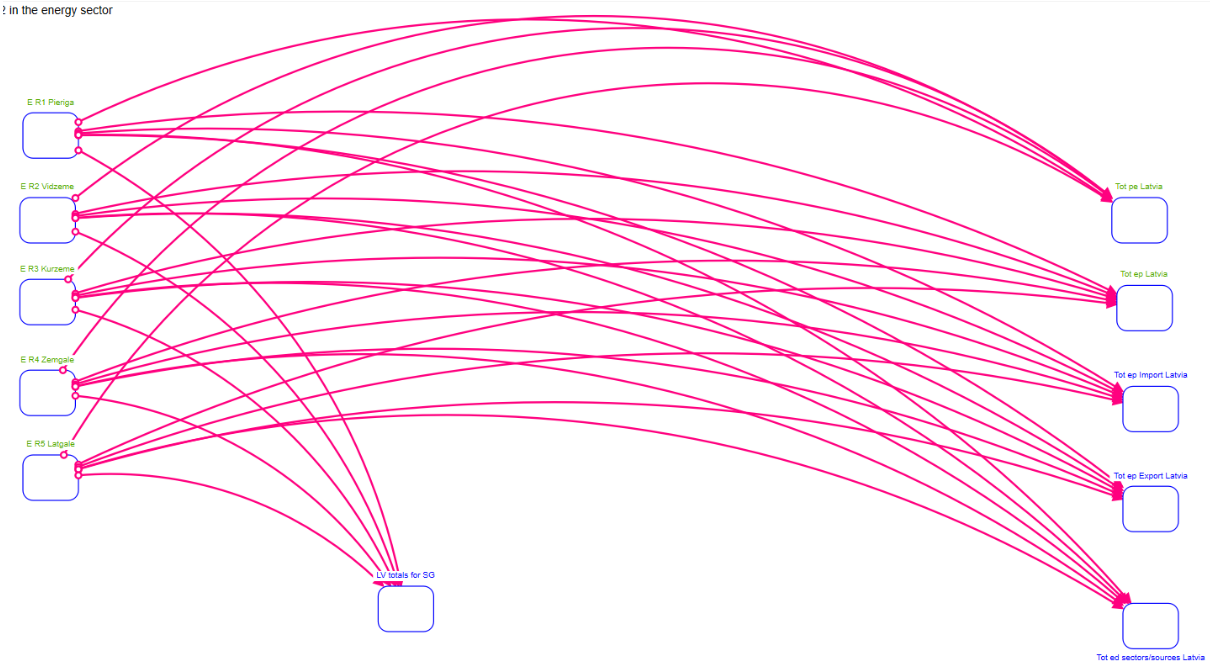


Figure 18: top level of the energy module in the Latvian case study.

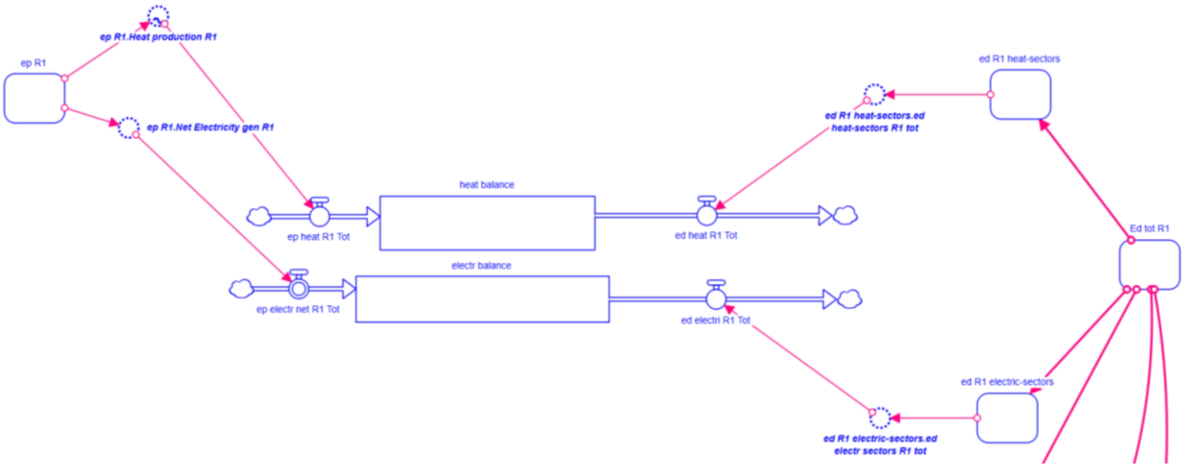
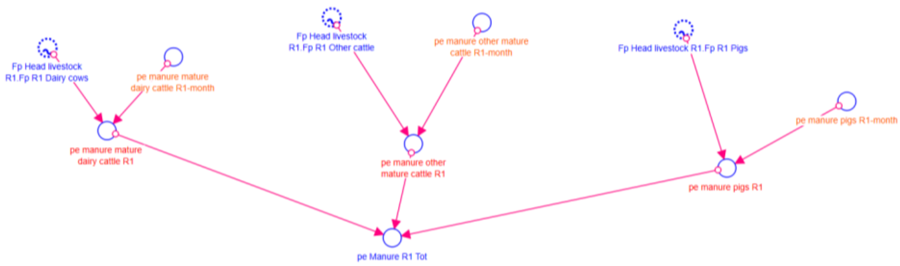


Figure 19: showing part of the Pieriga energy sub-module illustrating the structure of the model to calculate an energy balance (square box, middle) as the difference between energy production (rounded box, left) and energy consumption (rounded boxes, right).

In terms of primary energy (Figure 20), sources that are included are manure, oil, coal, bioethanol, peat, biodiesel, other biogas, fuelwood, landfill gas, charcoal, peat briquettes, natural gas, sewage sludge gas, and straw. The gas, oil, and coal can be consumed directly, or can be used in secondary energy production.



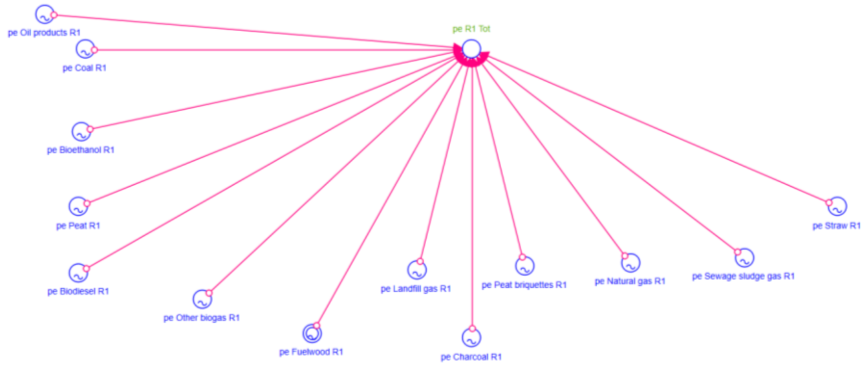


Figure 20: the primary energy production module.

In terms of secondary energy, electricity and heat are calculated for the Latvian case study (Figure 21) although for heat, a single value of total production is given, while for electricity, this is broken down by generation fuel/source.

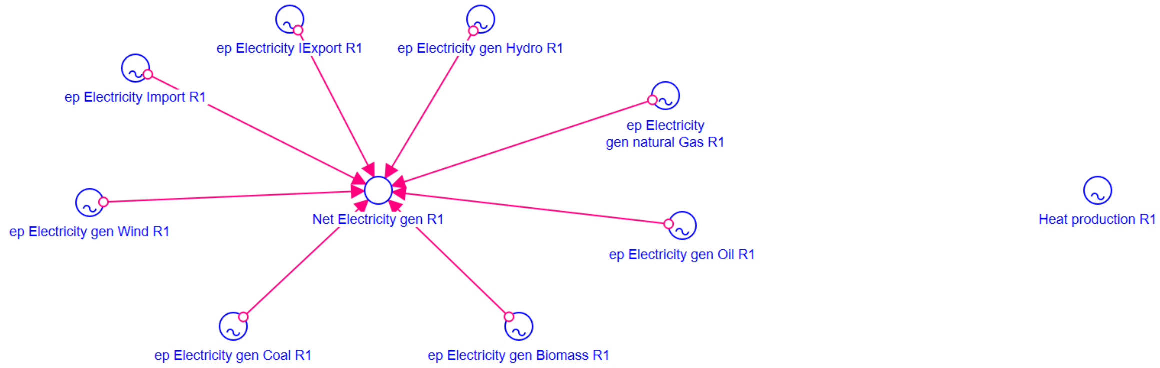


Figure 21: the secondary energy production module in the Latvian SDM.

Energy demand is broken down into five economic sectors: industry, transport, household, agriculture, and the tertiary sector (Figure 22). Within each sector, the module structure is the same, so here only the example from industrial energy demand is shown.

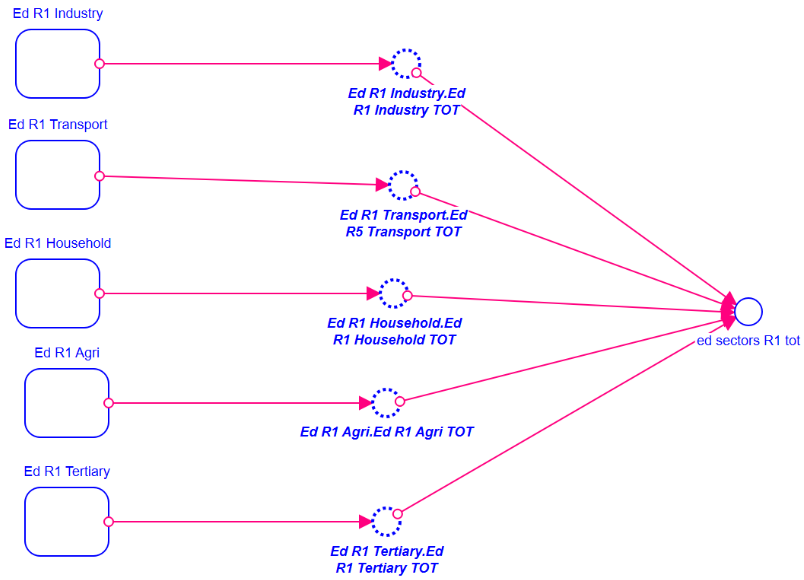


Figure 22: the energy demand module, showing the five economic sectors considered in the simulation.

Within each sector, the energy demand from a number of sources is quantified (Figure 23). Energy demand from oil, gas electricity, heat, biomass and combustible waste, and coal are quantified. These are summed to give the total industrial energy demand regionally or nationally (the same applied to the other sectors). In a similar way, the oil-related demand for example in all the sectors can also be summed (e.g. Figure 24) to give total regional or national oil related energy demand. This structure therefore gives great flexibility when conducting analysis on Latvian energy production and consumption (Figure 25).

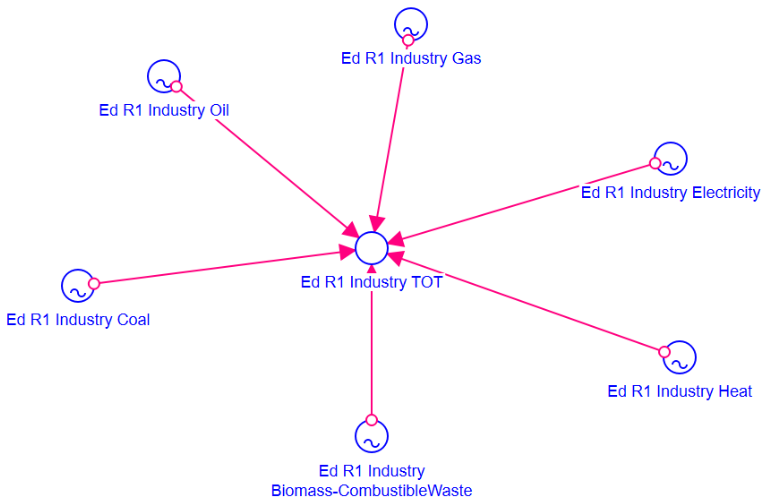


Figure 23: the energy demand sub-module in the Latvia case study. The other economic sectors are similarly structured.

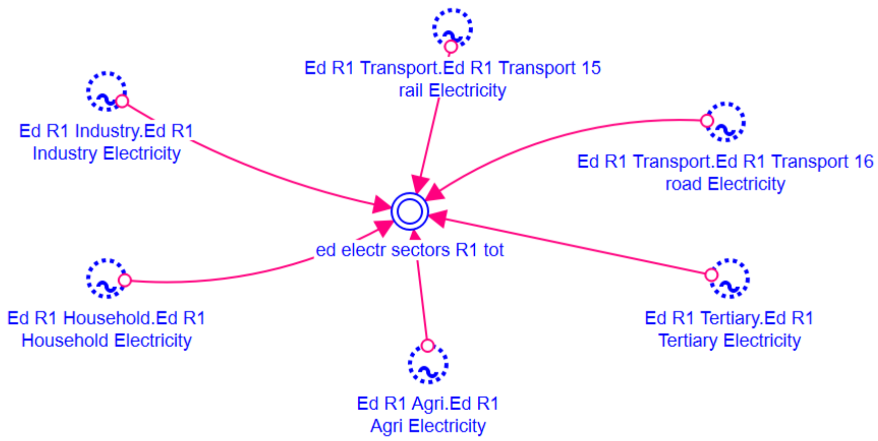


Figure 24: showing the summation of all the electricity demand from the different sectors in the Pieriga region of Latvia. Each region can also be summed to give total Latvian electricity demand, either in total or by sector.

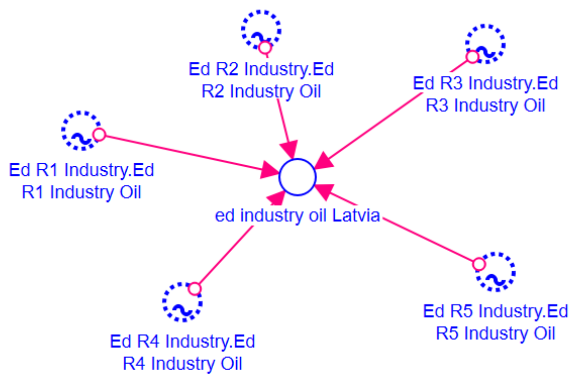


Figure 25: demonstrating how industrial oil demand is summed for all five regions, deriving Latvian national totals. A similar structure is applied for other fuel types and for other economic sectors.

3.4.1.6 Climate sector

In the climate sector, the emissions and sequestration of GHGs are simulated for each region and aggregated to the national level (Figure 26). As with other case studies, a GHG ‘balance’ between emissions and sequestration is calculated (Figure 27).

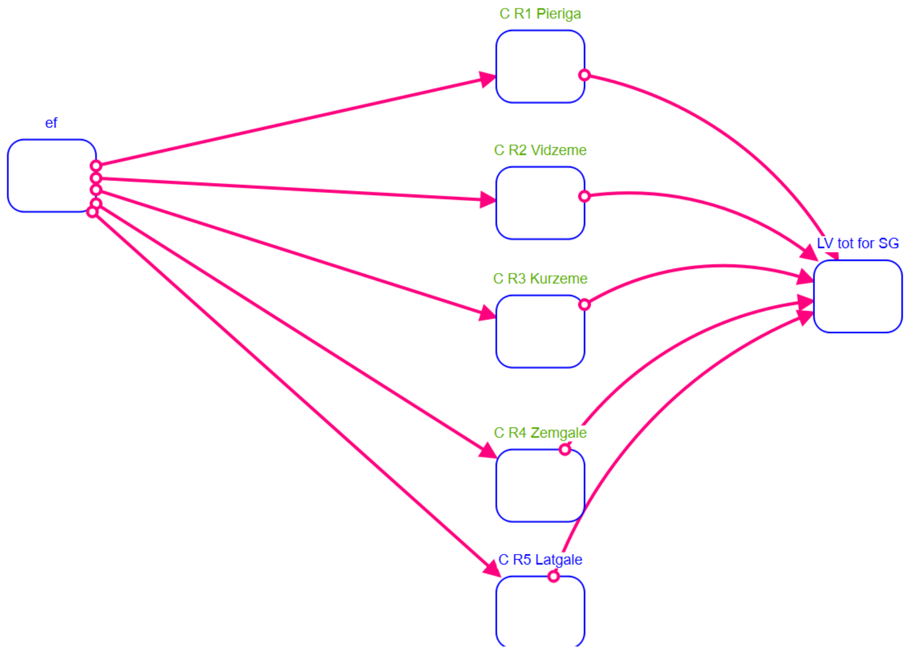


Figure 26: showing the top level of the climate module in the Latvian case study. Emissions and sequestration are calculated for each region (rounded boxes, centre) and aggregated to the nation (rounded box, right). Emissions factors are stored in their own module (rounded box, left) and used within each region in the calculations.

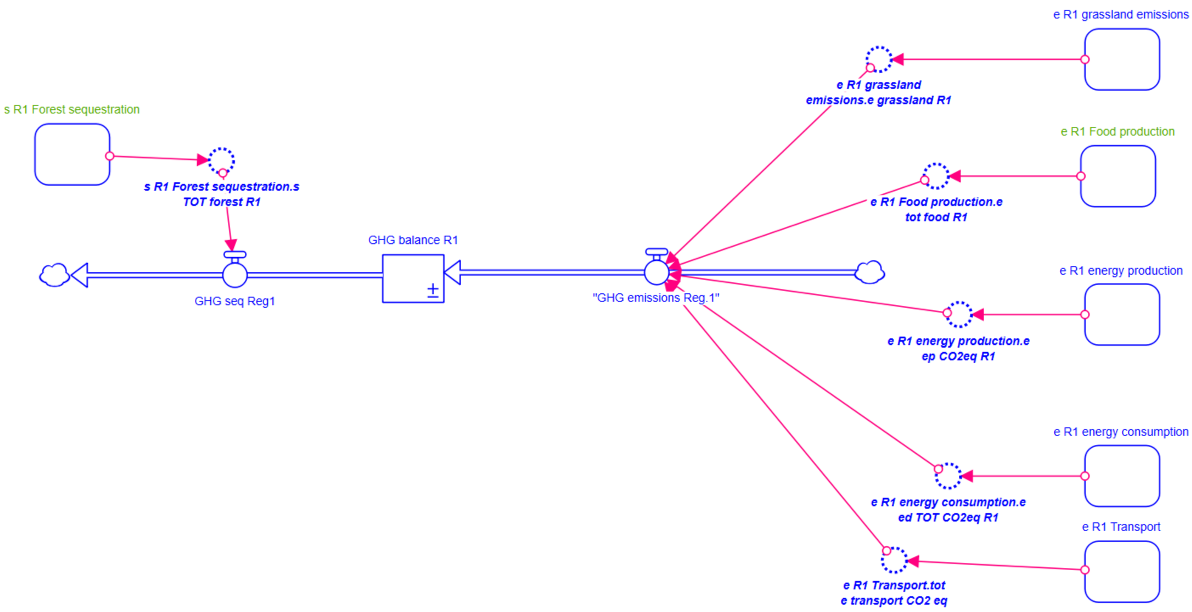


Figure 27: climate module for region one in the Latvian case study, showing the balance (square box, centre) between GHG sequestration (rounded box, left) and emissions from five different sources (rounded boxes, right).

For estimating GHG sequestration, only forest land is considered, along with a forest-land relevant GHG sequestration factor. For emissions, grasslands, food production, energy production, energy consumption and transport are the sectors taken into account. For grassland, only perennial grasslands are quantified in terms of GHG emissions. Food production is more complex (Figure 28). For the livestock categories, enteric fermentation related emissions, and methane and NO_2 related CO_2e emissions are estimated using relevant emissions factors. In addition, emissions from the production of cereals are also simulated. The total food related emissions is the sum of enteric fermentation, methane, NO_2, and cereals related emissions for each region. As previously, each region can be summed to the national level in terms of food production. Likewise, only the cereals related emissions can be computed nationally if desired, and so on.

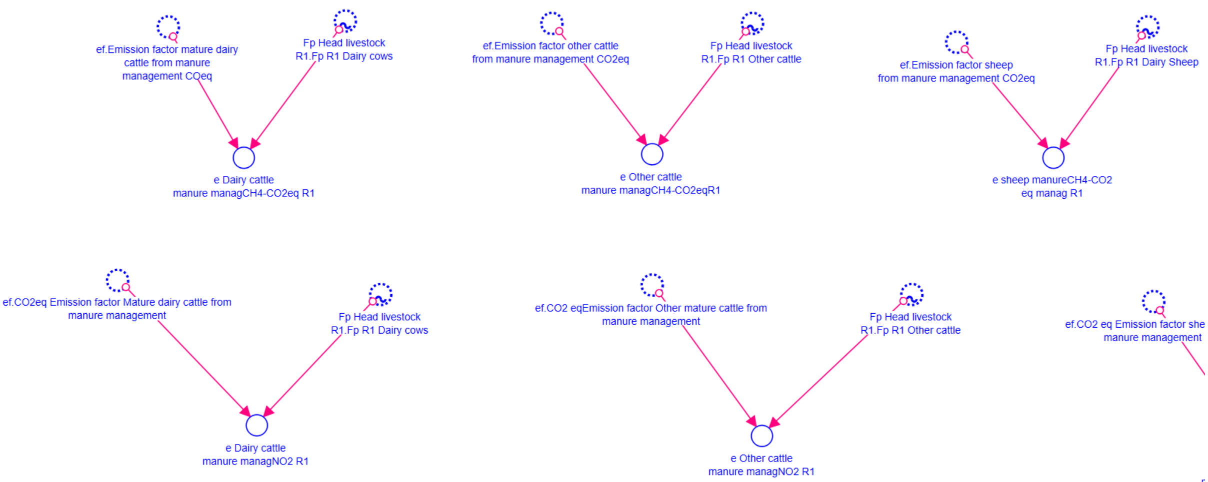


Figure 28: showing part of the emissions module for food production in region one of the Latvian SIM4NEXUS case study.

In terms of emissions from energy production, for gas, solid fuels, liquid fuels and biomass, direct CO_2, CH_4 in terms of CO_2e and N_2O in terms of CO_2e are estimated and summed to give totals for each fuel type. Again, the results are summed for all fuels to give regional energy production related GHG emissions, and can be summed to the national level.

For energy consumption, 16 categories are assessed: liquid fuels, solid fuels, gas, and biomass consumption in agriculture, industry, the domestic sector and the tertiary sector. As for energy production, direct CO_2, CH_4 in terms of CO_2e and N_2O in terms of CO_2e are estimated and summed to give totals for each fuel type consumed (Figure 29). The results are summed for all fuels to give regional energy production related GHG emissions, and can be summed to the national level.

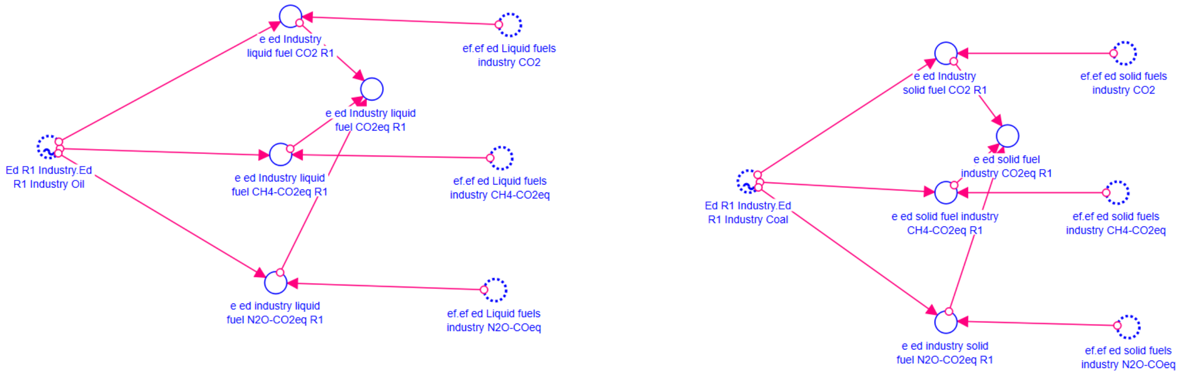


Figure 29: detail showing two of the 16 calculations of the energy consumption emissions module, highlighting how for each fuel considered, different GHGs are considered in the total emissions calculation (see text for details).

In the transport sector (Figure 30), road and rail are differentiated. For rail, emissions from oil and biomass/combustible waste consumption are estimated, in terms of direct CO_2, CH_4 in terms of CO_2e and N_2O in terms of CO_2e. For road transport, emissions from gas (LPG), biomass/combustible waste, oil and diesel consumption are estimated, again in terms of direct CO_2, CH_4 in terms of CO_2e and N_2O in terms of CO_2e.

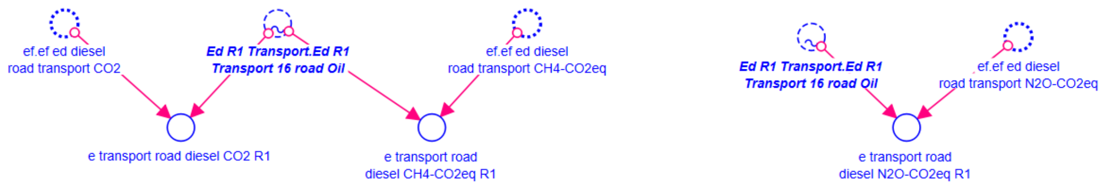


Figure 30: detail showing part of the calculations of the transport related energy consumption emissions module (showing road oil consumption related emissions in particular), highlighting how for each fuel considered, different GHGs are considered in the total emissions calculation (see text for details).

3.4.2 Description of the final results

3.4.2.1 Population

Figure 31 shows the results of population over line in Latvia from January 2000 to December 2049 under baseline conditions. A continuous decline in population is expected, such that by the end of the simulation, the total Latvian population has declined by nearly 700,000 people compared with the start of the simulation. This agrees with current population trends in the country. It is noted that there is a slight decrease in the rate of decline over time. Note that here, graphs show monthly and not annual timesteps.

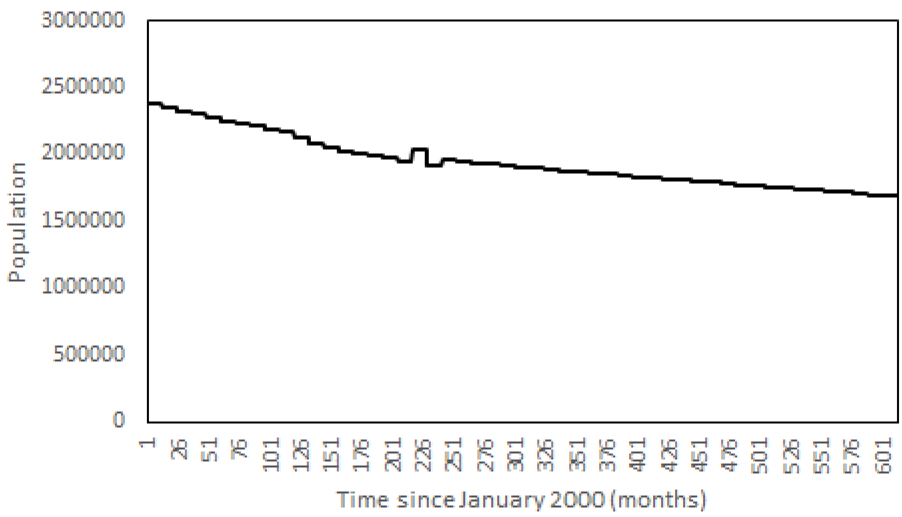


Figure 31: total Latvian population from 2000-2050.

3.4.2.2 Water sector

All regions contribute roughly evenly to the N runoff, although Zemgale shows higher N loads compared with other regions. From time ~ 163, there is a constant projected increasing trend of N runoff as more land is used for farming activities See Section 3.4.1.2). Before time 163, two sudden jumps are noted in the chart. This is due to different datasets being used for different periods of time. Although the values may be questioned, the trends still indicate increasing N loads. Therefore, a message for Latvian water quality policy is to find ways to reduce N load per-hectare, and overall in order to meet national goals and international (i.e. Water Framework Directive) standards.

3.4.2.3 Land sector

Forests are dominant, making up over 60% of the total land use. Cereal lands are the next biggest land user at the end of the simulation. However at the start of the simulation, non-utilised areas make up the second largest land use. This category quickly diminishes however as more land is utilised for other activities, and by the end of the simulation it is negligible. Meadows and pastures make up the third largest proportion of land use, and are relatively consistent over time. Overall, only forests and cereals are expected to appreciably expand in total area over time, with the other categories remaining nearly constant.

3.4.2.4 Food sector

As with land, both graphs are representative of each other, and the remaining four regions show trends very similar. Two main features are noted: 1) cereal production dominates over livestock production, and 2) total production is expected to markedly increase by 2050, especially for cereals, with livestock seeing only marginal levels of growth during the simulation.

As with land, both graphs are representative of each other, and the remaining four regions show trends very similar. The total consumption is initially observed to decline, largely owing to negative population growth. in the latter two-thirds of the simulation however, total consumption gradually increases again, levelling off just below the values at the start of the simulation. The reason for the gradual increase is due to expected increases in per-capita food consumption that are greater than the expected decline of population, thereby leading to gradually increasing overall demand. The 'other' food category dominates, as it is an amalgam of many food types, including fruit and vegetables. Milk, meat and cereals make up rough equal proportions of the remaining food consumption groups in Latvia and remain roughly constant over time with the growth in consumption largely coming from the 'other' food category.

3.4.2.5 Energy sector

Both show similar trends, and this is also true for the remaining four Latvian regions – all follow similar trends to those shown here. Primary energy production is expected to increase substantially through the simulation to 2050. By far the largest increase to the contribution of primary energy is expected to come from biodiesel, with this source starting as zero, as increasing markedly through the simulation to become the dominant source by 2050. Fuelwood will also remain a major primary energy source, though it will decrease from its starting value. All other primary fuel sources make up negligible contributions to the overall primary fuel mix in Latvia. It is pointed out that these sources only account primary sources native to Latvia. The import of other primary fuel sources (e.g. oil, coal) is not considered in this case study.

Hydropower and natural gas dominate electricity production. However, it is shown that biomass as wind energy are expected to become increasingly important to 2050, contributing to much of the growth in electricity generation in Latvia.

In terms of import and export of electricity, both are expected to increase roughly linearly over time, but exports will grow faster until exports exceed imports by the latter third of the simulation. This trend is apparent in all five of the Latvian regions.

The regional energy demand totals all follow very similar trends. In terms of non-transport energy demand the simulation suggests only moderate growth, with even a small decrease in the middle of the simulation period, and a small recovery towards the end. Biomass sources dominate final demand across all sectors (except transport), with electricity, gas, and heat all contributing roughly equal proportions of energy demand. Oil represents a much smaller fraction, and coal related energy demand in the non-transport sectors in negligible. For the transport sector, total energy demand is expected to remain roughly constant over time. However the proportions of different fuel sources change. Rail electricity demand is expected to grow considerably at the expense of rail oil fuels. Road oil remains constant over the simulation, and road gas demand (LPG) remains negligible.

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3.4.2.6 Climate sector

In the climate sector, results show the total GHG emissions from land use, energy production, and energy consumption, as well as GHG sequestration only from forest lands for the Pieriga region (Figure 32) and the whole of Latvia. Both the regional and national graphs have very similar trends, and the same is true for the other four Latvian regions. In terms of emissions from land use, cereal lands by far dominate as emissions sources. With energy production, CO_2 emissions derived from biomass and from liquid dominate over other sources. In terms of energy consumption, industrial biomass and domestic biomass fuel sources dominate emissions. In the transport sector, road-based emissions dominate other forms of transport (aviation was not considered in this analysis). GHG sequestration from forest lands only, denoted by the solid red line, is far below GHG emissions suggesting net emissions for the atmosphere, although it is acknowledged that not all sequestration sources are quantified in this model. Most worrying is the decline in forest land sequestration potential due to the conversion of forest lands to arable land mainly for additional cereal cultivation. To reduce emissions, better management of cereal lands seems to be critical, along with improved carbon capturing and storage techniques in the biomass and liquid energy producing sectors. To reduce GHG emissions from consumption, the industrial and domestic sectors should be looked at, along with road transport. Electrification, especially if the electricity is generated from renewable sources could represent a promising avenue to reduce consumption-related emissions in these sectors in Latvia.

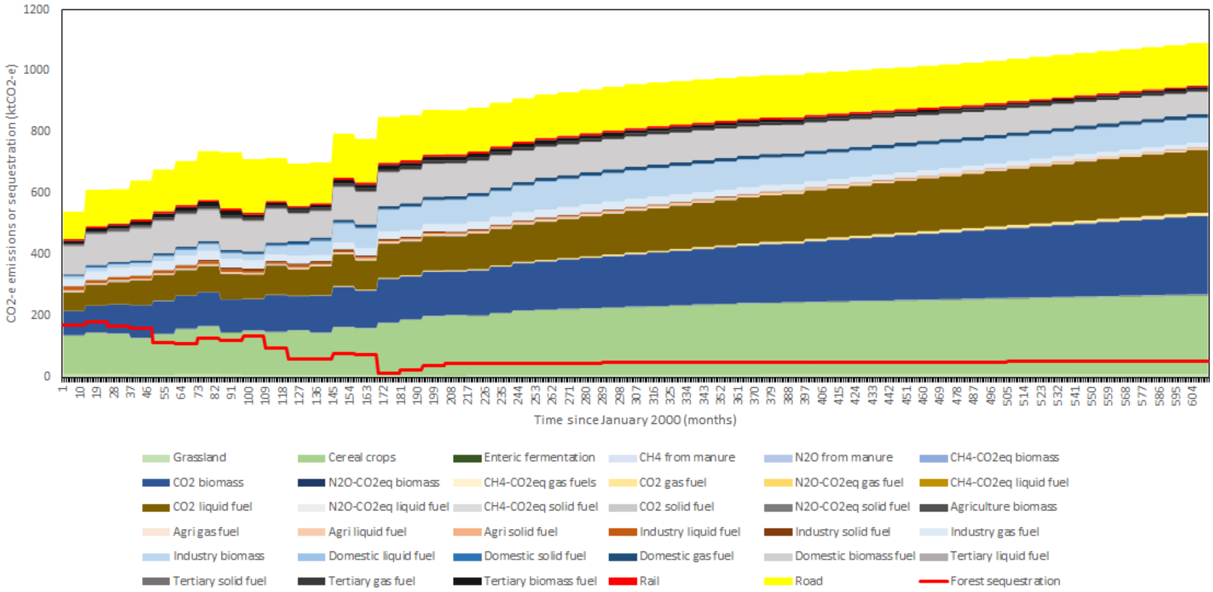

Figure 32: GHG emissions from land use, energy production, energy consumption, and GHG sequestration from forest lands (solid red line) in the Pieriga region of Latvia.

3.5 Sweden case study

3.5.1 Description of the final complexity science model

The Sweden system dynamics model describes the entire country split into three (3) sub-regions within the country. These regions are: north, southwest and southeast Sweden. In each nexus sector, the same (sub-)model structure is used in each geographical region, allowing replicability and consistency of data and result across the regions (allowing for comparable assessment), and also allows for easy scaling up to national totals. As a result of this feature, in the model presentation below, the structure from only one region will be shown, as all other regions are identical in structure, only differing in their data input. The final model consists of 146 variables in total, but with many connections between sectors adding great complexity and depth to the model. The model runs at monthly timestep, starting in January 2000 and ending in December 2050 (i.e. 612 timesteps in total).

Climate is impacted by the land, food, and energy sectors, while water is impacted by changes in the land and population sectors. The energy sector is impacted by changes to the land sector. In addition, population estimates drive demand in the food sector (e.g. food consumption per capita), along with land use values.

3.5.1.1 Population

The population module simply tracks the population of each region in Sweden (Figure 33). These can be summed to give the national total.

Figure 33: the three variables tracking population in each of the three Swedish regions.

3.5.1.2 Water sector

The water sector module calculates a water balance as the difference between supply and demand, and hydropower output is also calculated within this module. On the supply side, the total available water from freshwater resources is given, and added to this is additional water supplied from treated water that is returned to supply for re-use. This returned water comes from industrial, services, and household treated water. In addition, water returned to supply from so-called ‘self-supply’ sources (i.e. private supplies, both industrial and household not connected to the grid water supply) are included in the returned water for re-use. On the water demand side, public drinking water from official supplies is comprised of service water use which is modulated by service use per-capita multiplied by the population, household water used (calculated the same way as service use), and industrial water use, also modulated by industrial water use per capita. The self-supply water demand includes household self-supply use (again population multiplied by self-supply demand per-capita), and industrial and agricultural (split by crops and livestock) water self-supply demand. Finally, industrial use from seawater is also counted in water demand. To calculate hydropower output, the water runoff to the sea (i.e. supply remaining once consumptive demand has been deducted, is multiplied by an average power generation per m^3 runoff. Finally, nitrogen (N) and phosphorus (P) runoff to the sea are calculated as the product of the total amount of fertilisers used and a fraction of available nutrient flushed into water bodies, both of which derive from the land sector, thereby forming a nexus connection. This structure is repeated for all three regions and aggregated to national totals.

3.5.1.3 Land sector

The land sector module computes the area of land utilisation in Sweden split into two broad categories: forests and agricultural land. These are summed to give totals for each region. Within agriculture, arable land and livestock lands are differentiated, and the fertiliser use is also computed. Arable land is composed as the sum of winter and summer wheat, rye, autumn and spring barley, oats, triticale, fodder, food and 'starch' potatoes, sugar beets, autumn and spring rape, forests for energy, grazing grounds, fallow lands and 'other'.

Livestock is also made up of many classes. These include cattle (composed of cows for milk, cows for breeding, calves under one year, and heifers), sheep (composed of rams and ewes, and lambs), pigs (composed of boars for breeding, sows for breeding, large pigs for slaughter, small pigs for slaughter), horses, and chickens (composed of turkeys, chickens for slaughter, laying chickens and hens).

Finally, nutrient application is calculated as the product of the area of a given crop, multiplied with the nutrient (N or P) application in tons per hectare (left in Figure 90). The total application for each crop is then summed to give total nutrient application in each region (Figure 90), which can also be summed to arrive at national totals.

The forest land use sector in Sweden quantifies non-productive, productive, and protected forest land . Productive forest land is further elaborated, and quantifies stand age, and standing volume of five different tree species (lodgpole pine, pine, spruce, birch, other). In addition, for each species of tree, eight age classes are differentiated (0-20, 21-40, 41-60, 61-80, 81-100, 101-120, 121-140, 141-160 years). This yields two calculations: the total productive forest area by species and age, acting as a biodiversity indicator, and the volume of productive biomass in forests. For standing age, the area of each tree species can be broken down by the age distribution of that species, or alternatively, for each age class, the area of different tree species can be ascertained (Figure 93). As with the other sectors, these can be aggregated to the national level, giving total productive forest area, also split area of species in each age class, or by area of different trees within a given age class. In addition, the volume of each tree species felled is also accounted.

3.5.1.4 Food sector

The food sector module in the Swedish case also calculates a balance between supply and demand. On the food production (supply) side, food crops, livestock, and 'other' food are differentiated, while on the demand side the total food consumed, imports, and exports are calculated.

For food crops, winter and spring wheat, rye, potatoes for starch, autumn and spring barley, oats, triticale, fodder crops, food potatoes, grazing land products, autumn and spring rape, sugar beets, and production from energy forests are quantified, using a production per hectare and the total hectares from the land sector.

For livestock, calves, oxen, bulls and heifers, cows, large pigs, horses, lambs, rams and ewes, chickens, turkeys and hens are counted as food production. Other food consists of eggs, milk, sour products, cream, cheese, butter and milk powder, and has the same structure as for food crops.

For local (i.e. Swedish) food consumption, the per-capita consumption of flours and cereals, dairy products, meat products, and eggs are multiplied by the population. These are summed to give consumption per-region, and aggregated nationally.

The imports of flour and cereals, eggs, meats, and dairy products are counted and aggregated to the region and nationally, and the same categories are counted in food exports.

3.5.1.5 Energy sector

The energy sector module likewise calculates a balance between energy supply and demand. Energy production is split into primary energy production and secondary energy production, consisting of electricity and heat generation. Demand is split by fuel type in the household and services, industry, and transport sectors.

For primary energy production the sources are split into those used for heat and energy production. For heat, coal and cokes, oil and petroleum, natural gas, other fuels for heat, electric boilers, heat pumps, and waste heat are differentiated. For electricity, coal and cokes, oil and petroleum, natural gas, other fuels for heat, biomass/fuels/waste, hydropower, wind and solar are differentiated. For the production of heat and electricity itself, electricity combines production in combined heat and power plants (CHP), nuclear, hydropower, wind and solar sources, while heat combines CHP production, waste heat, electric boilers, and heat pumps. The sum of heat and electric combine to make the total secondary energy supply.

For energy demand, the household and services, industrial, and transport sectors are taken into account. In household energy demand, the energy source include oil and petroleum, natural gas, biomass, district heating, and electricity. Each energy type is given as a consumption rate per-capita, and multiplied by the population.

In industry, coal and cokes, oil and petroleum, natural gas, biomass, other, district heating and electricity are the fuel sources accommodated. Because of a lack of other data, industrial uses are scaled by the consumption per-capita, and again multiplied by the population.

Finally, in transport, oil and petroleum, natural gas, biomass, other, and electricity fuels are taken into account. This sector has the same structure as the households and industrial sectors.

3.5.1.6 Climate sector

The climate sector module calculates GHG emissions and sequestration in each Swedish region, and aggregates to the national level as a climate GHG 'balance'. Each of the three regions is separately considered, and accounts for sequestration from land, and emissions from the agricultural, food, and energy sectors.

For GHG sequestration, only sequestration from forest lands is considered. Lodgepole, birch, other, spruce and pine forest total areas are multiplied with a Sweden regional specific forest land sequestration factor per hectare. All tree types are assumed to have the same sequestration potential.

In terms of emissions, in agriculture, the emissions from cattle, sheep, pigs, poultry, horses, and arable land are calculated, where each type is multiplied with a specific emissions factor. In the food sector, all food types described in the Food Sector section are accounted for. In the energy sector, emissions from heat and electricity production, as well as emissions from the transport, household, and industrial sectors are all taken into account. These three sectors (agriculture, food, and energy) are summed to give national level emissions totals.

3.5.2 Description of the final results

3.5.2.1 Population

Region 1 (southeast) shows the largest share pf population, containing Sweden's capital and other major cities in Sweden. The southwestern and northern regions (2 and 3) of Sweden have much lower population shares. In general, a population increase of ~30% from ~9,000,000 to ~ 12,000,000 is expected nationwide. Relatively rapid growth is expected between timesteps 100 and 300, after which population growth rate gradually declines until 2050.

3.5.2.2 Water sector

Surface freshwater by far dominates supply, with the other sources only forming very small proportions of the totals. The supply shows considerable annual variations in the first half of the simulation for when data are available. After time ~ 220 , projections appear to show a historical 'average' supply that is expected to increase slightly over time, possibly a result of climate change impacts.

In terms of national level water demand , industrial self-supply, industrial use of seawater and household public water supply demand are the dominant sectors. Agricultural water demand is very low due to the predominance of rainfed irrigation. Total demand is expected to remain roughly constant over time, the relative proportions of the categories are not expected to change.

For hydropower production, the patter reflects that of water supply, as hydropower production is dependent on water supply. Just as with water supply, after initial variability, the total production is expected to slightly increase over the latter half of the simulation to 2050.

3.5.2.3 Land sector

Younger trees make up the greatest areas, with older trees making up smaller areas for birch trees. The total area of birch trees is expected to remain roughly constant to 2050. Spruce and pine make up the most of the forest volume, with birch and 'others' also making up appreciable standing volumes. The standing volume is expected to increase over time, largely due to increases in the volume of spruce trees.

For agricultural areal makeup, grazing lands and winter wheat are the dominant agricultural land types throughout the simulation. The area of these two crops is expected to remain approximately constant. On the other hand, the area of autumn rape is expected to increase over time while oats are expected to become less important along with spring barley. The total area of agricultural land in region 1 in Sweden is expected to remain roughly constant over time according to simulation results. Similar results are obtained for the other two Swedish regions.

3.5.2.4 Food sector

Production from grazing lands, winter wheat, sugar beets, and fodder (especially towards the end of the simulation) are the most important in terms of mass produced (in tons). Fodder is shown to have the largest growth, while most other categories remain roughly constant over time. Over the course of the simulation, the total food production in this region is expected to increase by about 10% from 2010 values.

Food consumption, imports, and exports in region 1 are dominated by meat consumption, imported flour, and exported dairy products respectively. Food consumption is expected to remain almost constant over time, reflected the moderate population growth rate. Imports are shown to grow somewhat since the levels in 2000 (i.e. the beginning of the simulation), while exports are expected to grow significantly from 2000 values. Indeed, exports are expected to grow about four times by the end of the simulation in 2050. The huge increase in exports could lead to increased revenue for the region, but care should be made regarding having sufficient food for local consumption as well as not polluting water bodies with the nutrients that may be applied to agricultural lands to allow for the increased production.

3.5.2.5 Energy sector

As with the food and land sectors, only results for region 1 are presented, although results are available for all three regions, and nationally. In terms of primary energy production, at the start of the simulation, and until about timestep 410, nuclear energy by far dominates over all other primary fuel sources. However, after this time, nuclear fuel sources play a vanishingly small role in energy production, until by the end of the simulation, there is no primary energy generation from nuclear sources, in line with Swedish policy goals. Biomass is next in terms of energy production. Most worrying is that no other primary fuel source is expected to replace nuclear fuel, leading to a dramatic decline in primary energy production in region 1 by 2050 compared with 2000. Either other fuels must make up the expected deficit (preferably renewable, clean sources), or imports to the region will become increasingly important.

For secondary energy generation in region 1, at the start of the simulation, electricity from nuclear sources is most important, but rapidly declines towards the end of the simulation, reflecting the drop in primary nuclear energy. This leads to an overall drop in secondary energy production in the last quarter of the simulation as the nuclear-based electricity production is not adequately compensated by other means. Heat production from CHP plants is the next most important secondary energy source, and remains so throughout. Encouragingly, electricity from wind and solar sources are expected to increase quite substantially, especially in the second half of the model results, but not sufficiently to compensate for the loss of nuclear electricity. It is suggested that a transition to renewable electricity generation must be accelerated in this region in Sweden.

All three sectors (households, industry, transport) show roughly constant energy demand over time. For households, electricity is the largest energy demand, followed by district heating. The demand for oil and petroleum is expected to reduced almost to zero by 2050. In the industrial sector, electricity and biomass dominate energy demand. As with households, oil and petroleum demand is expected to decline over time. The demand for biomass is expected to slightly increase to 2050. Finally, in the transport sector, oil and petroleum dominates throughout the simulation, although it does reduce slightly as natural gas demand for fuels increases. The demand for transport-related electricity demand remains small over the course of the simulation, contradicting policy goals regarding the electrification of vehicle fleets. Similar results are available for the other Swedish regions, and for Sweden as a whole.

3.5.2.6 Climate sector

For emissions and sequestration in Sweden, while emissions are greater than sequestration throughout the simulation, at the same time, emissions totals are expected to decrease slightly, while sequestration is expected to increase dramatically, possibly due to the increases in forest areas. The energy sector dominates emissions (within which transport emissions dominate over other sectors), with the agricultural sector also an important emitter of GHGs. If transport does become increasingly electrified and this energy is sourced from renewables such as wind and solar, and if better land and forest management can be implemented, then it is possible that emissions and sequestration in Sweden may become equal. At the same time, it is recognised that here, not all GHG emitting sectors were considered, and neither were all sequestration sectors. Therefore, both are underestimated, though it is not known by how much.

3.6 Netherlands case study

3.6.1 Description of the final complexity science model

The SDM was developed for the Netherlands as a whole. There are no regions distinguished in the model. There are five economic sectors distinguished: households, agriculture, transportation, manufacturing industry, services sectors and other sectors. GHG emissions are calculated from different activities in the economy.

The SDM covers a period of 40 years (2010-2050). From 2020 onwards, policy cards can be chosen every five years. The implementation in the game depends on the policy cards. The impacts are calculated at a 5-year basis. The time step in the model is months. The model included 493 time steps (December 2009-December 2050), see Figure 34.

Period	1	2	62	122	182	242	302	362	422	482	493
Month	dec-09	jan-10	jan-15	jan-20	jan-25	jan-30	jan-35	jan-40	jan-45	jan-50	dec-50

Figure 34: breakdown of modelling periods in the NL case study.

In the model, policy goals are formulated for every sector, which are represented by one or more variables. By implementing a policy card, these score variables are affected directly or indirectly, and positively or negatively. In the baseline scenario for 2010-2050 there are no shocks like the Covid19 outbreak. The data for the SDM is retrieved from E3ME, CAPRI, MAGNET and other sources where these models mentioned could not be used (e.g. more detail needed or for aspects not included in the models.

The SDM of the Dutch case consists of six subsystems, which are the five Nexus sectors (land, food, energy, water and climate) and a socio-economic system. The socioeconomic system includes population and economic developments of the four production sectors distinguished. The socioeconomic subsystem is connected to the Land subsystem (demand for build-up areas for housing and infrastructure), energy (energy demand per sector) and Food subsystem (demand for food).

The land subsystem includes different types of land use such as the build-up area, cultivated area for agricultural activities, nature and renewable energy technologies, such as solar power fields and on-shore wind power turbines. The land subsystem is connected to the energy subsystem (available land for renewable energy), food subsystem (available land for agricultural production), climate subsystem (emissions from peat land amongst others) and the water subsystem (water demand of agricultural activities and emissions from agricultural activities).

The food subsystem includes the production of biomass like food crops, fodder crops, energy crops and livestock. Moreover, the food crops also determine the availability of crop residues, and the livestock determines the amount of manure. For convenience, other biomass production is included as well in the food system, such as forestry residues, wastewater, and organic waste from households and public places. The food subsystem connects to the energy subsystem (supply of different types of biomass), the water system (water demand for agricultural production) and climate (non-energy related GHG emissions).

The energy subsystem includes the demand for energy and the supply of energy. The energy subsystem is connected to climate due to the GHG emissions from energy production. In addition, the energy subsystem also includes the biomass demand of the Manufacturing industry as resources for production.

The SDM for the Netherlands considers one geographical unit: the Netherlands. It distinguishes different economic sectors as mentioned above. The land subsystem, the agricultural subsystem and the energy subsystem were developed in more detail.

Below, the subsystems are discussed in more detail.

3.6.1.1 Socio-economic sector

The socioeconomic subsystem includes the developments of the population (Pop) and value added/GDP of the economic sectors agriculture (VA_AGR), manufacturing industry (VA_IND), transport sector (VA_TRA) and service sector including the public sector (VA_OTH), see Figure 3. An indicator is defined to incorporate any differences observed in total value added and GDP (GDP_rest). The value added of the sectors and the GDP_rest sum to total GDP. And the GDP per capita (GDP_CAP) is the GDP divided by population (Pop). GDP and value added are the driving forces of (non-)renewable energy demand, food demand and urban land use.

3.6.1.2 Water sector

The water subsystem has got two subsystems (water emissions and water demand). First, there is the agricultural emissions to water subsystem. In this system, the diffuse sources of nitrogen en nitrous dioxide emissions (e_N_TOT) and phosphorus (e_P_TOT) related to agricultural activities are included. One of the policy objectives of water is to reduce the nitrogen and phosphorus emissions from agriculture to water. The SDM distinguishes a policy target for emission reductions for nitrogen (pol_N_TOT_target) and phosphorus (pol_P_TOT_target) which are compared to the level of emissions in the baseline scenario (e_N_TOT_base and e_P_TOT_base respectively). For the policy objective, there is a score indicator (score_e_N) which reflects the degree of the target achievement. The formulae of the score for the nitrogen emissions is:

$$score\_e\_N = \frac{(\mathrm{e\_N\_TOT\_base} - \mathrm{e\_N\_TOT})}{(\mathrm{e\_N\_TOT\_base} - \mathrm{pol\_N\_TOT\_target})} 100$$

The score for the phosphorus emissions is based on a similar formulae. The score for the achievement of the water quality objective (score_e_water) is defined as:

$$score\_e\_water = \min(\mathrm{score\_e\_N}, \mathrm{score\_e\_P}).$$

Second, there is the agricultural water demand subsystem. Water demand covers water demand from the agricultural and forestry sector. The policy objective is to reduce water demand of the agricultural sector (wd_AGR), where there is set a policy target (pol_AGR_wd_target). The score indicator for the achievement of this policy objective is:

$$score\_AGR\_wd\_reduction = \frac{\mathrm{wd}_{\mathrm{AGR}_{\mathrm{base}}} - \mathrm{wd}_{\mathrm{AGR}}}{\left(\mathrm{wd}_{\mathrm{AGR}_{\mathrm{base}}} - \mathrm{pol}_{\mathrm{AGR}_{\mathrm{wd}_{\mathrm{target}}}}\right)} 100.$$

3.6.1.3 Land sector

The land subsystem considers four main land covers: urban areas, agriculture, nature areas and areas for renewable energy such as on-shore wind power turbines and solar power fields. For the solar power fields, the so-called "solar rural" in the model, we consider it to be an alternative for agricultural activities. Note that solar power options in urban areas, on farms or stables, and near infrastructure do not require additional land, and are not considered in this land subsystem. In particular, we refer to these types of solar power generation as "solar urban", which is part of the energy subsystem.

The agricultural part of the land subsystem is modelled in more detail. First of all, there are three main uses for agriculture distinguished namely i) land for food and fibre, ii) land for energy crops and iii) land for fodder (including land for grazing).

Land for food and fibre

The subsystem of land for food and fibre distinguishes land use for five different groups of food crops namely vegetables and fruits, other high value crops, cereals, sugar beets and potatoes. The sum of areas represents the total land use for food crops (lu_AGR_Food_tot).

The area for cereals (lu_AGR_Food_cereals) are considered to be an indicator of less intensive soil use, which corresponds to the policy objective of sustainable land use, and the objective "Promote nature inclusive farming: crop rotation with less intensive crops". There is defined a minimum area of extensive crops (pol_AGR_extensiveCrops_min) and a target area of extensive crops (pol_AGR_extensiveCrops_target). For a sustainable land use, the area of extensive crops should be increased to the targeted level (pol_AGR_extensiveCrops_target). The current area of extensive crops (i.e. area of cereals for food production) is in the range of the minimum and targeted land area for extensive food crops. The score of the objective "Promote nature inclusive farming: crop rotation with less intensive crops" is:

$$score\_extensiveCrops = \frac{(lu\_AGR\_Food\_cereals - lu\_AGR\_extensiveCrops\_min)}{(lu\_AGR\_extensiveCrops\_target - lu\_AGR\_extensiveCrops\_min)}$$

The higher the area cereals the higher the score will be as the target is constant. Vegetables and other food crops are high-value crops in agriculture, which contribute to a viable agricultural sector. The area for vegetables (lu_AGR_Food_veg) and other food crops (lu_AGR_Food_Other) sum to the total area of high value crops, which reflects the indicator of the policy objective "viable agricultural sector". There is a minimum area of high-value crops (pol_AGR_HVcrops_min) and targeted area of high-value crops (pol_AGR_HVcrops_target). For a viable agricultural sector, the area of high-value crops need to be increased to the target area (pol_AGR_HVcrops_target). The current area of high value crops is in the range of the minimum and targeted land area for high-value crops food crops. The score of the objective "Promote nature inclusive farming: crop rotation with less intensive crops" is:

$$score\_HVcrops = \frac{(lu\_AGR\_Food\_veg + lu\_AGR\_Food\_other - lu\_AGR\_HVcrops\_min)}{(lu\_AGR\_HVcrops\_target - lu\_AGR\_HVcrops\_min)}$$

Land for fodder

The land for fodder distinguishes three main types of land use namely i) grass land (lu_AGR_Fodder_grassTot), ii) land for maize (lu_AGR_Fodder_maize) and iii) land for other fodder crops (lu_AGR_Fodder_other). For grass land, there is also a distinction between the three different soil types because these soil types have different impacts across Nexus sectors. Grass on peatland (lu_AGR_Fodder_grassPeat), for instance, has larger GHG emissions as the consequence of subsidence in periods of droughts. Grass on sandy soils (lu_AGR_Fodder_grassSand) requires irrigation in an earlier stage than grass on clay soils ((lu_AGR_Fodder_grassClay). In the SDM, the area of grass land is proportional to the herd size of cattle.

3.6.1.4 Food sector

The food subsystem consists of two main (non-food) subsystems: the agricultural production of food, fodder and energy crops, and the food consumption/food demand. Supply and demand of animal-based and plant-based proteins are balanced. If there is more supply than demand, part of the production is assumed to be exported. If there is less supply than demand, there is assumed that these proteins are imported.

From a food perspective, the food production and food consumption are measured in proteins and caloric intake. Agricultural food production includes livestock production (fp_livestock_cal and fp_livestock_protein) and crop production (fp_crops_cal and fp_crops_protein). From an agricultural perspective, agriculture non-food production includes fodder production which is input for livestock production, see Figure 130, and energy crop production which is input for the energy production, see the energy subsystem. Additionally, the food crop production can also produce crop residues that are used for energy production, see Figure 130. In addition, the production of biomass from forests are also part of the production part of the food subsystem.

The demand for food is measured in proteins en caloric intake. The demand for food is measured in the daily consumption of proteins from animals (d_protein_animals) and plants (d_protein_plant) in the baseline scenario. Based on those protein sources, the share of plant-based proteins in the diets (score_protein_plant) can be calculated (see Sector 3). One of the policy objectives for food is to increase the share of plant-based proteins in the diet.

3.6.1.5 Energy sector

The energy subsystem includes the energy production and the energy consumption. Throughout the energy subsystem, there is a distinction between renewable energy (RE) and non-renewable energy (NRE). In the energy subsystem, there is assumed the energy users demand for RE and NRE separately. There are demands for renewable energy of households (ed_DOM_RE), agriculture (ed_AGR_RE), transport sector (ed_TRA_RE), manufacturing industry (ed_IND_RE) and the service sector (ed_OTH_RE), see Figure 131. Similarly, there are demands for non-renewable energy of households (ed_DOM_NRE), agriculture (ed_AGR_NRE), transport sector (ed_TRA_NRE), manufacturing industry (ed_IND_NRE) and the service sector (ed_OTH_NRE).

For the energy production, there are nine main energy sources distinguished; 5 renewable energy sources 4 non-renewable sources. The renewable energy sources are wind power (se_Wind_tot), solar power (se_Solar_tot), small-scale biomass (se_biomass), large-scale biomass (se_import_RE) and other renewable energy sources (se_RE_other). The category "other renewables" include new energy sources like hydrogen, geothermic power etc.. The small-scale biomass for energy consists of 6 subcategories namely manure, waste water, energy crops, crop residues and organic waste from private sources (organic waste from households) and public sources (organic waste from public locations, such as municipal waste, waste from road sides or water ways). The small-scale sources of biomass are mainly from Dutch origin. The non-renewable energy sources are coal (se_coal), natural gas (se_gas), oil (se_oil), and nuclear energy (se_nuclear).

Below, the subsystems of the energy subsystem will be discussed in more detail.

Energy demand/consumption

Within the economic sectors, the main drivers of the energy demand are the price levels of energy and the intensities of renewable and non-renewable energy. Based upon the domestic sector, the structure of the demand systems are explained.

The demand for renewable energy is determined by the multiplication of the energy intensity of renewable energy (ei_DOM_RE) and the population (Pop) from the socioeconomic subsystem. the renewable energy intensity is based upon the renewable energy intensity in the baseline scenario (ei_DOM_RE_base) and the change in the renewable energy intensity (cei_DOM_RE). This renewable energy intensity is determined by the following indicators:

- The price changes in the renewable energy price (p_RE);
- The non-renewable energy price (p_NRE);
- The price changes in the renewable energy price (p_RE_base);
- The non-renewable energy price (p_NRE_base);
- Price elasticity of the renewable energy demand (pel_DOM_RE);
- The cross-price elasticity of the non-renewable (cpel_DOM_RE-NRE) and
- The renewable energy intensity in the baseline scenario (ei_DOM_RE_base).

The formulae for the calculation of the change of the renewable energy intensity (cei_DOM_RE) is:

$$\text{cei\_DOM\_RE} = (\text{p\_RE} - \text{p\_RE\_base}\,)\,\frac{\text{pel\_DOM\_RE}}{\text{p\_RE\_base}}\,\text{ei\_DOM\_RE\_base} + (\text{p\_NRE} - \text{p\_NRE\_base}\,)\,\frac{\text{cpel\_DOM\_NRE}-\text{RE}}{\text{p\_NRE\_base}}\,\text{ei\_DOM\_RE\_base}+$$

The demand for non-renewable energy is determined in a similar way. It is the multiplication of the energy intensity of non-renewable energy (ei_DOM_NRE) and the population (Pop) from the socioeconomic subsystem. the non-renewable energy intensity is based upon the non-renewable energy intensity in the baseline scenario (ei_DOM_NRE_base) and the change in the non-renewable energy intensity (cei_DOM_NRE). This non-renewable energy intensity is determined by the following indicators:

- The price changes in the renewable energy price (p_RE);
- The non-renewable energy price (p_NRE);
- The price changes in the renewable energy price (p_RE_base);
- The non-renewable energy price (p_NRE_base);
- Price elasticity of the renewable energy demand (pel_DOM_NRE);
- The cross-price elasticity of the non-renewable (cpel_DOM_NRE-RE) and
- The renewable energy intensity in the baseline scenario (ei_DOM_NRE_base).

The formulae for the calculation of the change of the renewable energy intensity (cei_DOM_NRE) is:

$$\text{cei\_DOM\_NRE} = (\text{p\_NRE} - \text{p\_NRE\_base}\,)\,\frac{\text{pel\_DOM\_NRE}}{\text{p\_NRE\_base}}\,\text{ei\_DOM\_NRE\_base} + (\text{p\_RE} - \text{p\_RE\_base}\,)\,\frac{\text{cpel\_DOM\_RE}-\text{NRE}}{\text{p\_RE\_base}}\,\text{ei\_DOM\_NRE\_base}.$$

The renewable and non-renewable energy demand for agriculture, transport, manufacturing industry and the service sector sectors are determined in a similar way. The only difference is that the energy intensities for those sectors are determined with the value added of the sectors (from the socio-economic subsystem).

Small scale biomass for energy

There are 6 sources of small-scale biomass for energy distinguished: energy crops (_EC), crop residues (_CR), manure (_manure), organic waste of households (_organic_private), organic waste from public places and infrastructure (_organic_public) and waste water (_WasteWater). For all type of biomass, there is a potential (or theoretical) amount of energy based (pe_*) based on the physical input and the energy coefficient of the biomass (caf_*). For instance, the potential energy of energy crops (pe_EC) is determined by the available production of energy crops in dry matter (d_EC_tot) and the energy coefficient of energy crops (caf_EC).

Based on the potential energy and the energy efficiency coefficient of the biomass type (eec_*), the available energy (se_*) is calculated. For instance, the available energy from energy crops (se_EC) is

$$se\_EC = \frac{pe\_EC \ \cdot eec\_EC}{100}$$

For energy crops, there is also allowed to be imports of imputs (dm_EC_import). The total amount of available energy from small scale biomass is se_biomass.

Large scale biomass

The large-scale biomass is the biomass derived from timber on a large scale. Most of this woody biomass is imported (av_biomass_import) and a small fraction is produced in the Netherlands (pr_biomass_Forest). With the total available woody biomass (av_biomass), the first step is to fulfil the demand for woody biomass of the manufacturing industry (bd_IND_non-energy), so that the remaining biomass can be used for energy production (av_biomass_re). With the energy coefficient for woody biomass (caf_import_RE), the total amount of potential energy (pr_RE_biomass) is determined.

3.6.1.6 Climate sector

The climate subsystem reflects the GHG emissions from the whole system. As mentioned above, GHG emissions are calculated from different activities in the economy. It includes GHG emissions from energy production, GHG emissions not related to energy production from different economic sectors (transport, industry, domestic and other) and agricultural GHG production related to agricultural activities (forest, peatland, livestock and crops).

3.6.2 Description of the final results

3.6.2.1 Socioeconomic sector

The socioeconomic subsystem consists of two aspects: population and income per capita and value added and GDP of the economic sectors. These indicators are drivers for development in energy demand (energy subsystem), food demand (food subsystem), and land (urban areas for living purposes). There are no policy objectives for the indicators in the socioeconomic subsystem.

Population development is derived from recent statistics from Statistics Netherlands. Population (Pop) grows from 17.6 million in 2010 to 19.3 million in 2050. Gross domestic product per month (GDP) is derived from the baseline scenario results of the E3ME model and grew from 83.0 bn euro per month in January 2010 to 135.7 bn euro per month in December 2050, see right panel of Figure 136. It is used to calculate the GDP per capita per month (GDP_CAP) grows from € 5,050 in January 2010 to almost € 7,000 in December 2050 in the baseline scenario, i.e. . € 60,600 in 2010 and almost € 72,000 in 2050.

In the SDM, there are four economic sectors distinguished. The development of the value added is derived from the E3ME baseline scenario results.

The value added of service sector increased from 29.9 bn euro in January 2010 to 50.5 bn euro in December 2050. The manufacturing industry had the second highest value added, see Figure 138. In January 2010, value added of the transport sector amounted 1.21 bn euro and increase to 2.14 bn euro in December 2050. For agriculture, the value added in 2010 amounted 0.79 bn euro and it increased to 0,.87 bn euro in December 2050.

3.6.2.2 Water sector

The water system in the SDM is included in an indirect way: agricultural water demand and emissions of nitrogen to water. The water system could be modelled in much more detail, but that falls outside the scope of the SDM to model the NEXUS.

The water demand for crops i.e. irrigation (wd_crops) and for livestock (wd_livestock) is within the same range. The water demand for livestock is gradually declining due to the decline in livestock.

Nitrogen and phosphor emissions to water from agriculture amount 46.8 million kg N in 2010 and 3.9 million kg P in 2010. It is assumed that the emissions are proportional per month, the nitrogen and phosphor emissions to water from agriculture amount 3.0 million kg N per month in 2010 and 0.325 million kg P per month in 2010 (see https://www.clo.nl/indicatoren/nl0192-belasting-van-oppervlaktewater-met-vermestende-stoffen?ond=20880, checked on April 30, 2020).

The general policy goal is sustainable use of water resources. Two policy sub-objectives included in the SDM address emissions of nutrients to water from agriculture and water demand. The policy objective is to reduce water demand to zero (pol AGR wd target). Water demand in the base-run is higher as compared to calculated water demand.

The overall objective of the Nexus sector Water is calculated as the average of the scores for agricultural water demand reduction and the emission reduction.

3.6.2.3 Land sector

In the land subsystem, there are four land uses distinguished namely land for agriculture (lu_AGR_Tot), land for urban areas including the road infrastructure (lu_URB), land for nature (lu_NAT_TOT) and land for renewable energy (lu_RE_TOT). Agriculture covers almost 2 mn ha in 2010, and it was gradually reduce towards 2050. Agriculture land is transformed into urban areas and natural areas. Current trends for transforming agricultural land into solar power fields are limited in the current policy. On shore wind turbines make the use of agricultural land also less productive, but the impact in terms of surface areas is very low.

The urban areas were expected to increase in the period 2010-2050. This is partly due to the increase of population, see the section on the socioeconomic subsystem, but it is partly compensated by more efficient use of area per person. The area per 1 mln people gradually decreased from 36,300 ha in January 2010 to 34,600 ha in December 2050.

Land use for renewable energy remains relatively unimportant as compared to other types of land-use. However, this does not reflect changes in the value of landscapes because of new and large wind turbines. This aspect is not included in the SDM. In the base-run, solar fields are not yet included.

Land for fodder (grassland and maize) is decreasing in the base-run. The area for food and fibre is relatively stable and finally land use for energy crops is limited in the baseline scenario.

In the SDM 5 categories of crops are distinguished: cereals, vegetables, potatoes, sugar beet and other crops. Non-food crops are included in the other category.
The area for vegetables increases (lu AGR Food veg) where the area for cereals decreases slightly (lu AGR Food cereals). There is an intensification of landuse. The other areas remain stable. The increasing area for vegetables will lead to a large demand for water

In the baseline scenario, the area maize land decreases where grassland (lu_AGR_Fodder_grassTot) and other fodder crops remain more or less stable. Three soils types for grassland (clay, peat and sandy soils) are distinguished because of the differences in GHG emissions. Especially, peat land is important in (policy) debates because of GHG emissions and water related impacts.

For nature, there are three types of land for nature distinguished, namely forest land for biomass production (lu_NAT_forestB), land for non-biomass production(lu_NAT_forestN), and land for non-forest nature ((lu_NAT_non-forest) like meadows, protected in-land water ways for instance. The non-biomass forests covered approximately 350,000 ha, and the area for non-forest nature amounted almost 160,000 ha. There is only a small share of land dedicated to forest for biomass production. In the baseline scenario, there will not change much in the area of land for nature.

To get insight in the extend policy objectives are already met in the baseline scenario we will discuss the policy objectives for maintain or increase protected natural areas and to increase the share of less intensive crops. We will show that those objectives are not yet met in the baseline scenario.

Nature
In the base-run, the policy goal for protected natural areas increase only a little bit due to policy plans or the next 10 years. To achieve this goal changes additional policies will be needed.

3.6.2.4 Food sector

Demand and supply measured in kg protein per capita per day are central. Supply is split in proteins from livestock and plants to be able to include a transition towards consumption of plant proteins. The paragraph will be closed with a discussion of the policy goals.

Already in the baseline scenario, protein consumption from animal sources is decreasing . Consumption per capital per day of proteins from plants is stable.

The total production of protein from cattle decreases were the consumption from poultry increases in the baseline scenario.

From the different areas for crops the total protein production is calculated. It follows that the production of plant-based protein is relatively stable in the baseline scenario. Consumption will also depend on the import and export of protein.

In the baseline scenario, the policy objective for plant-based diets is already partly met (score_protein_plant). However, additional policies are needed to meet the objective of a transition to more plant-based diets.

In the baseline scenario, the policy goal on high-value crops increases already in the baseline scenario. However, more is needed to achieve this policy goal.

3.6.2.5 Energy sector

Energy demand/consumption is driven by population for the domestic sector and by value added for the other economic sectors. There are two types of energy demand distinguished: renewable energy and non-renewable energy. In the baseline scenario derived from the E3ME result, the non-renewable energy demand/consumption dominates the renewable energy demand/consumption throughout the whole period, although the non-renewable energy demand/consumption gradually declined from 319 PJ in January 2010 to 252 PJ in December 2050. The renewable energy demand/consumption gradually increased for most of the period to almost 60 PJ in December 2050.

For all sectors, non-renewable energy demand is much larger than the demand for renewable energy. For most sectors, there was an increasing trend for renewable energy demand though. The non-renewable energy demand in the manufacturing industry (ed_IND_NRE), service sector (ed_OTH_NRE) and domestic sector (ed_DOM_NRE) remained constant while it declined for the transport sector (ed_TRA_NRE) and the manufacturing industry including the energy sector).

The wind power (se_Wind_tot) generation showed the largest increase mainly due to the construction of large off-shore wind power parks. The energy generation from small-scale biomass in the Netherlands (se_biomass) was the largest renewable energy source, and it grew but not as fast as wind power. The solar power generation (se_solar_tot) increased gradually due to increase of solar power capacity in urban areas and due to construction of solar power fields in urban areas. Large-scale biomass represent timber residues which are mainly imported from European or North-American timber exporting counties and it is used for cogeneration in coal-fired power plants or specific biomass power plants to generate electricity and heat. The large-scale biomass (se_import_RE) remained constant over time in the baseline scenario.

As mentioned above, the small-scale biomass for energy consists of six subcategories. The energy from private organic waste (se_organic_private) and from public organic waste (se_organic_public) are the largest within the small-scale biomass category. Both indicators increase over time, because they are positively connected to the population development (Pop). The energy from energy crops (se_EC), crop residues (se_CR), manure (se_manure) and waste water (se_WasteWater) are small. In the case of generating energy from manure and waste water, there are technological innovations in progress or present experiments, but these technologies were not implemented at a larger scale yet.

The main energy sources in the Netherlands are still natural gas (se_gas) and oil (se_oil). Coal use is gradually banned in the baseline scenario, although current policy practices might indicate a faster process of closing coal-=fired power plants in 2024-2030 in the Netherlands. The energy source nuclear remains constant over time. The date of closing the single nuclear power plant in the Netherlands is extended.

In the previous section, large-scale biomass was discussed. In the SDM, there is another demand for biomass by the manufacturing industry, so that they can transform towards a bio-based industry. As a result, the demand for large scale biomass from the manufacturing industry (bd_IND_non-energy) was included in the model. Since we assumed that the import of timber residues was constant, the available timber residues for energy production (declined). As a consequence, the energy generated from biomass (pe_RE_biomass) also declines, see the right panel of Figure 164.

For the nexus sector energy , there are two policy objectives which are reflected in to score indicators: share of renewable energy and the share of sustainable biomass use. The policy objective of renewable energy is to increase the share of renewable energy to a share of 90 %. In the baseline scenario, the share of renewables increase gradually, which is caused by a gradual but modest increase of demand for/production of renewable energy on the one hand, and a reduction of the demand of non-renewables energy on the other hand. Note that we assumed that the reduction of energy per capita is fully translated in the reduction of the demand for non-renewable energy.

The policy objective is the sustainable use of biomass, and we assumed that the use of timber biomass is more sustainable than the use of it for energy generation. Based on the available biomass from timber residues, the sustainable use of biomass is 15 % in 2010 and more than 20% in 2050. The objective is to increase the share to a maximum of 100%.

3.6.2.6 Climate sector

The climate subsystem reflects the GHG emissions from the whole system. It includes GHG emissions from energy production, GHG emissions not related to energy production from economic sectors and agricultural GHG emissions related to agricultural activities. The climate policy goals towards a low carbon economy address a 95% reduction of non-agriculture GHG emissions in 2050 and a 95% reduction of total GHG emissions from agriculture.

The thematic models needed to be supplemented with (sometimes more detailed) data from other sources as for the parts on energy and non-agricultural land use (e.g. nature areas).

Agricultural emissions are classified into 4 categories: emissions from peatland, emissions from livestock, emissions from corps and emissions from forests. Emissions from livestock are the most important category. Figure 168 shows that in the base-run emissions from agriculture remain more or less stable until 2050. Only GHG emissions from livestock decrease in this period.

The low-carbon economy links to climate policy and focusses on a 95% reduction of total non-agricultural and agricultural GHG emissions in 2050. The link to corresponding policies is strong: energy, agriculture and food, waste, nature, spatial planning and water. Policy objectives on a viable agricultural sector and healthy population (food) and sustainable land use are added as policies to be investigated. Non-agricultural GHG emissions decreased relatively mores as compared to the agricultural emissions. Non-agricultural GHG emissions decreased much more as compared to agricultural GHG emissions.

3.7 Greece case study

3.7.1 Description of the final complexity science model

The Greek case study (CS) SDM includes five modules/sub-models, one for each nexus component—Water, Energy, Food, Land Use and Climate. Definitions of the five nexus components in the context of the Greek CS are included in Laspidou et al. (2018). The modules use spatial and statistical datasets to quantify the interlinkages among components and estimate the water, energy, agricultural production and GHG emissions of different land uses and of the built environment, comprising population and tourists. A description of the five modules of the SDM is summarized below. All data and figures presented in this study are published in Mellios and Laspidou (2020) and Laspidou et al (2020).

3.7.1.1 Water sector

To ensure that the uneven distribution of water resources in the country is captured the SDM model is subdivided and modelled in 14 River Basin Districts (RBDs) (Figure 35).

Figure 35: Greek CS SDM disaggregated into 14 sub-domains

This was proven to be a valid approach, especially when taking hydrologic balances, since RBDs offer boundary conditions, i.e. they are more or less hydrologically independent. For each RBD, all water demands are mapped—public water supply covering household and commercial water uses, irrigation, and livestock, industrial and cooling water for thermoelectric power plants.

A further distinction on all water demand categories is done between surface water and groundwater sources. Negative deficits in water-scarce RBDs with aquifers that are heavily exploited by agriculture, e.g., Thessaly (GR08), can now be seen in the model and the effect of different policies and water use or Nexus scenarios can be evaluated. Figure 36 shows a schematic representation of the water module where all water demands are mapped; out of all demands, urban, industrial and cooling water are associated with the built environment. Nexus interlinkages of the water sector with other sectors are also shown: Energy is needed for pumping, Cooling Water is needed for Power Generation, Irrigation and Livestock Water lead to Food Production and Wastewater treatment leads to GHG (GHGs) emissions.

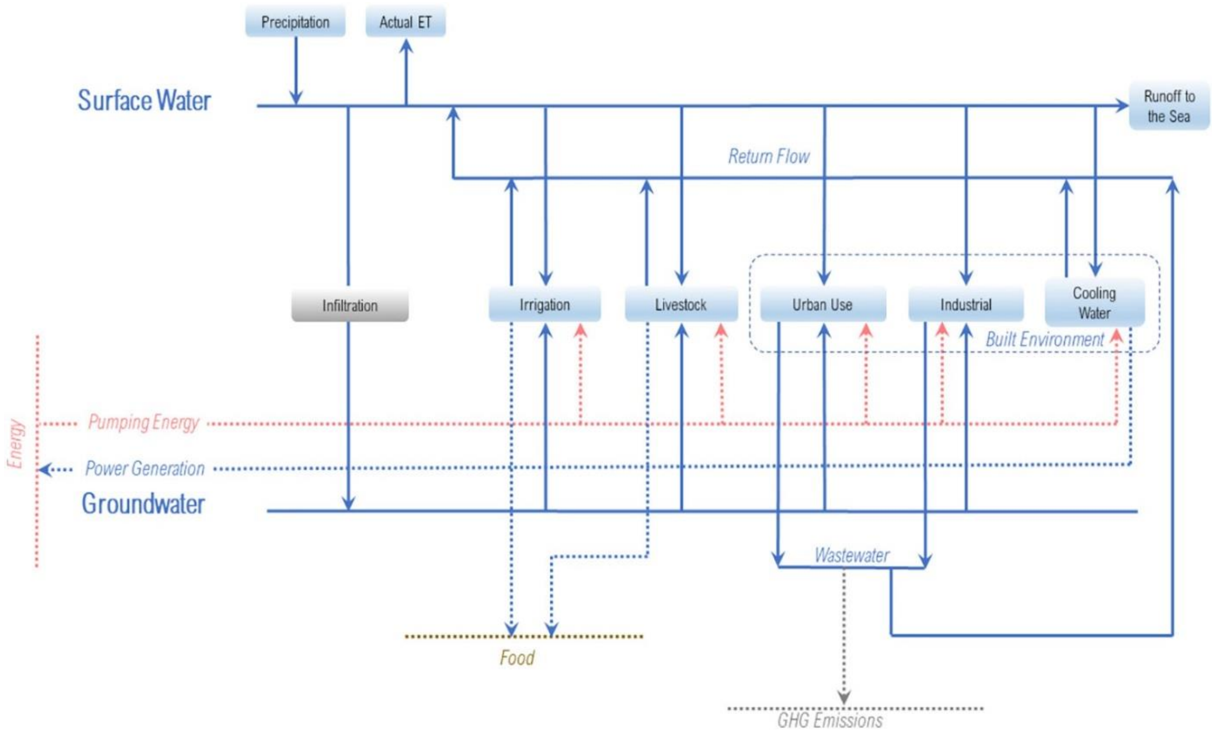

Figure 36: The Water module for the Greek CS SDM

Data originate from a series of databases and are worked through algorithms to produce spatio-temporally disaggregated results, i.e., monthly values for each RBD. In the Greek CS SDM, input data come from published databases along with model outputs, information form the literature and computational results from calibration, or from data mapping and aggregating/processing via Geographic Information System (GIS) software. Combining all this information culminates to the calculation of Nexus Interlinkage factors, which reduce all quantities on a “per unit” basis, such as an “urban water-use per capita & tourist”. As shown in Figure 37, Eurostat provided all water demands per RBD for groundwater and surface water, while current population and projections were provided by thematic model E3ME-FTT (https://www.e3me.com/). To quantify pressures from human consumption, population data was combined with data on tourism in Greece, obtained from the Association of Greek Tourism Enterprises (https://sete.gr/). Monthly data for year 2010 for tourist overnight stays was mapped to all RBDs using Geographical Information System (GIS) software; when added to permanent population (assumed to remain constant throughout the year), a total human population was produced that varied in space and time, per RBD and per month, respectively. To calculate the Nexus Interlinkage factor “urban water use per capita & tourist”, the Greek CS SDM takes (i) permanent population from E3ME, (ii) tourists from SETE, (iii) water consumption per tourist from the literature [Goessling et al., 2012] and (iv) performs calibration to calculate the Interlinkage factor in order to match the total RBD-level urban water use reported by ELSTAT.

An important dataset was provided by the Hellenic Electricity Distribution Network Operator (DEDDIE) (https://deddie.gr/), which included a monthly electricity consumption set for 2010 for all municipalities in Greece for different sectors (urban, industrial and agricultural). Using GIS software, municipality data was aggregated to RBD level and then the produced data set (DEDDIE dataset) was used to produce four different monthly "activity profiles"— industrial activity, agricultural activity, urban activity and total electricity use profile. These profiles distribute the yearly activity across all months and allow for the temporal disaggregation of yearly values for not only energy but also for water, since energy consumption patterns can be used as proxy for water consumption patterns. Industrial water is expressed as water per industrial plant capacity. All industrial plants are obtained by ELSTAT and mapped in the RBDs. The corresponding Nexus Interlinkage factor "industrial water use per industrial plant capacity" is derived by using RBD-level plant capacity, industrial water use (EUROSTAT) and industrial activity profile (DEDDIE), as shown in Figure 37.

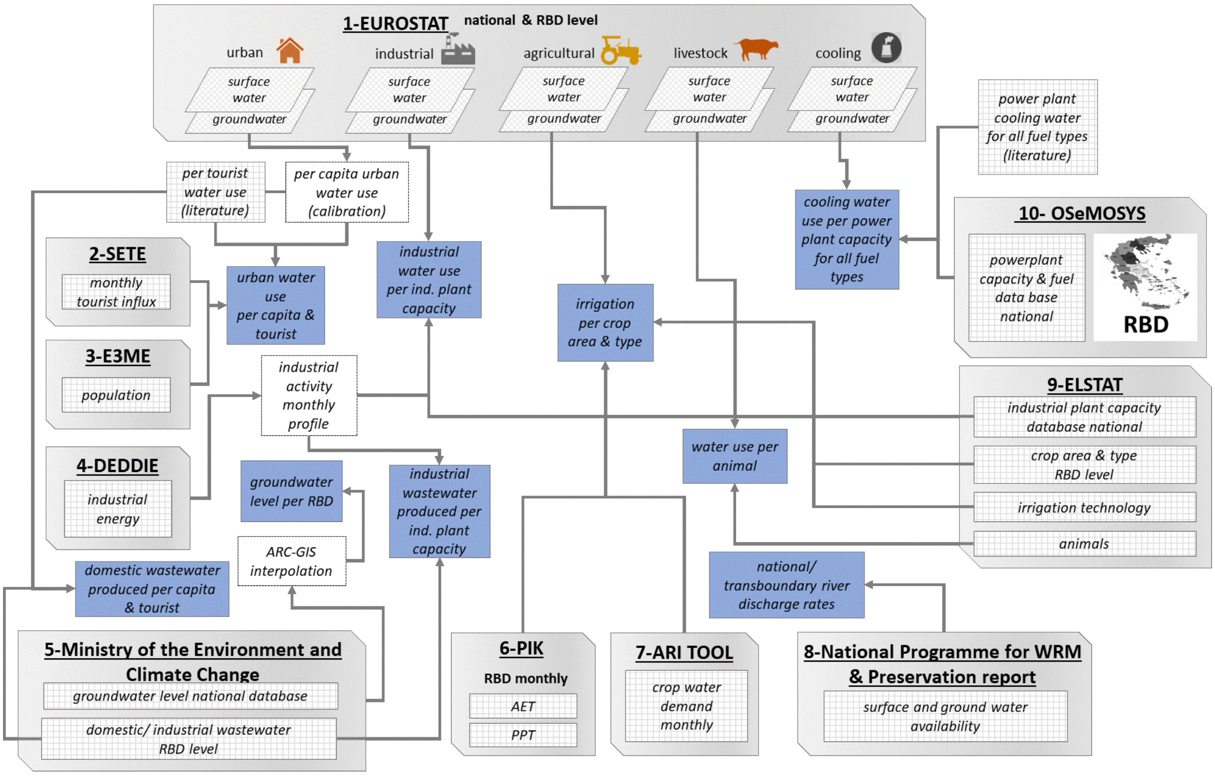

Figure 37: Data sources and data processing in the Greek CS SDM for the Water Module: Computational steps are shown in white boxes; Input data from published databases, model outputs, or the literature are shown in hatched boxes; Nexus Interlinkage factors for the Water sector are shown in blue boxes.

Water availability on surface water and groundwater is mapped on each RBD with data from the National Programme for Water Resources Management and Preservation [Koutsogiannis et al., 2008], while parameters such as river flows, transboundary water bodies, groundwater infiltration rates and outflow to the sea also come from Koutsogiannis et al. (2008). A series of groundwater level values for 2010 were obtained from the Ministry of the Environment and Climate Change and provided several values per RBD, which were aggregated to a single "groundwater level value per RBD" with Thiessen polygon analysis. Depending on aquifer level, all groundwater demands exert a corresponding pumping energy demand (a Water-Energy Nexus interlinkage). Modeling the hydrological cycle as a whole includes a climate dataset provided by Potsdam Institut Klimatologie (PIK), which provides regional climate change projections for Greece within the timeline of the Fifth Assessment Report (AR5) and beyond at a spatial resolution of EUR-11: 0.11° (12 km). The relevant climate model used is the GFDL-ESM2M. For the calculation of actual evapotranspiration (ETa), the thematic model SWIM is used. SWIM is spatially discretized by hydrotopes, areas characterized by unique combinations of soil profiles, distance between soil surface and groundwater level, land use, crop rotation (if agriculture), elevation, and sub basin allocation. According to the daily meteorological variables, potential ET (ETp) is calculated at the individual locations of the hydrotopes. This is the first step and is based on a Turc-Ivanov approach with monthly tuning factors. In a second step, ETa is derived from ETp for the two components soil evaporation and plant transpiration in an approach similar to Ritchie [1972]. The hydrological cycle is modeled as follows: precipitation and actual evapotranspiration are mapped on RBDs as input (a single value per RBD calculated from given spatial resolution using Thiessen polygons); for each time step, surface and ground water balances are calculated using precipitation, evapotranspiration, aquifer recharge, return water, wastewater recharge and runoff to the sea, while exerting demands on surface and groundwater by all sectors.

A detailed power plant dataset was based on the OSeMOSYS dataset (www.osemosys.org), allowing the mapping of all power plants in Greece into the 14 RBDs along with their capacities and fuel type. The following fuel types were listed: coal, oil, gas, biomass and combustible waste, as well as the renewables wind, hydropower and solar for the production of electricity. Cooling water use per RBD is combined with the mapped power plant capacity and with power plant cooling water factors from the literature for different fuel types [Spang et al., 2014] to generate the Nexus interlinkage factors “cooling water use per power plant capacity for all fuel types”. Wastewater treatment plants were also mapped in the RBDs (http://astikalimata.ypeka.gr/, data from the Hellenic Ministry of the Environment and Climate Change), along with their discharge rates (m3/month) and discharge location (sea, or adjacent freshwater body). Wastewater data are differentiated for urban and industrial uses, producing corresponding Nexus interlinkage factors for the two waste streams. Agricultural water demand was computed from a variety of sources, including historical irrigation data for typical irrigated crops in the region and statistical data (ELSTAT; Agricultural Research Institute (ARI), 2019) [Mellios et al., 2018]. Datasets were calibrated to match reported crop areas and types and agricultural water demand for base year 2010 and the Nexus Interlinkage factor “irrigation per crop area and type” was obtained (Figure 38). In a similar way, livestock water is modeled via the “water use per animal” interlinkage factor. In Figure 38 the WATER SDM module is shown.

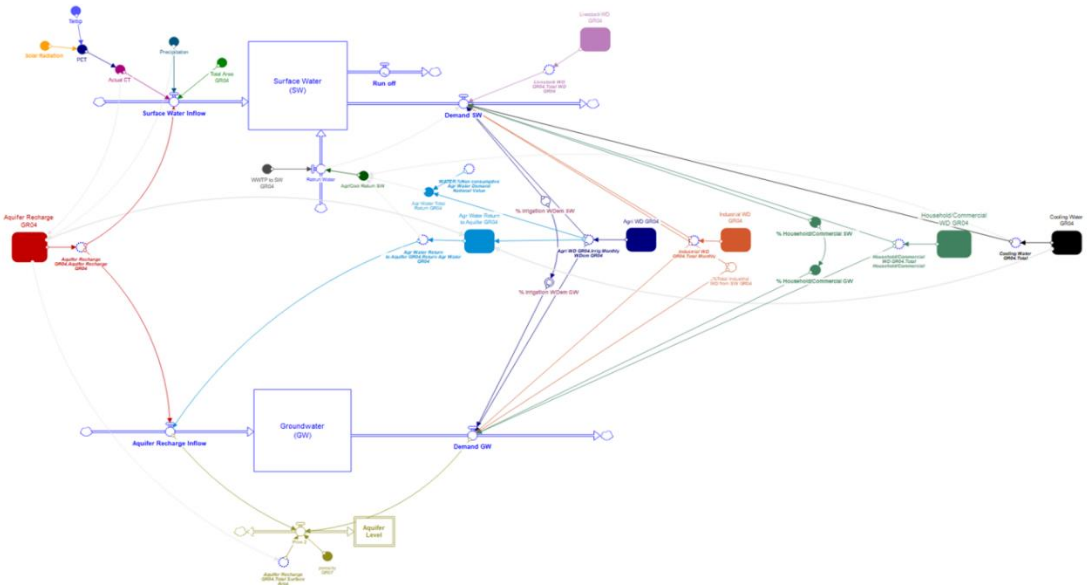

Figure 38 Greek CS SDM Water module in STELLA

In Figure 39 indicative screen shots for WATER SDM module for RDB 1 is shown.

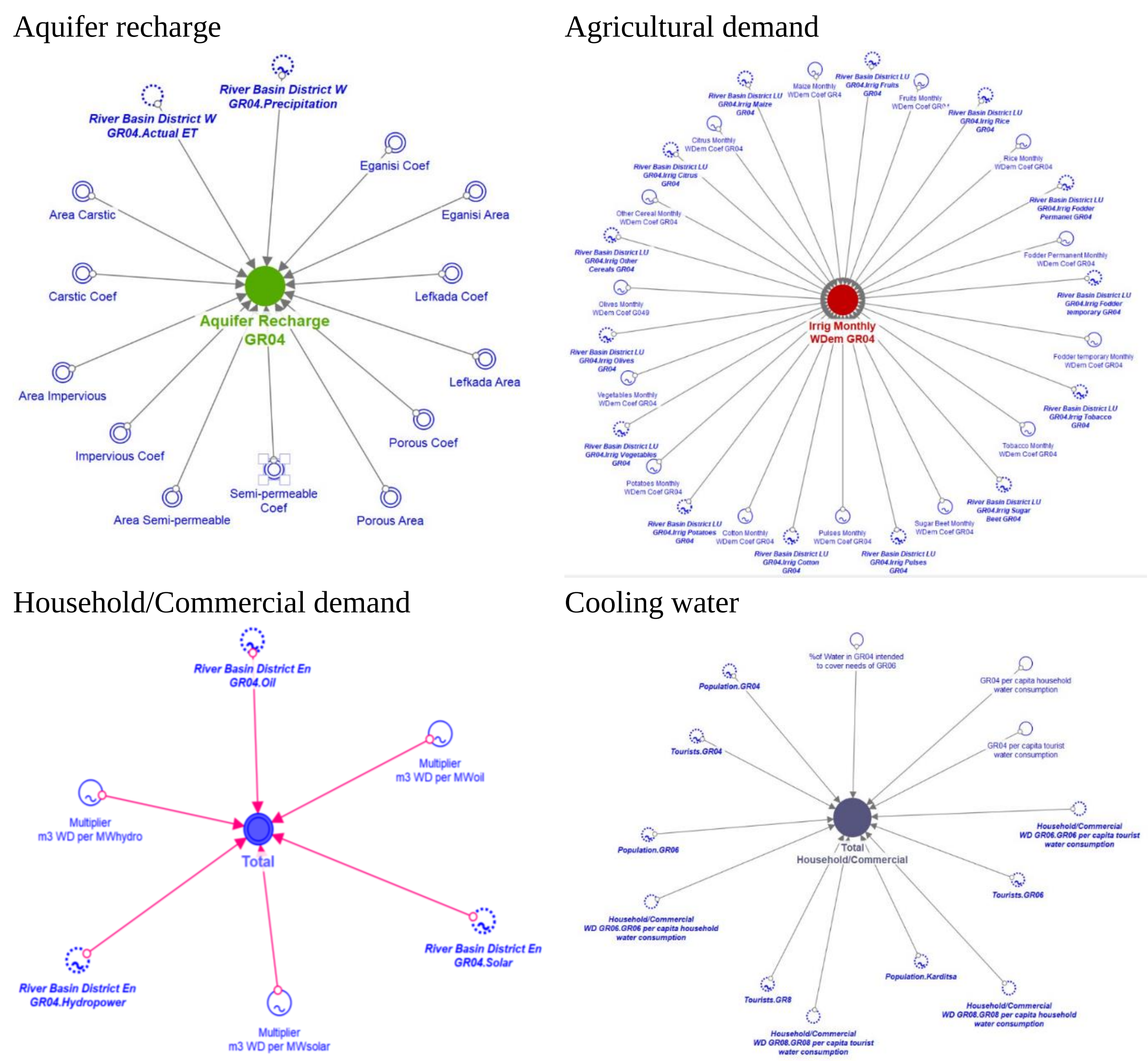

Figure 39: Indicative screenshots for RBD1 (Water Module)

3.7.1.2 Land sector

Land use is divided in Agricultural (includes Cropland and Livestock Area), Forest, Wetland, Grassland and Artificial Area (Built Environment), as shown in Figure 40. Interlinkages with the Climate Sector also shown -specifically emissions related to Land Use, Land Use Change and Forestry (LULUCF).

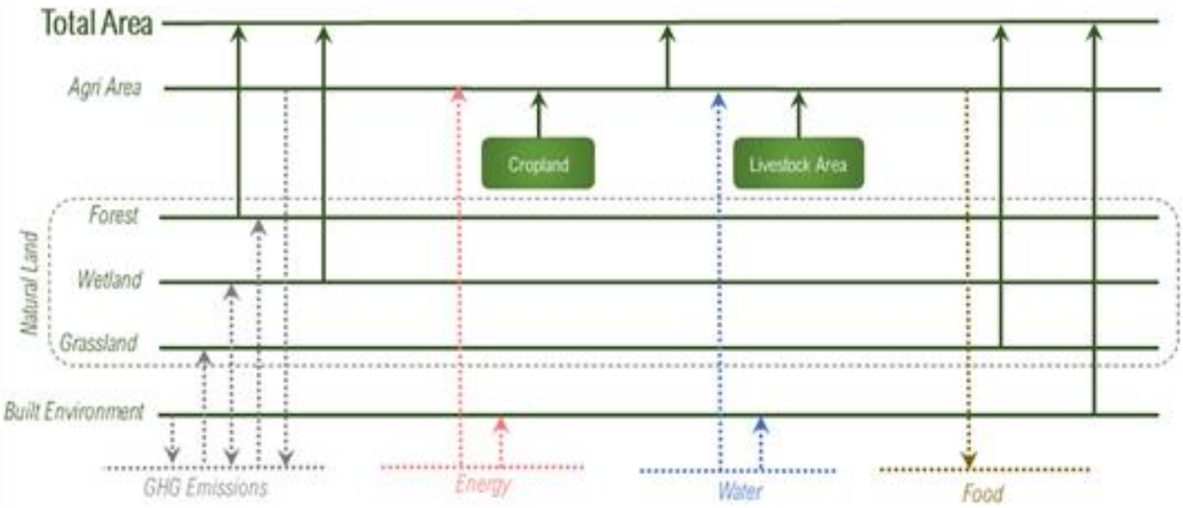

Figure 40: The LAND module in the Greek CS SDM

Data on land uses for the national case was obtained from the CORINE database (https://land.copernicus.eu/). To spatially disaggregate this information, national land uses are uniformly distributed throughout the RBDs, taking into account the RBD surface areas (Figure 41). Crop areas are obtained directly from ELSTAT at RBD level. Regarding cropland, two categorizations were done per RBD based on a) the water use and b) the crop type:

a) irrigated & non irrigated

b) maize, fruits, citrus, olives, vegetables, potatoes, cotton, pulses, tobacco, fodder permanent, fodder temporary, rice, cereals, sugar beet

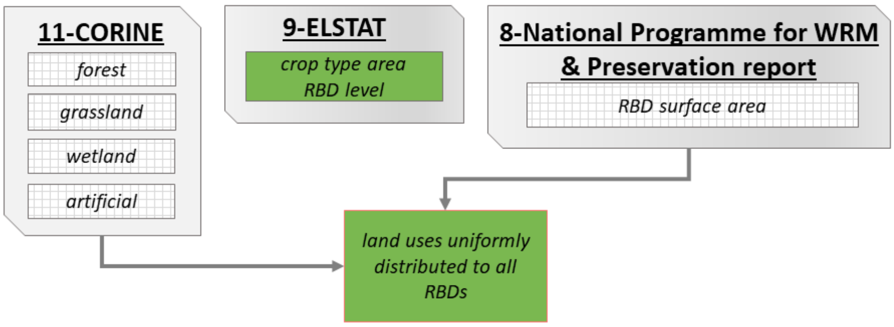

Figure 41: Data sources and data processing in the Greek CS SDM for the Land Module: Input data from published databases are shown in hatched boxes; Resulting datasets for the Land module are shown in green boxes.

In Figure 42 an indicative screen shots for LAND SDM module for RDB 1 is shown.

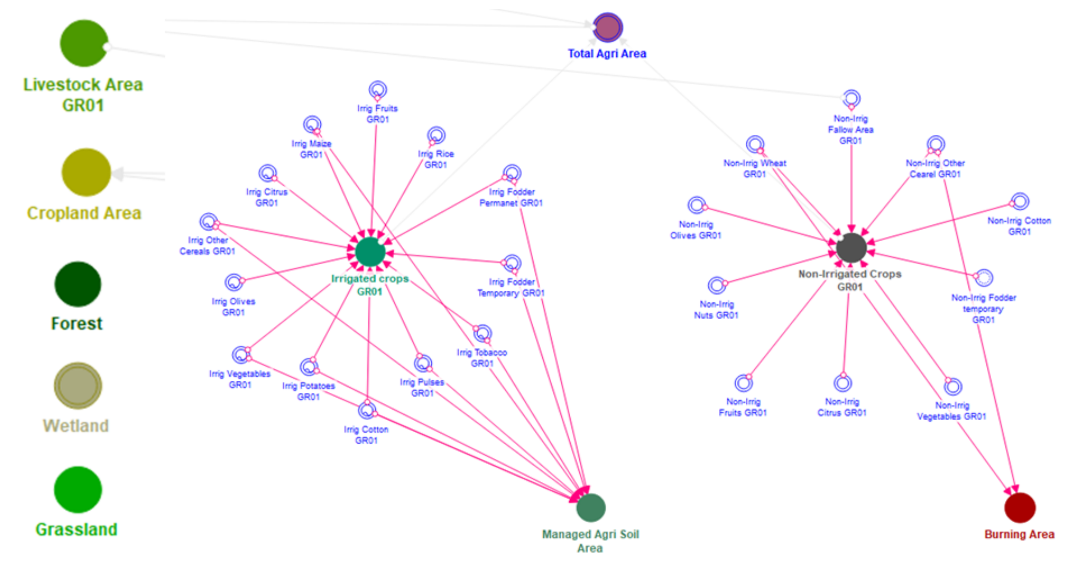

Figure 42: Stella SDM screen shot for RDB 1 (LAND Module)

3.7.1.3 Food sector

Food production is directly linked to land uses through cropland type, yields and livestock. It links to water through water demand for livestock (no food consumption association) and it also links to climate through GHGs. Agricultural production in the Greek CS SDM includes the production of crops and livestock, with the latter comprising a series of irrigated and non-irrigated crops (14 in total) and the latter eight animal types and their products (Figure 43). Crops are classified as Food, Feed and Industrial Crops. In terms of interlinkages with other Nexus components, Water is required for irrigation of irrigated crops and livestock breeding, while energy is required for both crops and livestock. Agricultural production also results in GHG emissions from both crops and livestock.

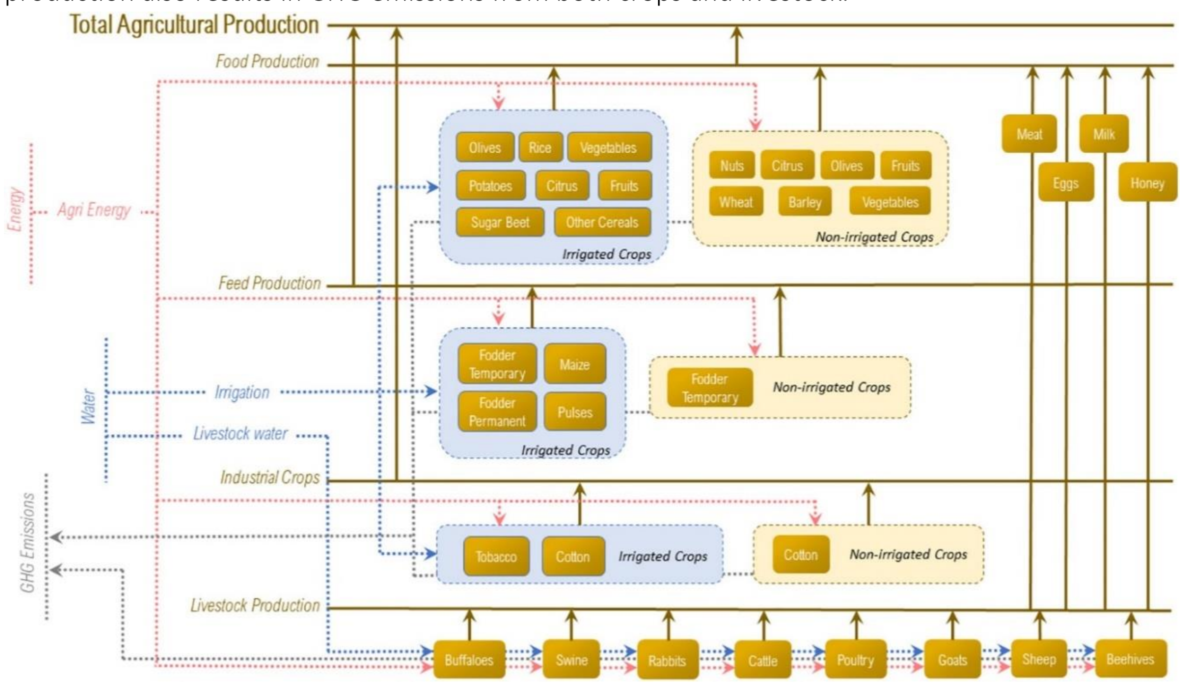

Figure 43: The FOOD module in the Greek CS SDM

All input data in this module (Figure 44) come from ELSTAT and include all crop areas and crop types and all animal types at RBD level. In combination with the total crop production data, this module produces crop yields at RBD level and then translates this livestock and crop production in total Agricultural Values for each RBD.

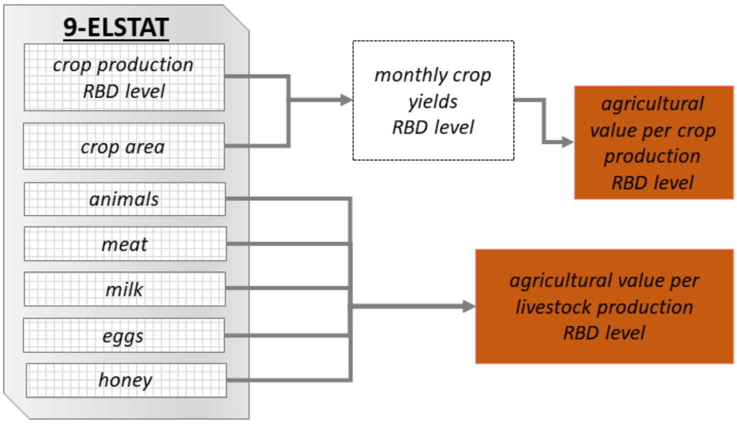

Figure 44: Data sources and data processing in the Greek CS SDM for the Food Module: Computational steps are shown in white boxes; Input data from published databases are shown in hatched boxes; Nexus Interlinkage factors for the Energy sector are shown in brown boxes.

The livestock products included in this analysis are: meat (cattle, buffaloes, sheep, goats, swine, rabbits, poultry), milk, eggs, honey. In Figures 45 and 46 indicative screen shots for FOOD SDM module, including food production and livestock, for RDB 1 are shown.

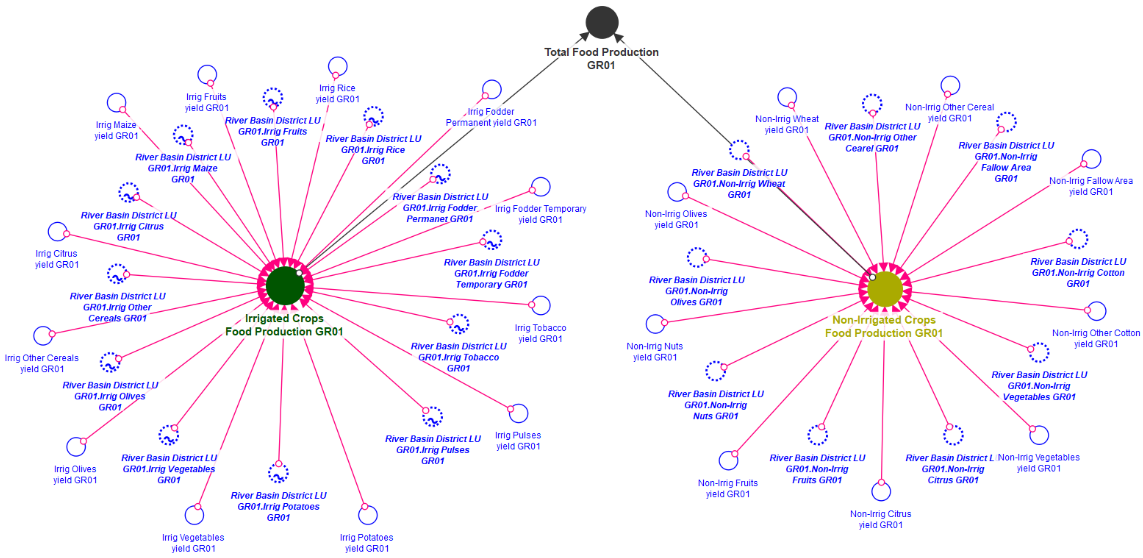

Figure 45 Stella SDM screen shot of food production for RDB 1 (FOOD Module)

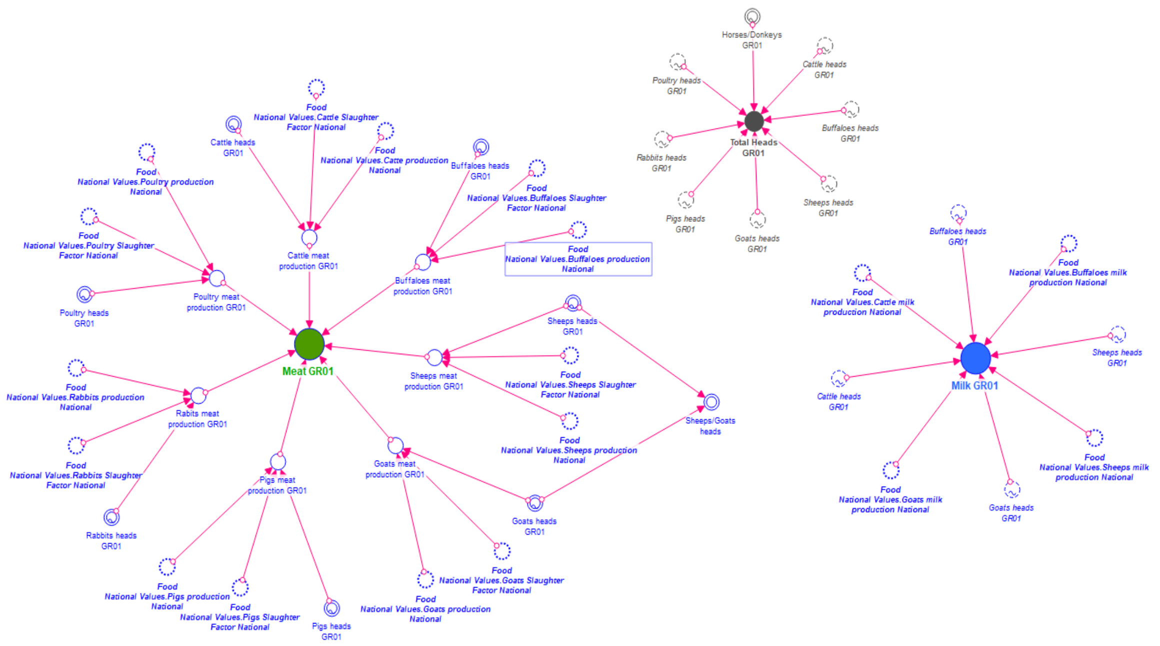

Figure 46: Stella SDM screen shot of livestock for RDB 1 (FOOD Module)

3.7.1.4 Energy sector

An important source of data for the case study of Greece has been the E3ME-FTT model (https://www.e3me.com/) from Cambridge Econometrics. E3ME is a macroeconomic simulation model that is demand- driven and characterized by non-optimization (post-Keynesian economic principles); it includes behavioral aspects by employing macro-econometric behavioral equations, further fitted into the standard national accounting framework of Greece, in this case. E3ME is combined with FTT (Future Technology Transformations), a model of technology diffusion that enables the user to simulate the impact of de- tailed climate policies. E3ME-FTT models the power and transport sectors and has delivered relevant data for Greece by sector on GDP, employment, population, output, CO2 emissions, energy demand for coal, oil, gas, electricity, heat, biomass & combustible waste, as well as electricity generated by all sources including renewables. Sectors include (i) power generation, (ii) industries, (iii) construction, (iv) transport, (v) households, (vi) other final use and (vii) agriculture, with uses (i) through (vi) being associated to “built environment” (Figure 47).

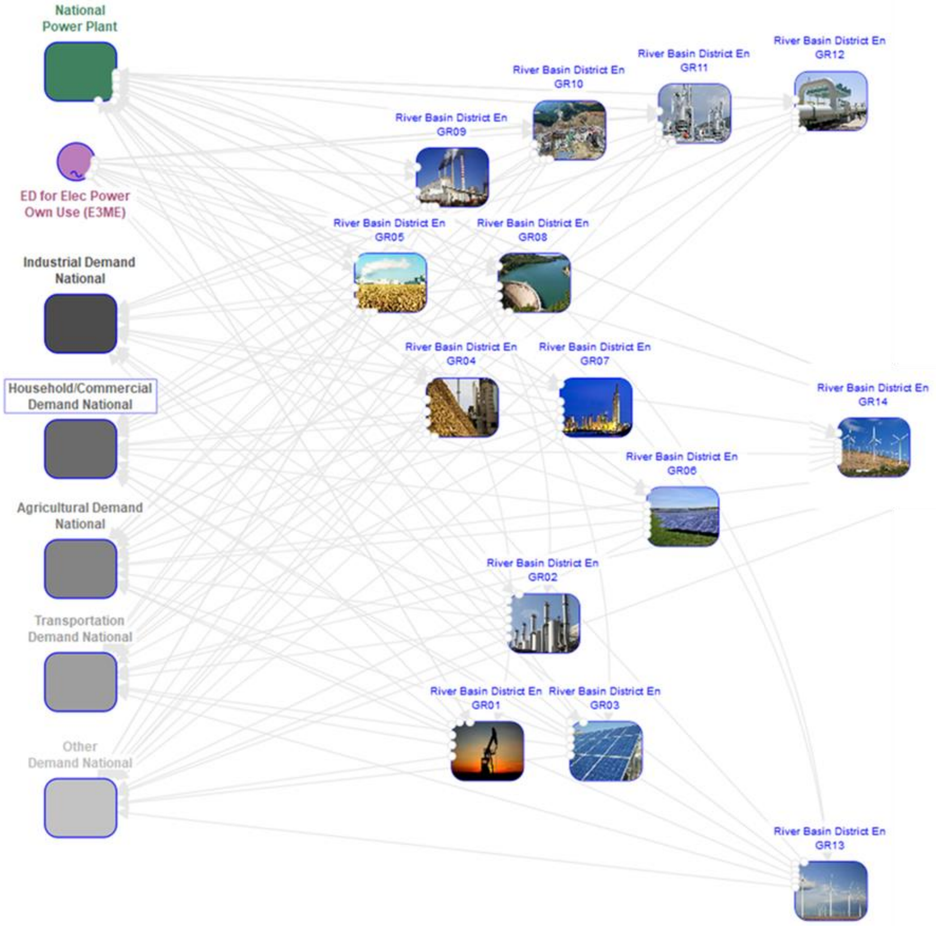

Figure 47: Energy demand and supply at RBD level in Greek CS

This “master” E3ME-FTT has provided all of the Energy module data and has allowed establishing direct interlinkages with the Climate module by associating energy demand by fuel and sector with their corresponding Green House Gas (GHG) emissions, in CO2 equivalents (Figure 48).

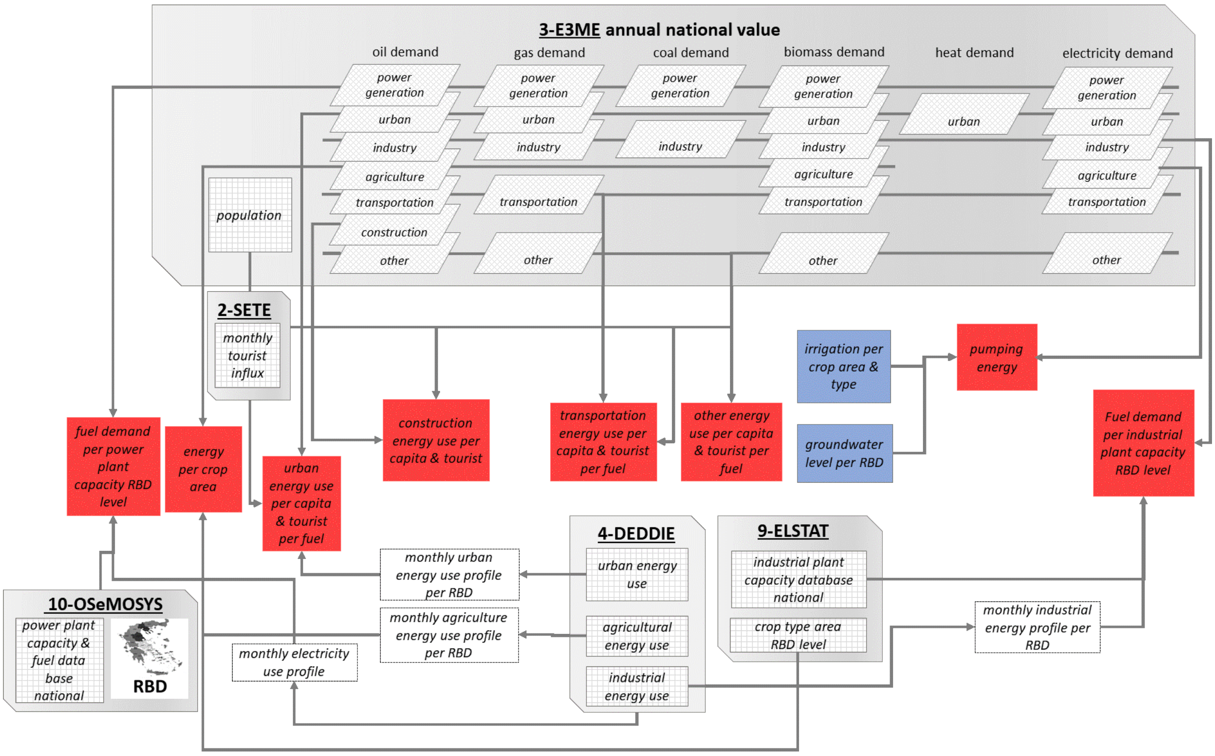

Figure 48 Data sources and data processing in the Greek CS SDM for the Energy Module: Computational steps are shown in white boxes; Input data from published databases, model outputs, or the literature are shown in hatched boxes; Nexus Interlinkage factors for the Energy sector are shown in red boxes, while blue boxes are factors coming from the Water module.

Figure 49 presents a schematic diagram of the energy module in the Greek CS SDM, where all energy uses, fuels and cross-sectoral interlinkages with Water and Climate (GHG emissions) are shown. Nexus Interlinkage factors for energy are computed for all energy uses in the Energy Module of the Greek CS SDM. Different energy demands along with population and tourist influx are used to reduce urban, construction, transportation and other energy use on a per capita & tourist basis.

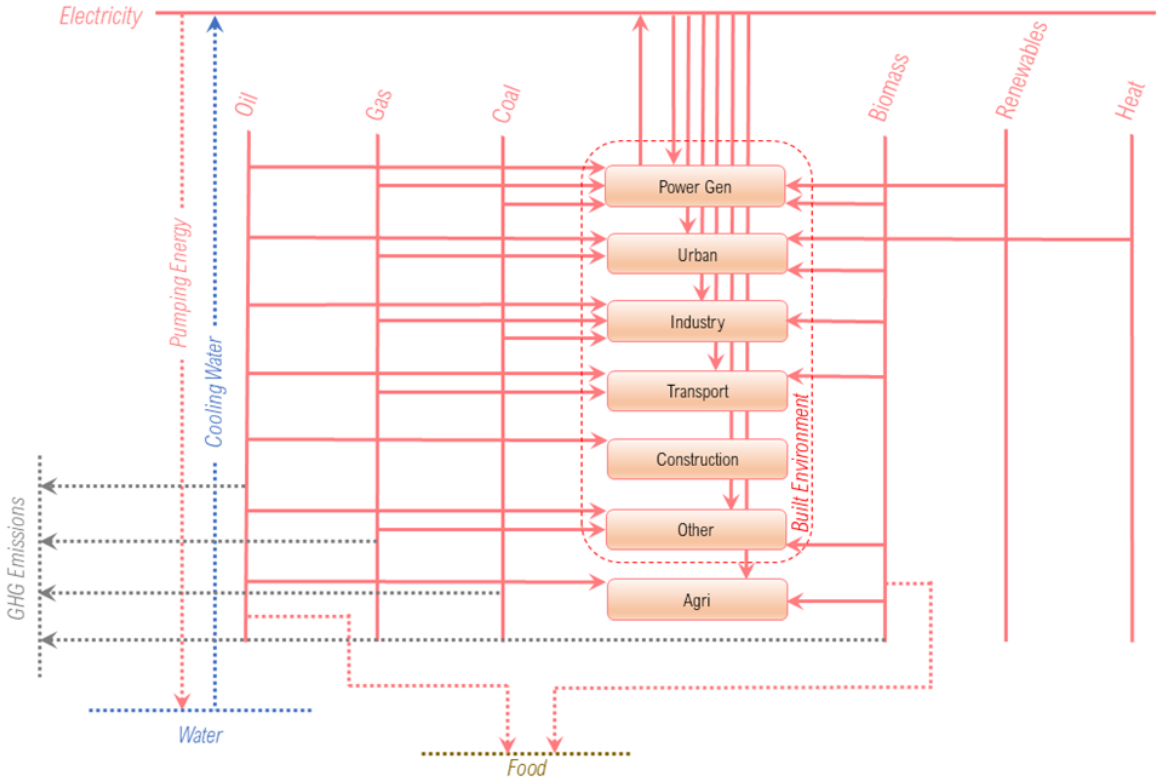

Figure 49: The ENERGY module for the Greek CS SDM

Power generation is modeled using the dataset by E3ME and is disaggregated per RBD using the national power plant capacity database provided by OseMOSYS that maps all power plants for all fuels in Greece. A map of all power plants and corresponding fuel used distributed per RBD in Greece is provided in Figure 50. Monthly time step for power generation is produced by using the total DEDDIE electricity use profile that includes all electricity uses. Industrial energy is modeled using demand by E3ME that is spatio-temporally disaggregated using the industrial activity profile by the DEDDIE dataset. Agricultural energy is modelled on a “per crop area” basis, using the E3ME agricultural energy dataset, the ELSTAT crop area dataset and the DEDDIE agricultural energy use for the spatio-temporal disaggregation. Pumping energy is calculated using groundwater level and irrigation water demand via standard water pumping calculations, quantifying a Water-Energy interlinkage.

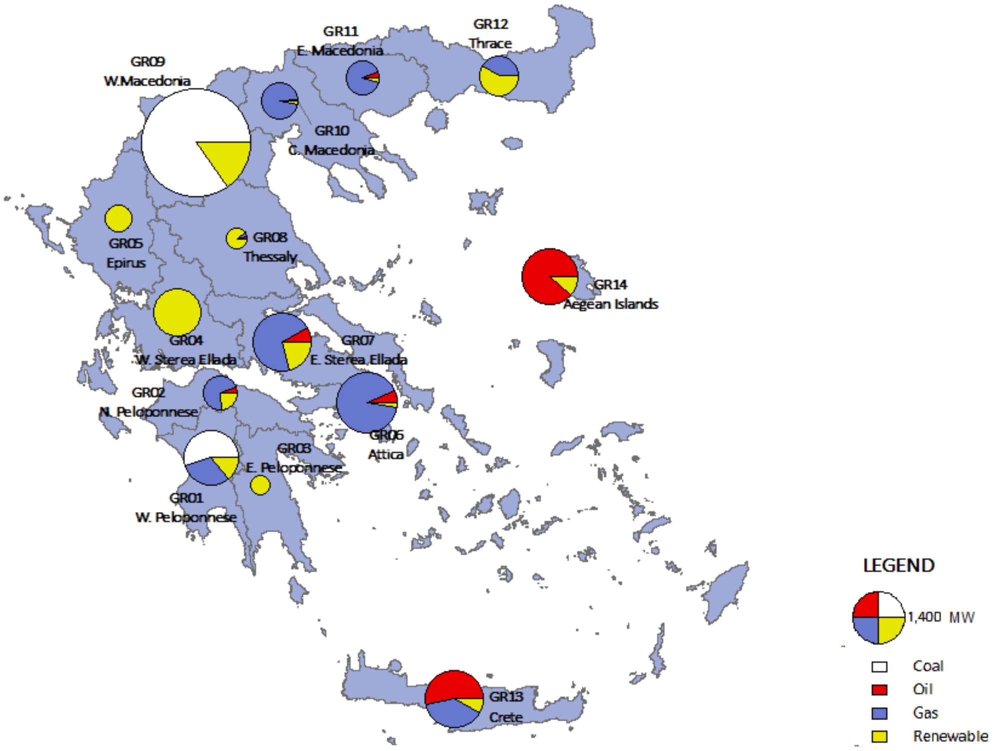

Figure 50: Map of power plants per RBD in Greece. The size of the circle corresponds to the total capacity of power generated, while pie charts show distribution of fuel types used.

In Figure 51 indicative screen shots for ENERGY SDM module for RDB 1 is shown.

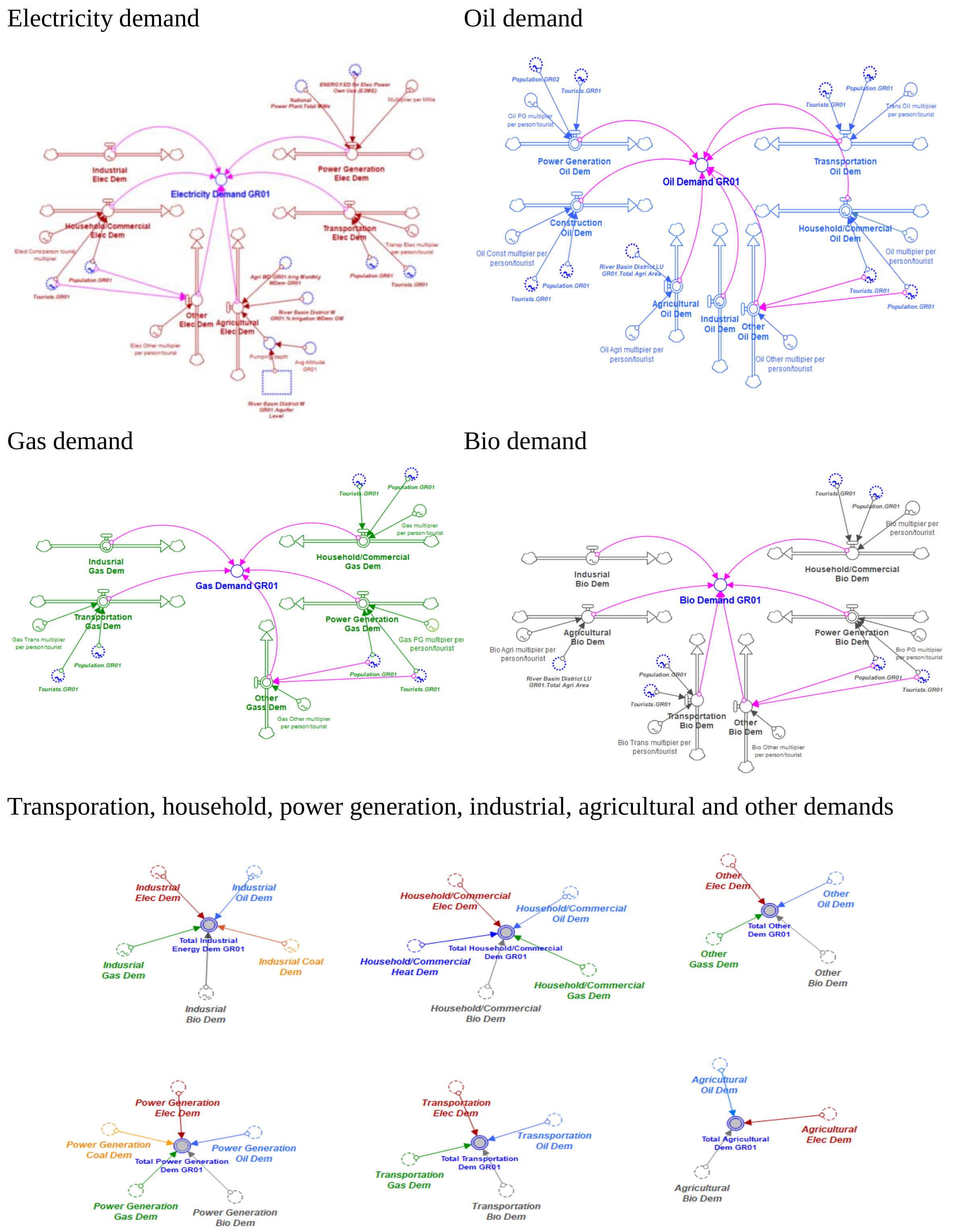

Figure 51: Indicative screen shots for RDB1 (ENERGY Module)

3.7.1.5 Climate sector

The climate module sums up all GHG emissions coming from all other modules. This information is summarized in Figure 52:

c) Water: through wastewater treatment emissions—domestic and industrial

d) Energy: through fuel emissions. A distinction between emissions covered by the European Union Emissions Trading Scheme (ETS) and those not covered (non-ETS) is made.

e) Food: through agricultural activities, such as rice crops, field burning urea application and emissions associated with managed agricultural soils and livestock emissions, i.e., enteric fermentation and manure management

f) Land: with mostly negative emissions from forest, cropland, grass-land, and wetlands

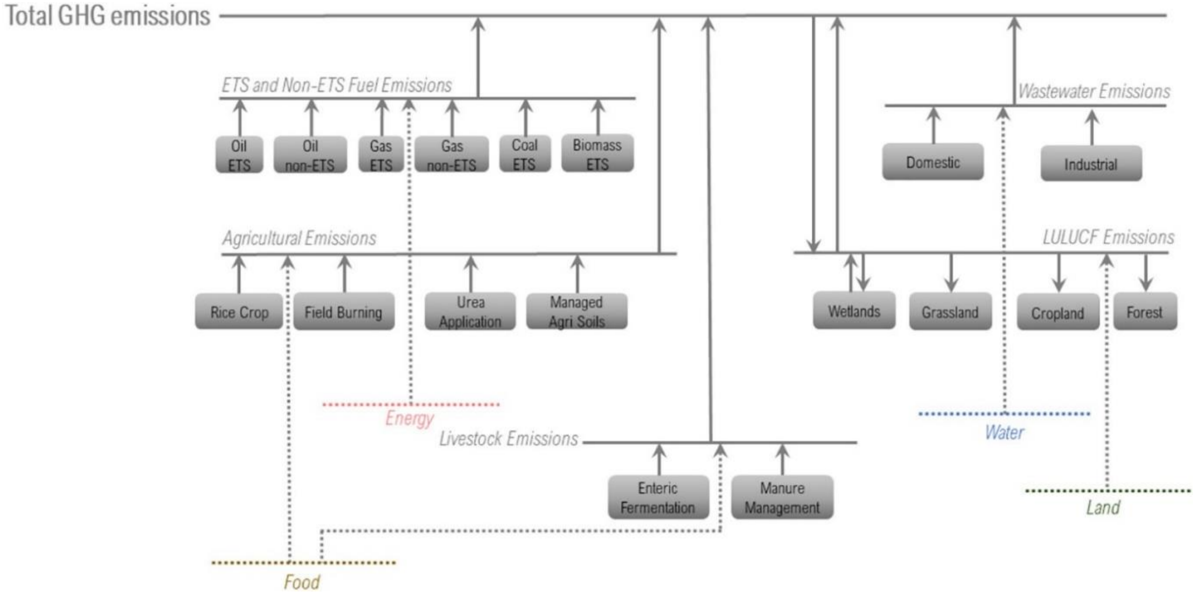

Figure 52: The CLIMATE module in the Greek CS SDM

Figure 53shows the databases used to calculate all emissions in this module. E3ME provided a detailed (by fuel and by sector) annual national emissions dataset that was used together with the energy use data for all fuels (presented in the Energy module). The spatio-temporal discretization that was done in the Energy module is used here to discretize the same way the fuel emissions, producing a comprehensive list of GHG emission factors for all sectors and all fuels. Eurostat provided all other emission data that correspond to the Water, Energy, Food and Land modules and they were reduced on a "per unit" basis through Nexus Interlinkage Factors.

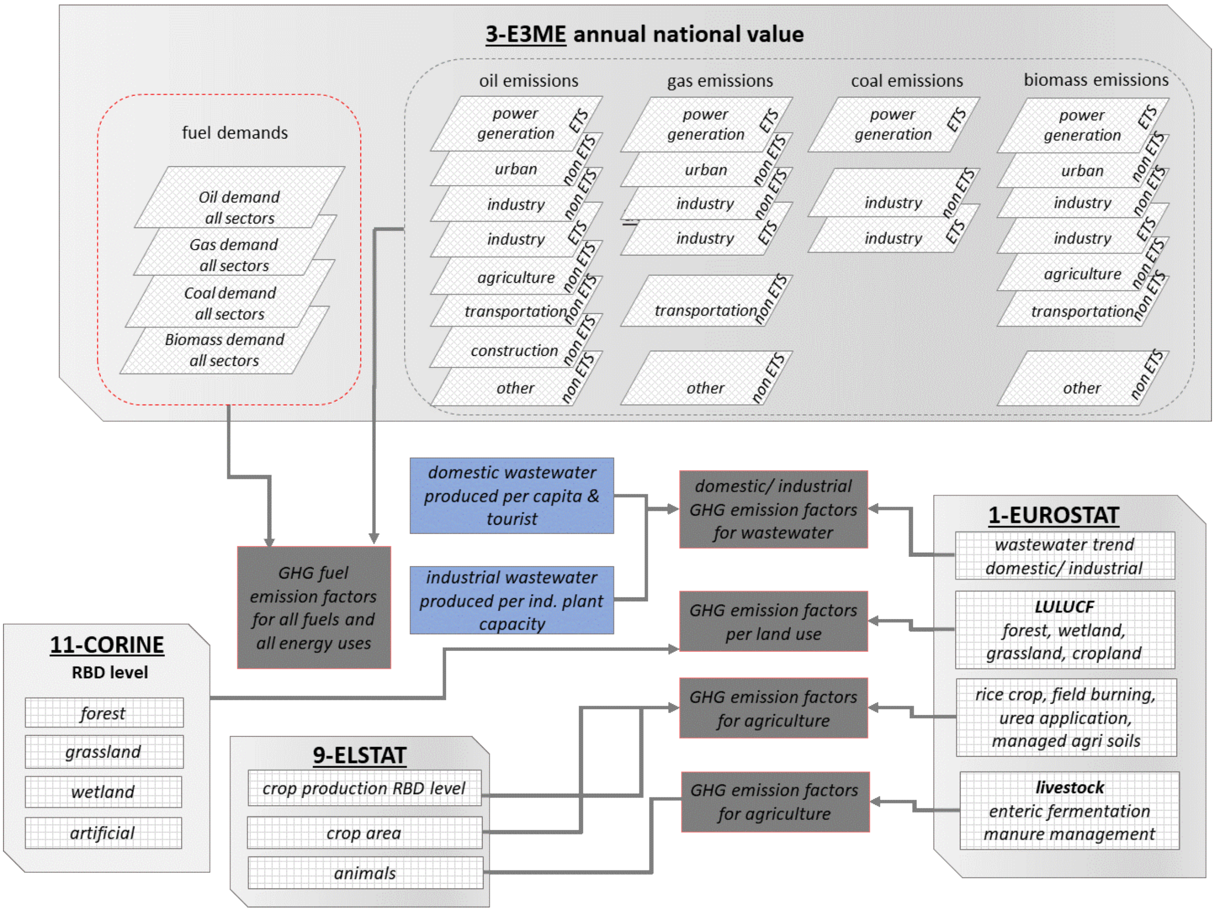

Figure 53: Data sources and data processing in the Greek CS SDM for the Climate Module: Input data from published databases and model outputs are shown in hatched boxes; Nexus Interlinkage factors for the Climate sector are shown in grey boxes, while blue boxes are factors coming from the Water module.

In Figure 54 total emissions screen shot for CLIMATE SDM module at national level is shown.

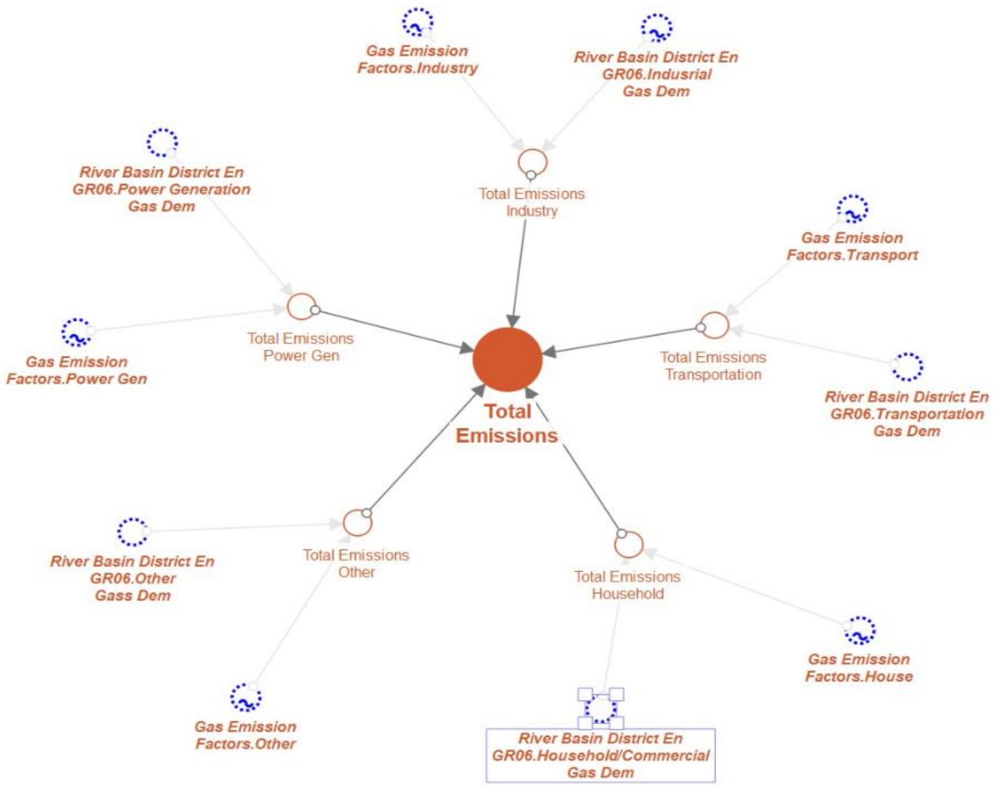

Figure 54: Stella diagram of total emissions in Greek CS

3.7.2 Description of the final results

Nexus interlinkages are modeled in the Greek CS SDM by reducing all major variables to a "per unit" basis, producing relevant factors that could be used for different scenarios, when the "unit" changes. On the Energy module, for example, an aggregate national yearly oil demand figure for agriculture was provided by E3ME-FTT. This value was disaggregated in 14 RBD values and each one of the RBD values was further disaggregated in a time series of 12 monthly values per year, using the DEDDIE dataset. For each RBD, the Land Use module includes the cropland area in m2, so dividing the disaggregated oil demand time series by the agricultural area produces a time series of factors that express agricultural oil demand units per m2 of cropland, used mainly for tractors and other oil-burning agricultural machines. This factor establishes the interlinkage between cropland area and agricultural oil demand and enables the user to quantify this interlinkage and try out scenarios either extending or limiting cropland and seeing the effect on oil demand. A comprehensive list of such factors that establish interlinkages throughout the Nexus is presented in Table 1. Interlinkage factors may be used either within each module or linking two different modules. Changes in quantities listed in the first column of Table 1 triggers, in a domino-like fashion, changes in all variables listed in the second column, which in turn may bring about changes to other variables, thus quantifying the interlinkages among Nexus components. As a result, we can see for example that a change in population or tourism will trigger a series of changes in various different variables and different Nexus sectors. This way, cross-sectoral implications are identified and quantified and critical interlinkages and hotspots can be singled out.

Table 1: List and Description of Nexus interlinkage factors

Unit	Nexus Interlinkage Factors: Ratios of quantities in this column per *Unit* listed in column to the left
Per capita (including population and tourists)	• Public water supply (distinguishing origin of water—surface or groundwater, according to current practice) • Household/commercial electricity demand • Urban wastewater produced • Industrial wastewater produced • GHG emissions from urban wastewater treatment plant • Fuel demand for transportation • GHG emissions from transportation • Fuel demand for construction • GHG emissions from construction • Fuel demand for other final uses • GHG emissions from other final uses
Per power plant capacity (either new installations, or retirements, or increase/decrease of power in plants)	• Fuel demand for power generation per MW of power plant (different factor for each fuel type: coal, oil, gas, biomass) • Cooling water for power plants (different factor for each fuel type; numbers based on Macknick et al. [2012] and Spang et al. [2014]) • Electricity generated (different per power plant, depending on fuel type used) • GHG emissions (different factor for each fuel type)
Per agricultural land area	• Fuel demand for agricultural land use • GHG emissions from agriculture energy use
Per specific crop type area	• Agricultural water demand for different crop types (irrigated only) • Yield for each crop type (Food/Feed/Industrial crop produced); different yields for irrigated and non-irrigated crops.
Per irrigation technology (sprinkler, drip, or furrow)	• Losses in irrigation network • Agricultural water demand • Fuel demand for agricultural land use • GHG emissions from agriculture energy use
Per livestock land use	GHG emissions associated with manure management

Understanding and assessing the significance of interlinkages can become quite complex, especially when all sectors are quantified, since there is a lot of information that needs to be processed. Figure 55 shows the distribution of both surface- and groundwater among the 14 Greek RBDs; it also shows how this fresh water is used in the RBDs. At a national level, we see that about half of the water used comes from surface water, while the rest comes from groundwater; at the same time, we see that a large percentage (about 82%) of water in the country is used for irrigation and/or livestock use, so it is associated with Food production, thus establishing a strong interlinkage between Water and Food. Urban water supply comes second, while industrial water use and cooling water follow. Urban and industrial water use are grouped under demands associated with the "Built Environment (BE)", so the interlinkage established between Water and BE is considerably weaker than the one with Food. The same is true for "Cooling Water", which expresses the interlinkage from Water to Energy. From Figure 55, one can see which RBDs are the ones exerting the biggest pressures on the country's water resources, namely GR08 (Thessaly), GR09 (W. Macedonia), GR10 (C. Macedonia) and GR04 (W. Central Greece). The former three are predominantly agricultural regions producing a large percentage of the country's agricultural products, thus they spend most of the water for Irrigation, while the latter has the largest contribution in the country in the urban water supply category. This is true be- cause the country's capital, Athens, located in GR06 (Attica) has insufficient water resources to meet demand and has water transferred from GR04 and GR07. This is why the Attica RBD (GR06) shows a small urban water supply consumption overall.

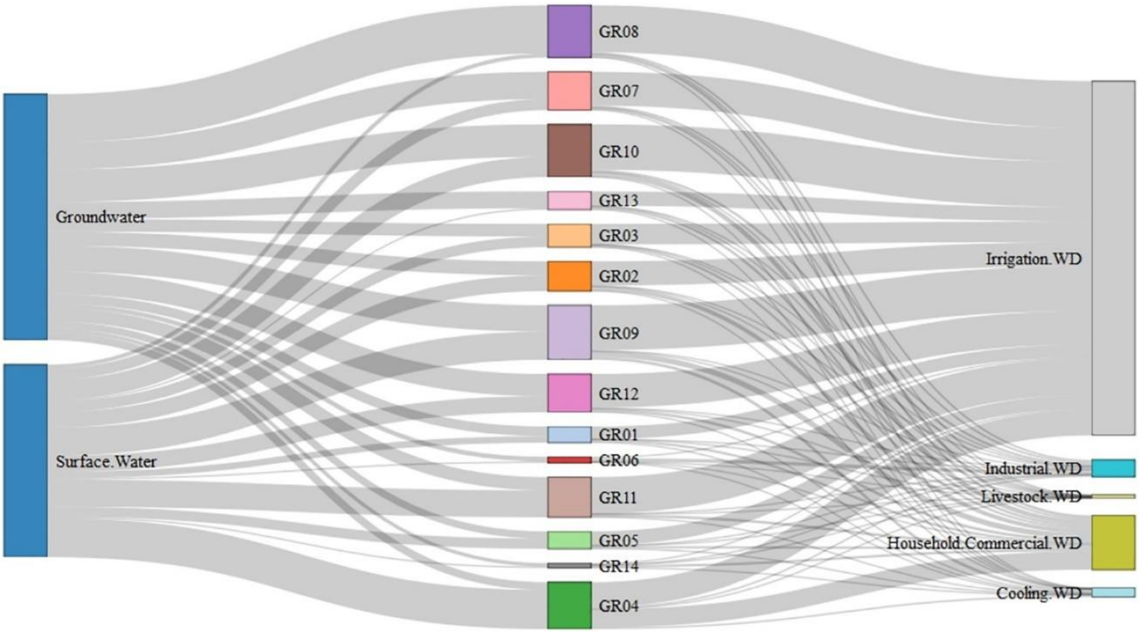

Figure 55: Allocation of national surface and ground water consumption in Greece per RBD and per water use type for year 2010.

Figure 56 shows an analysis of agricultural production in relation to three factors: surface area of cultivated land with a specific crop, the corresponding agricultural monetary value of the crop and the irrigation water needed. It is interesting to observe how these three quantities relate to each other for the national case, as well as for the 14 RBDs. The bars for water-intensive crops are longer under the "water" category, when compared to other crops. For the same crop, the latter reflects blue water used according to Water Footprint Terminology (https:/waterfootprint.org/), so when green water meets crop demand, or when part of the crop area is non-irrigated, then the bar will appear smaller, compared to the length of the "area" bar. On the other hand, "value" is related to the market value of the crop and is important to relate to "water" and "area" making the crops with high "value" and low "water" or “area” really desirable for sustainability, since they enhance the economic benefits and do so with relatively little water and occupying relatively little land. Olives, fruits and vegetables exhibit high “value” and low “water” and “area” for the national case, while cot- ton appears very water-intensive offering relatively little “value” overall. Examining the data for all RBDs, along with the national case, shows the importance of scale: when “zooming in”, crop data can be very different, since precipitation quantities and patterns differ throughout the country, as well as crop yields and extent of food production from non-irrigated crops. Nevertheless, vegetables consistently score higher in “value” when compared to “water” and “area” and cotton is a very water-intensive crop; olives and fruits show a high “value” while cereal/pulses a relatively low value. Examining the data for all RBDs, along with the national case, shows the importance of scale: when “zooming in”, crop data can be very different, since precipitation quantities and patterns differ throughout the country, as well as crop yields and extent of food production from non-irrigated crops. Nevertheless, vegetables consistently score higher in “value” when compared to “water” and “area” and cotton is a very water-intensive crop; olives and fruits show a high “value” while cereal/pulses a relatively low value.

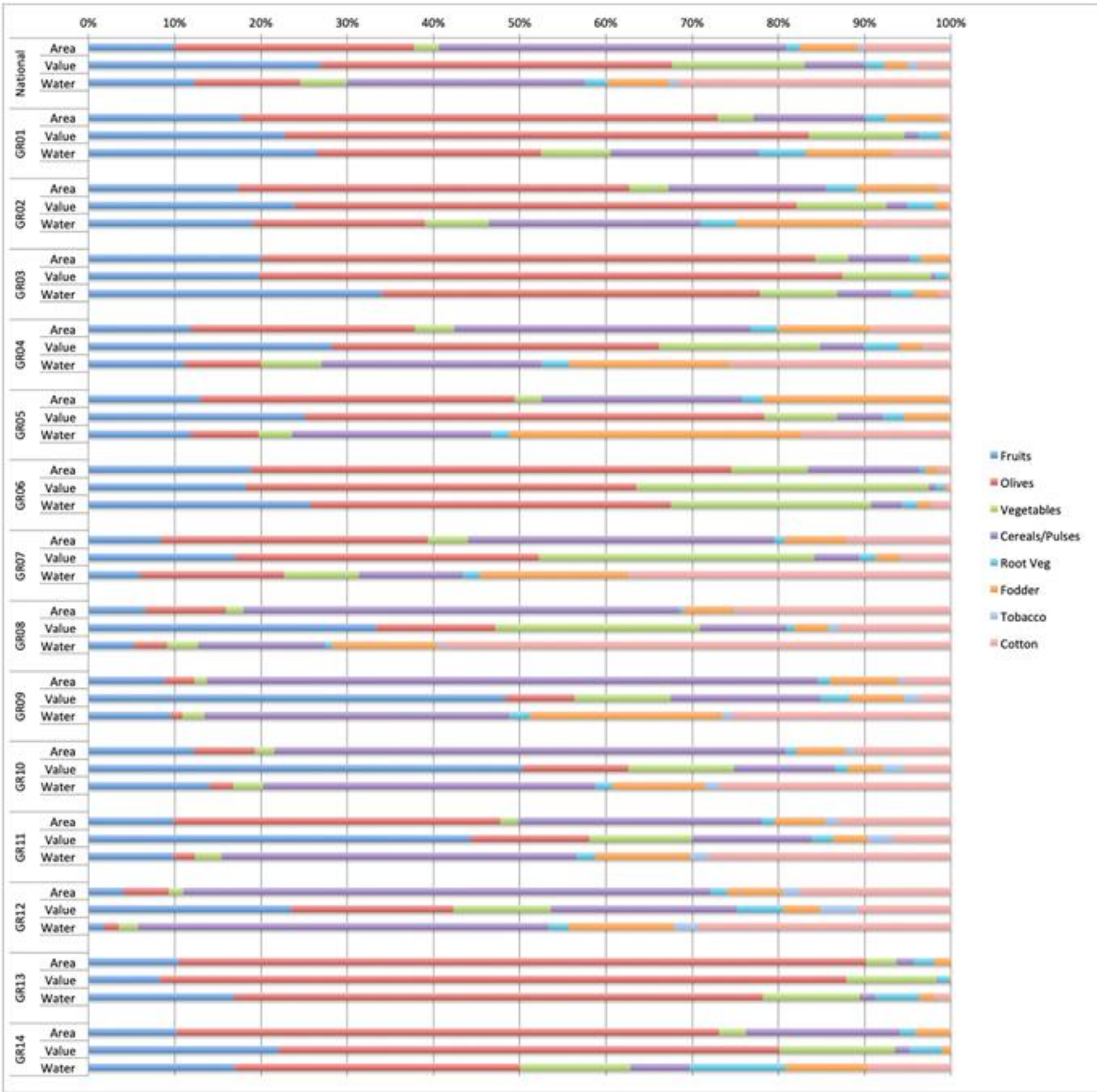

Figure 56: Percent proportional split in cropping in terms of surface area, agricultural value & irrigation water in Greece (at RBD & national scale)

In Figure 57 an innovative resource nexus visualization tool (the Nexus Directional Chord plot) for energy sector for national case study of Greece is introduced (Laspidou et al., 2020). Figure 57 shows results in a chord diagram, where an analysis of the energy sector at national scale is presented. In this chord diagram, half of the circle is fragmented in energy-consuming entities/sectors (Power Generation, Construction, Transport, etc.), while the other half is fragmented in fuel type/technology (Coal, Oil, Gas, Electricity, etc.). The arcs drawn between the entities show the interconnection between the two categories. The arcs have the same color with the originating entity and they end up in another entity from the other category, linking the two categories of the circle; the size of the arc is proportional to the size of the flow. Thus, a thick teal arc (Oil) leaves the “Oil” entity and ends up in “Transport” signifying that a large part of oil is used. By the transportation sector. A very fine yellow arc (electricity) ends up in “Transport” as well, indicating that only a tiny part of energy demand by this sector is met by electricity. This diagram identifies which sectors consume Oil in Greece, which consume Coal, etc. It also shows for each sector which fuel/technology is used to meet its demand. The units are the same throughout the chord diagram for both entity categories. Having mapped the energy data this way, one can see which fuel types dominate energy consumption and which sectors are the major consumers of these fuel types.

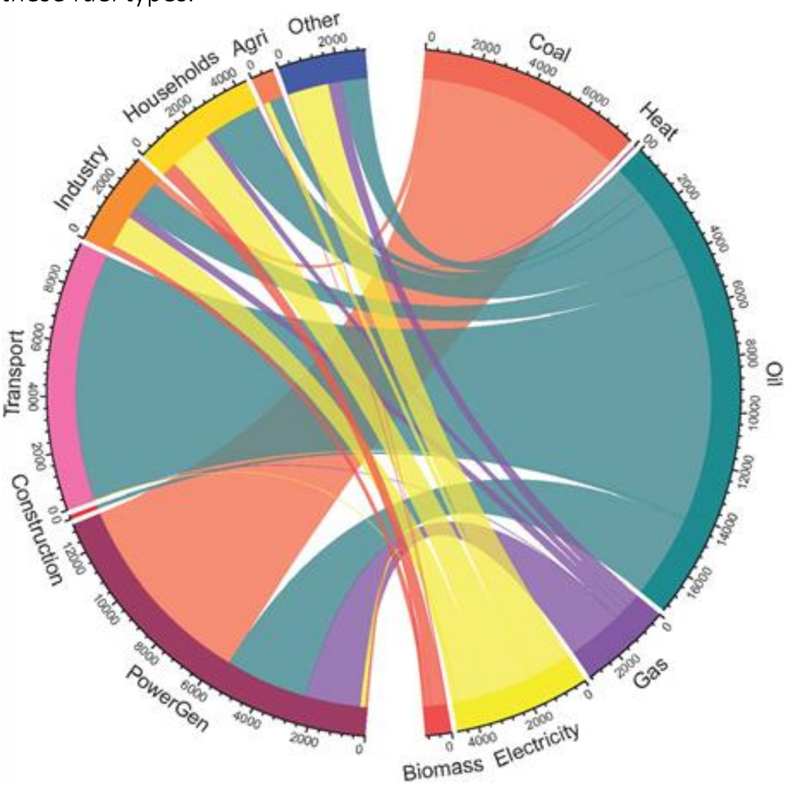

Figure 57: Analysis of the energy sector at Greek CS, linking energy sources to energy uses (Mtoe)

The biggest part of the national energy needs are met by Oil and the largest part of that is consumed by the transportation sector. Coal is used mostly for power generation, while Gas use by households is quite small. Other than transportation, large Oil consumers are Power Generation, while household heating and industrial use are quite significant as well. Power generation also uses up large parts of Gas in Greece, while Electricity is split among households, industry and other uses. The largest part of Biomass is used by households for heating, while Heat is only a very small part of all energy sources and is used exclusively by households. Directly related to the energy sector is the analysis of climate impact, which is conducted by quantifying GHG emissions. Figure 58 uses a Sankey diagram to show how total GHG emissions on a national scale are distributed among the 14 RBDs in Greece and which sectors are responsible for these emissions. The biggest GHG emission generation by far is associated with fuel (Oil, Coal and Gas) consumption, with oil maintaining its first place. The RBD with the largest GHG emissions is Western Macedonia (GR09); this is the region where the largest power plants in Greece are located serving the needs of the whole country. The communities in W. Macedonia are the ones that endure the effects of large GHG emissions, showcasing that emissions associated with fossil fuel power plants have an intense "localized character", even though the power generated is fed through the grid to serve the needs of the rest of the country. Livestock and agricultural emissions are the categories that follow in size and appear to be relatively significant. There is a lot of potential for improvement in the national GHG emissions that could be realized by switching to renewable energy sources both in power generation, but also in the transportation sector, with the replacement of conventional vehicles by electric ones. Negative emissions by LULUCF could be enhanced by actions like reforestation in order to alleviate massive emissions associated with fuel consumption.

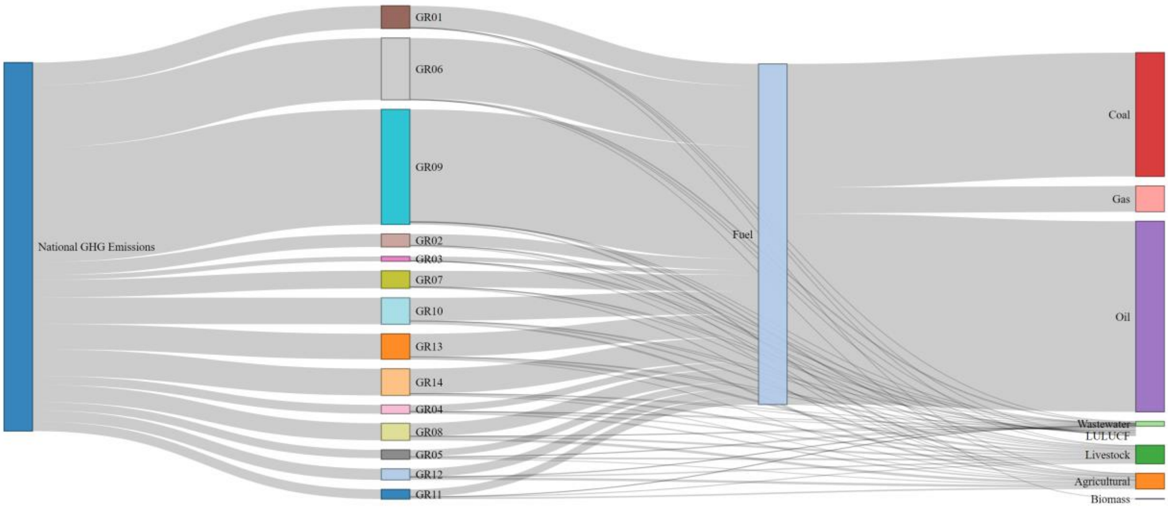

Figure 58: Analysis of Climate Impact by quantifying GHG emissions at national and RBD scale. It should be noted that LULUCF emissions are negative

3.8 Azerbaijan case study

3.8.1 Description of the final complexity science model

The Azerbaijan model describes the entire country without subdivision into smaller regions within the country (unlike for example Greece or Latvia). The final model consists of 410 variables in total. The model runs at monthly timestep, starting in January 2017 and ending in December 2050 (i.e. 408 timesteps in total).

Climate is impacted by the land, food, and energy sectors, while water is impacted by changes in the energy sector. Limitations regarding data availability meant that this model was relatively simple in complexity, but this case study might be ideal to use as a basic introductory training example.

3.8.1.1 Water sector

The water sector comprises of a water balance, accounting for water sources from surface water, groundwater and reuse of water, along with water demand from the domestic, irrigated agriculture, and industrial sectors. The generation of hydropower is also estimated within the water sector.

3.8.1.2 Land sector

The land sector tracks the area of land used for different purposes. Forests, livestock land, wetlands, irrigated lands, rainfed agricultural land, and fallow land are accounted for. In addition, this sector also estimates the fertiliser runoff from irrigated and rainfed agricultural lands by multiplying the area of these lands with a fertiliser application rate per hectare.

3.8.1.3 Food sector

The food sector comprises of a balance between food production and food demand of different food types. Food production accounts for grains, vegetables, fruits, meat, dairy, and other basic food products. Food demand accounts for the same categories of food products. In Figure 198, it is seen that each food category has its own module (denoted by the rounded boxes). The production and consumption of each food type is elaborated in more detail within each module. For example, in the grains module for grain production, it is shown that total grain production is comprised of wheat, porridge, rice, maize, barley, and other grains. In addition, the current stock of each grain is take into account, along with the actual monthly production, and any imports associated with each product.

Similar structures are developed for the other food producing sectors. In vegetables, potatoes, onions, other vegetables, market garden vegetables, legumes and ‘miscellaneous’ vegetables are accounted for. In fruits, grapes and fruits and berries are differentiated, while in meat, pork, beef, goat and mutton, fish, and poultry are assessed. In dairy only milk and cheese are assessed, while other basic food comprises of vegetable oils and sugars.

As mentioned, the same categories and sub-categories are assessed for food demand. The difference is that for food demand, the following variables are included: food demand for industrial applications, production for domestic consumption, production for seed stock demand (where applicable), food losses, food exports, and production for fodder (where applicable). The final food balance is the difference between production and consumption.

3.8.1.4 Energy sector

The energy sector also comprises a balance between energy supply and energy demand. On the supply side, oil and gas (from closed and open circuit systems) are considered as fossil fuel sources, as well as hydropower, wind, and solar production from renewable sources. On the demand side, energy demand from the domestic, services, agricultural, industry and transport sectors are quantified. The energy balance is the difference between supply and demand.

3.8.1.5 Climate sector

The climate sector is a greenhouse gas (GHG) balance between emissions and sequestration to the climate system. All units are measured in CO_2e. On the climate emissions side, emissions related to food production and energy production are considered (each with their own sub-modules), while on the sequestration side, sequestration from forests and wetlands and fallow lands are considered. The climate emissions balance is the difference between total emissions and sequestration.

In emissions from food production, cereals, cattle, sheep, chicken, pigs, cows and rice are multiplied by a corresponding emissions factor to derive total emissions for each product, which are summed to get total emissions from food production. In a similar way, oil and gas are multiplied by emissions factor and summed to derive emissions from fossil fuel based energy production.

In a similar manner, sequestration is estimated as the area of land of forests and wetland, and of fallow land, and each is multiplied by a corresponding sequestration factor. These are summed to derive sequestration from these two land use categories.

3.8.2 Description of the final results

3.8.2.1 Water sector

Supply and demand are predicted to fall over time in Azerbaijan. The total drop is in the range 10-20% from current conditions by the end of the simulation. As both fall at a very similar rate, the overall water balance in Azerbaijan is positive throughout the simulation, and remains at almost the same level throughout (~1690-1715 Mm^3). It is shown that surface water dominates supply, while on the demand side domestic water demand and agriculture dominate near the beginning of the simulation, however interestingly, domestic water demand is shown to fall dramatically while irrigated agriculture and industrial demands remain roughly constant.

3.8.2.2 Land sector

Wetlands comprise a substantial proportion of the total land use assessed. Irrigated and non-irrigated agricultural lands also comprise a significant fraction of the total land area. Livestock and forest lands make up the remainder. It is also shown that the area of wetlands is expected to increase, with only negligible increases in the other land use areas.

3.8.2.3 Food sector

In the food sector, results for total food production and consumption (show that production is significantly lower than food consumption for the products analysed, suggesting that the deficit must be made up either in other products, or in imports not recorded in the statistics. Both production and consumption are expected to increase over time until 2050. In terms of production, grain and vegetables make up the majority, with dairy also playing an important role. For consumption, dairy dominates all other categories, although grain and vegetable consumption are also relatively important.

3.8.2.4 Energy sector

In the energy sector, both energy production and consumption are expected to increase to 2050. For production, it is suggested that energy produced from oil sources will dramatically decline, with this reduction being replaced by energy production from gas sources. Renewables remain a very small share of the total production to 2050. For consumption, the residential and services sectors dominate, although there is a notable increase expected in the transport sector regarding energy consumption. For both production and consumption, results suggest an accelerating rate of growth to 2050.

In terms of the overall balance between energy production and consumption, production is greater than consumption, although the gap between the two does decrease slightly over time, and both are expected to increase to 2050.

3.8.2.5 Climate sector

In terms of the climate sector, while sequestration of GHGs from forest and fallow land remains roughly constant over time, only slightly increasing during the simulation, emissions grow rapidly in the middle of the simulation, drop off markedly, and then start to grow again at the end of the simulation. Emissions are greater than sequestration during the simulation. This temporary large increase in emissions is due to a short lived but dramatic rise in oil based energy production, leading to corresponding high emissions. Once this is exhausted, emissions drop, and follow the energy production from gas sources.

3.9 Transboundary France-Germany case study

3.9.1 Description of the final complexity science model

The transboundary France-Germany (FR-DE) system dynamics model describes the region along the Rhine shared between France and Germany. The model is split into two regions, one for the French portion (Grand Est region), and one for the German (Baden- Württemberg region). There is interaction not only between nexus sectors, but also between the regions. In each nexus sector, the same (sub-)model structure is used in each geographical region, allowing replicability and consistency of data and result across the regions (allowing for comparable assessment), and also allows for easy scaling up. As a result of this feature, in the model presentation below, the structure from only one region will be shown, as all other regions are identical in structure, only differing in their data input. The final model consists of 1298 variables in total, with many connections between sectors adding great complexity and depth to the model. The model runs at monthly timestep, starting in January 2006 and ending in December 2050 (i.e. 540 timesteps in total).

Connecting the Grand Est and Baden-Württemberg through the water sector in the SDM.

The water sector in each region was restructured to render case-study-specific issues. First, given the central role of the Rhine for energy generation, navigation and biodiversity conservation, the Rhine system was modelled separately from the rest of the surface water system and is considered as a two-part system, shared between the two regions, and comprising the canal and the Old Rhine. The runoff in the Rhine system as determined by SWIM is thus broken down into two parts:

- The annual runoff in the Old Rhine is considered constant and equal to the ecological flow (see EDF, 2010).
- The annual runoff in the canal is computed as the difference between the runoff in the Rhine system as determined by SWIM and the ecological flow.

Second, to render the shared nature of the groundwater table between part of the Alsace and part of the Baden-Württemberg regions, the groundwater resource was considered as a single stock variable for the whole CS area (Grand Est and Baden-Württemberg).

The top level of the model (Figure 59) shows how the five nexus sectors are related, plus the link with population. Climate is impacted by the land, food, and energy sectors, while water is impacted by changes in the land and population sectors. The energy sector is impacted by changes to the land, food, water and population sectors. Food is mediated by changes in population and land. The following sections describe in detail the six model sectors in turn.

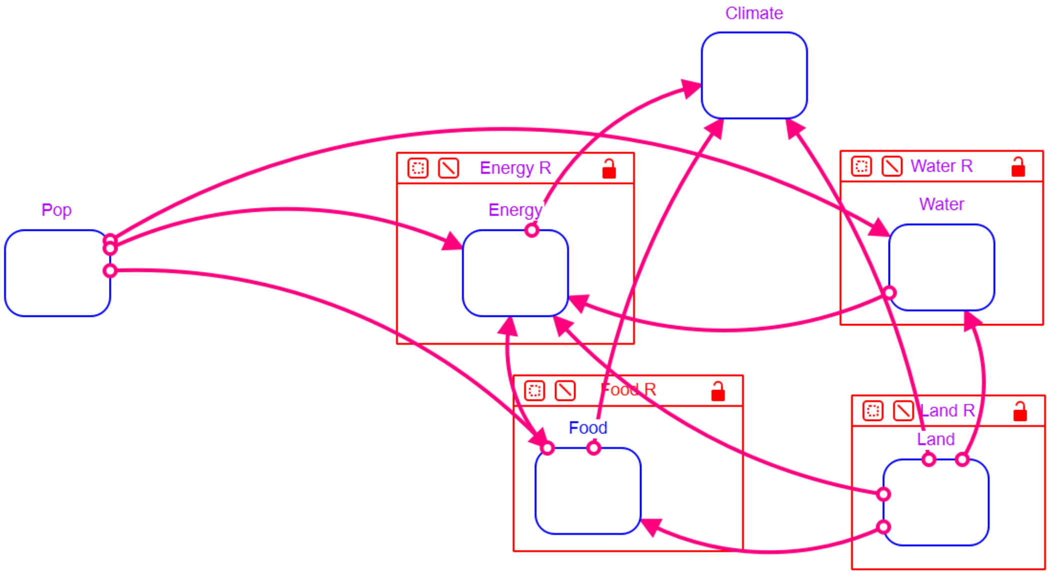

Figure 59: the top level of the transboundary France-Germany SDM of SIM4NEXUS, showing the high-level nexus connections.

3.9.1.1 Population

The population module consists of two variables that tracks the population in each region (French part and German part) over time. The data derive from national statistics.

3.9.1.2 Water sector

In the water sector module (Figures 60 and 61), two main parts are considered: i) the balance between water supply and water demand from surface and groundwater sources (Figure 60), and ii) the flow of water between the Old Rhine and the Grand Canal of Alsace (Figure 61). In terms of the supply and demand of water (Figure 60), surface and groundwater sources are considered. Most recharge/inflow data comes from the SWIM hydrological model, setup up specifically for this case study. In addition, treated wastewater is also counted as a return flow to surface water supplies. For groundwater demand, food crops (consisting of grapes, maize, and others), fodder crops (maize and others), energy crops (rape, sunflowers, maize, other), cattle demand, industrial use, and public water supply are the categories considered. For the crops, a water demand per hectare is multiplied by the crop areas from the land module, forming a nexus connection here. For surface water, evaporative losses from open water bodies, industrial use, public water supply, cattle water use, crop water demand (maize, grapes, others), fodder crops demand (maize, others), energy crop water demand (rape, maize, sunflowers, other), and water for energy generation are all taken into account. In addition, the volume of (waste)water that goes to treatment is calculated, as is the actual treated volume, which subsequently returns to surface water supply[2].

[2] The amount of waste of wastewater computed by the SDM is combined with the share of waste water being treated, the share of treated waste water being reused and the share of treated waste water discharged in surface water. These three shares are defined based on the literature for both case-study regions.

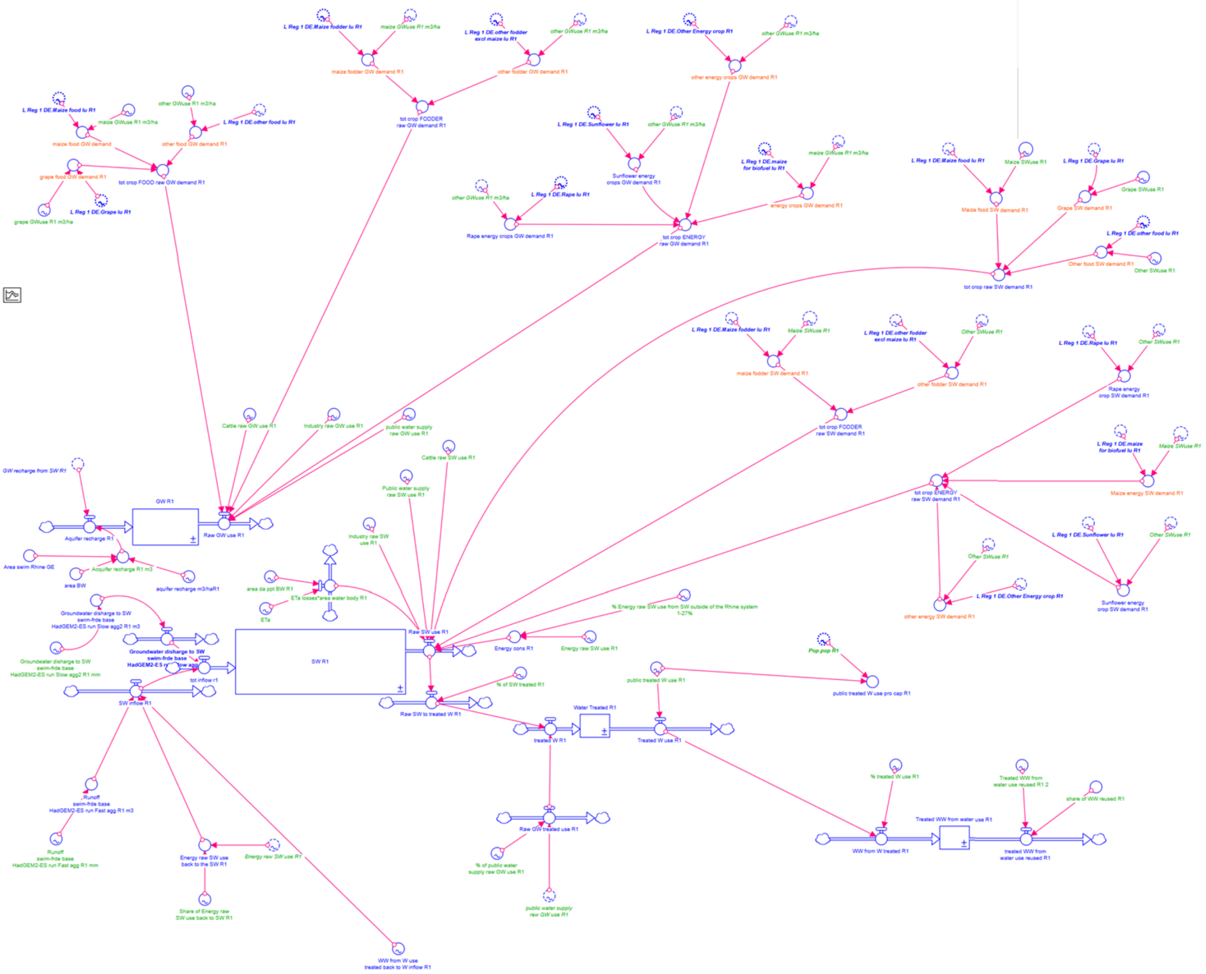

Figure 60: first part of the FR-DE water module, showing the relationships between supply (far left) and demand (right) of surface (lower square box) and groundwater (upper square box) sources.

For the part of the module dealing with water transfers between the Grand Canal of Alsace (where hydropower generation takes place) and the Old Rhine (Figure 61), water inflow and outflow from the main Mulhouse canal is quantified using data from SWIM. Two constraint variables "hydropower", and the "ecological flow" were included in the SDM to signal the impossibility for water flow entering the Rhine system to sustain both the production of hydropower in the canal and the ecological flow required for water ecosystems in the Old Rhine. Finally, the fraction of ecological flow (in the Old Rhine) that flows back into the Grand Canal of Alsace is also accounted for. The Old Rhine, and the Grand Canal of Alsace outflow contribute to the total river flow at Karlsruhe (Figures 60 and 61).

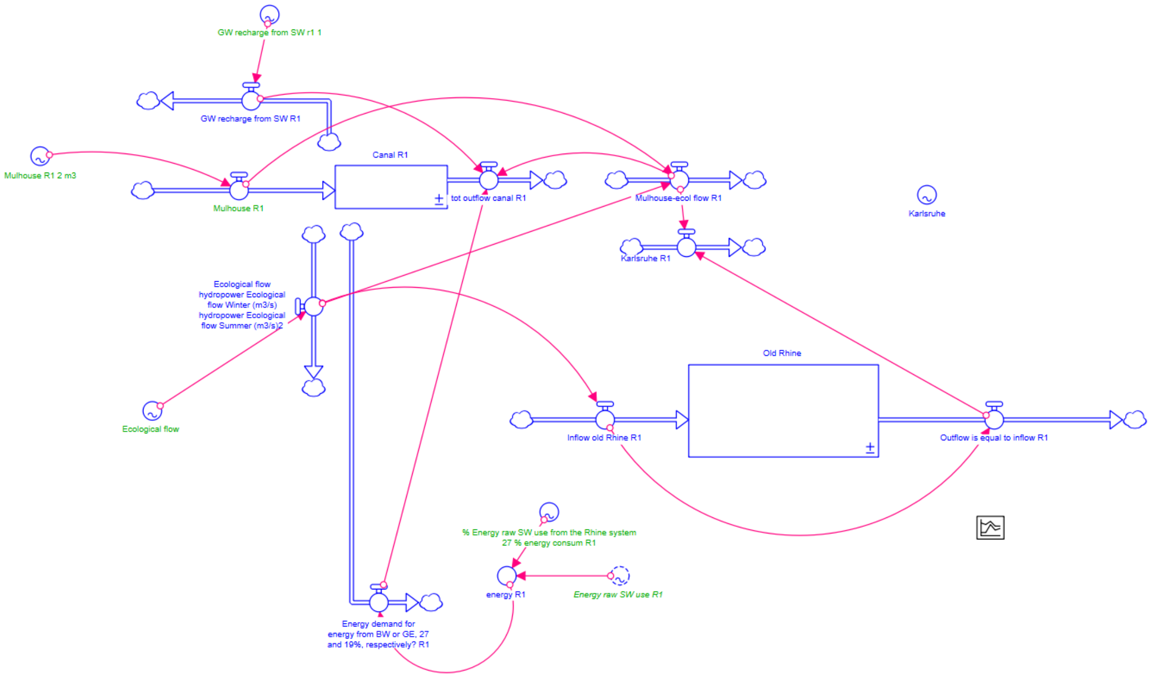

Figure 61: second part of the FR-DE water module describing how water flows between the Old Rhine and the Grand Canal of Alsace in the region, and the connection with the hydropower variable.

3.9.1.3 Land sector

The and sector module tracks a wide number of different land use classes, differentiates agricultural from non-agricultural lands (Figure 62), and assesses the application of fertilisers and ammonia emissions in agriculture (Figures 63 and 64). In terms of the non-agricultural land uses, grasslands, mining sites, wetlands, sealed urban areas, green urban areas, transport infrastructure, forests, and industrial lands are all accounted for. In terms of agricultural lands, fallow land and set-aside is assessed, as well as crop foods (maize, grapes, others), crops for livestock (fodder, maize), and energy crops (maize for biofuels, sunflowers, rape and others). Therefore, the land use sector in this case study is relatively more detailed than in most other SIM4NEXUS cases. The data originates from national statistics, CAPRI data and IMAGE-GLOBIO trends.

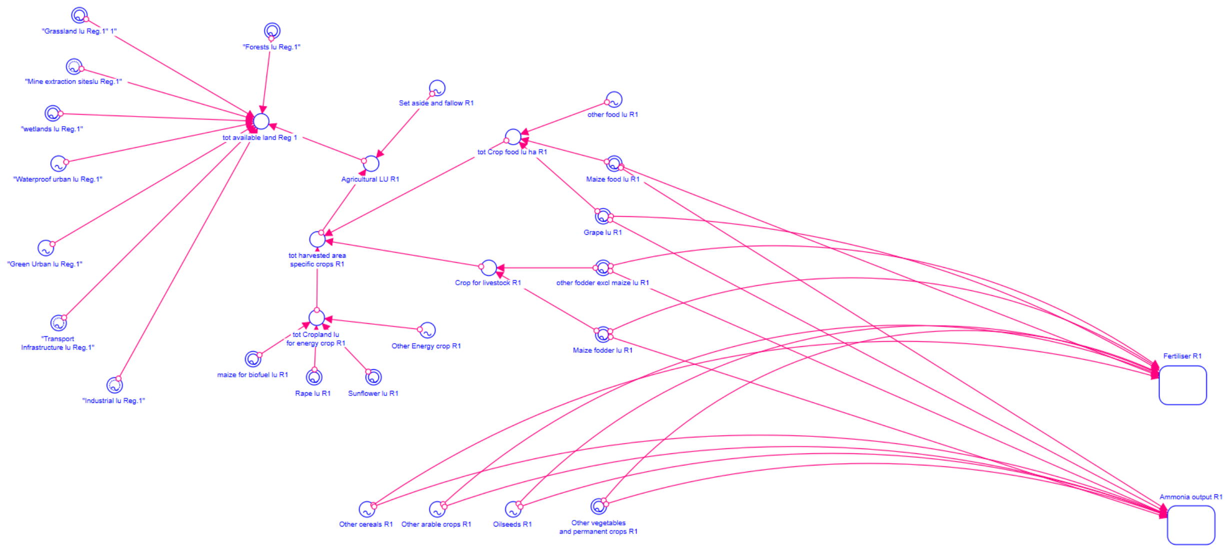

Figure 62: the main land sector module, differentiating between non-agricultural (circles, left), and agricultural (circles, centre) land uses. In addition, the application of fertilisers and ammonia emissions (rounded boxes, right; Figures 63 and 64) is assessed.

For fertiliser application and ammonia emissions, the areas of maize (food and livestock), grapes, other fodder crops, cereals, other arable crops, oilseeds, and vegetables are multiplied with application/emission rates per hectare. The application/emission rates are also specific to the crop types. Therefore, as the areas change, or as application/emission rates per hectare change, the total nutrient application/emission will likewise change.

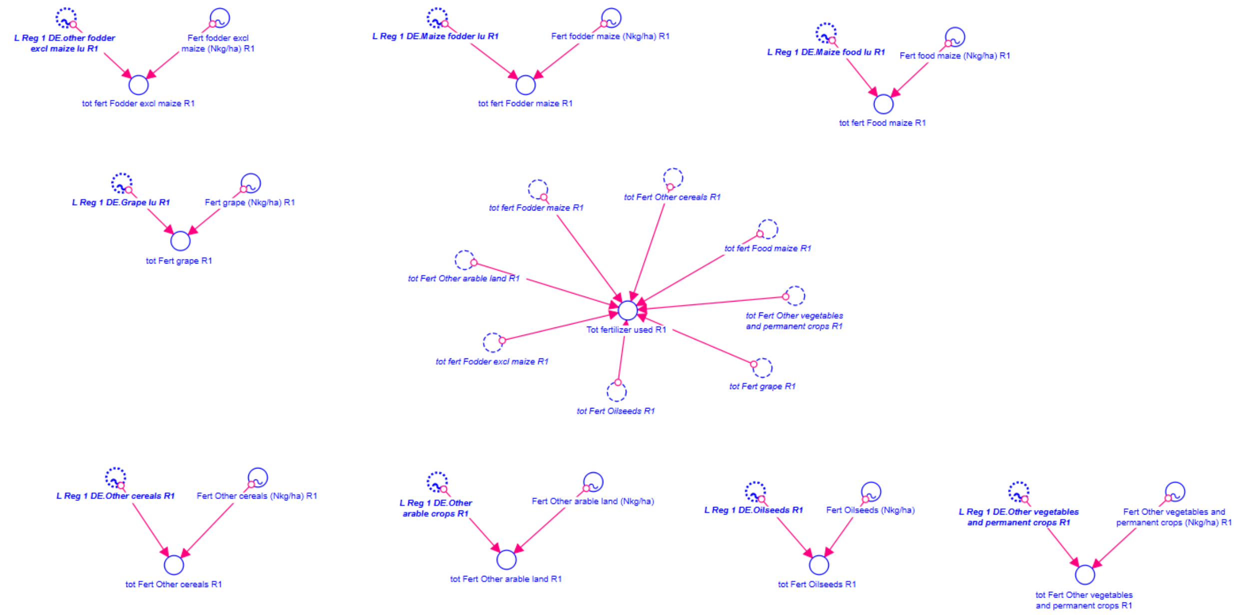

Figure 63: fertiliser application sub-module in the FR-DE case study.

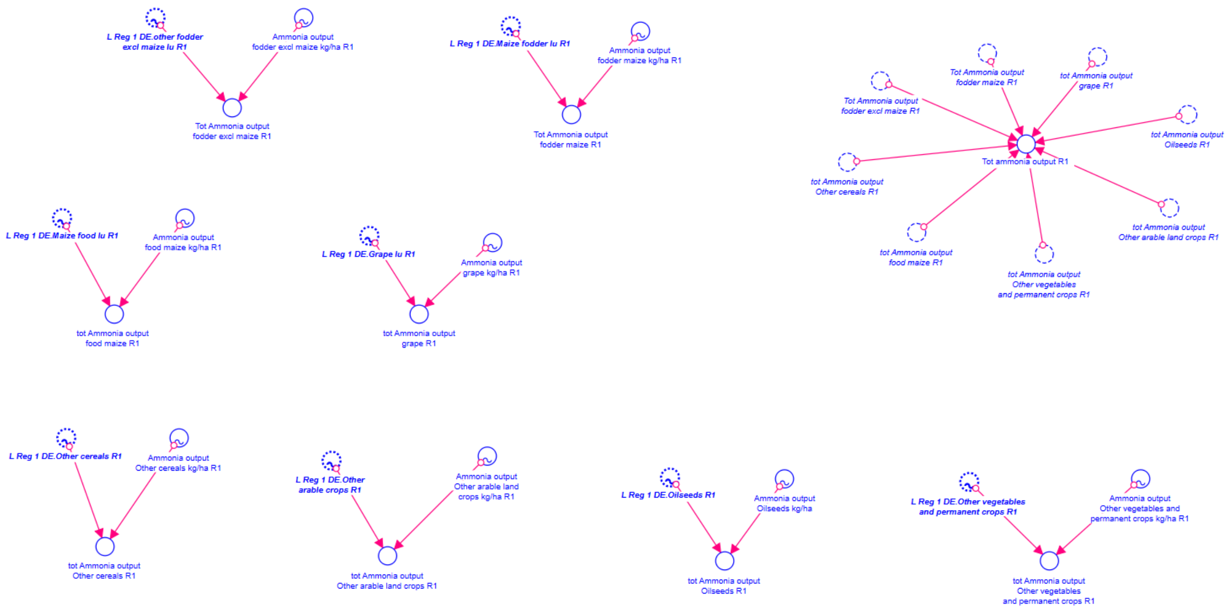

Figure 64: ammonia emission sub-module of the FR-DE case study.

3.9.1.4 Food sector

The food sector module is extremely detailed and complex (Figures 65 to 71). Eleven food types are recognised: wine, meats, fodder, milk, eggs, fodder excluding maize, other cereals, maize, other food from arable land, oilseeds and vegetables. For each food type, the local production, in some cases modulated by land area covered, as well as the net production once imports and exports have been accounted for, are both calculated. In addition, the production of each food type is also assessed in terms of 'raw' food available and in terms of 'processed' food available (Figure 66, 67). The number of livestock (sheep and goats, beef cattle, dairy, ewes and goats, hens, pigs, and poultry) is also tracked and used to estimated methane and manure production (Figures 70 and 71). The input data is taken from CAPRI model.

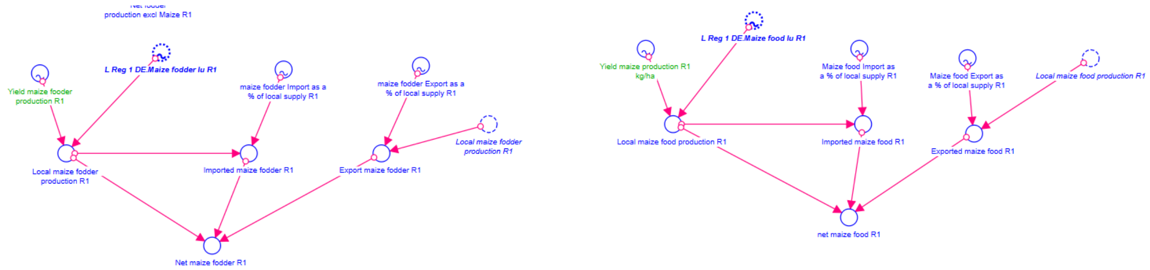

Figure 65: detail showing the structure for two (maize food and maize fodder) of the 11 types (see text for details) in the FR-DE food module. A similar structure is used for the remaining nine types.

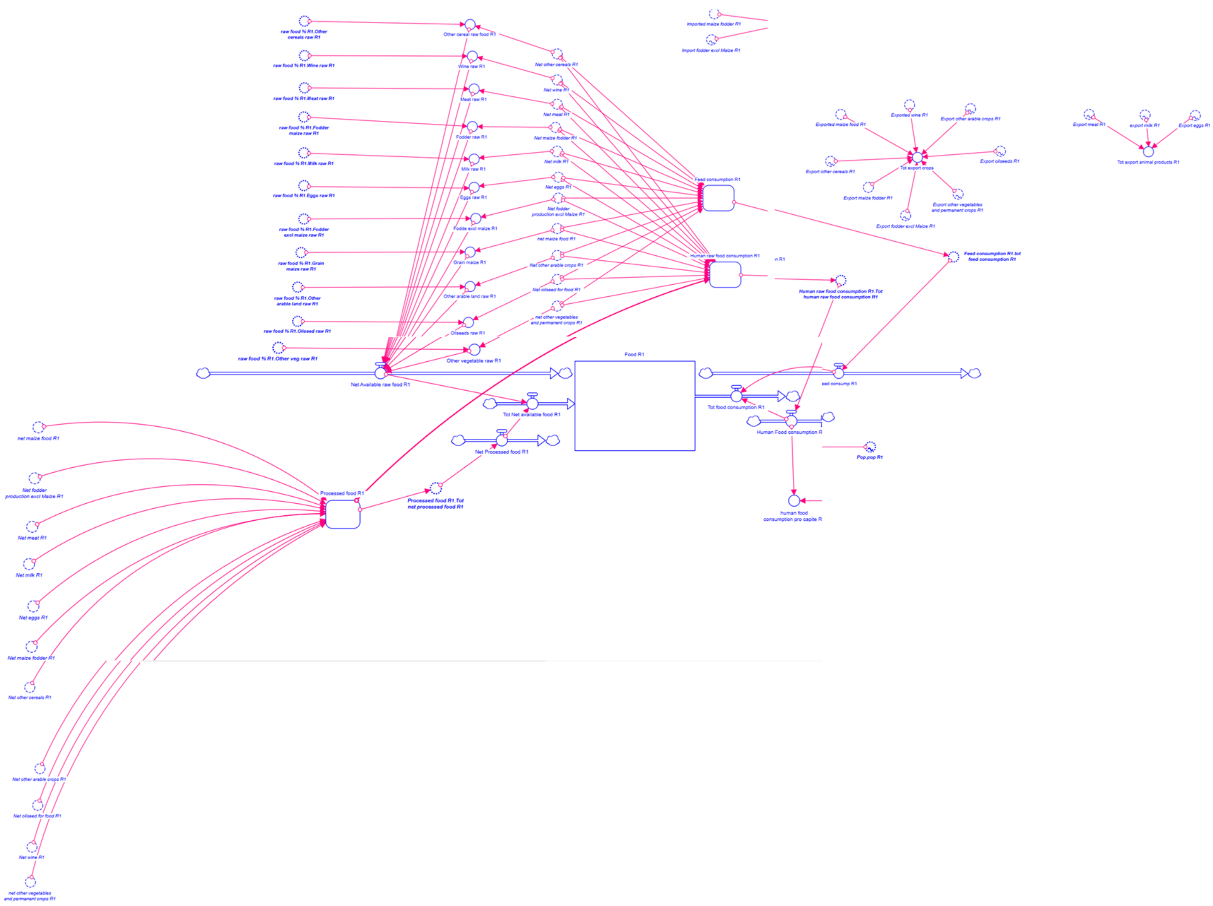

Figure 66: view of the main calculation section of the food module. On the top left the amount of raw food production is calculated. On the bottom left (rounded box), the calculation for processed foods is carried out (Figure 67). The large square box at centre calculates the difference (balance) between food

supply and consumption. The two rounded boxes in the centre-right calculate the food consumption by animals (Figure 68) and humans (Figure 69).

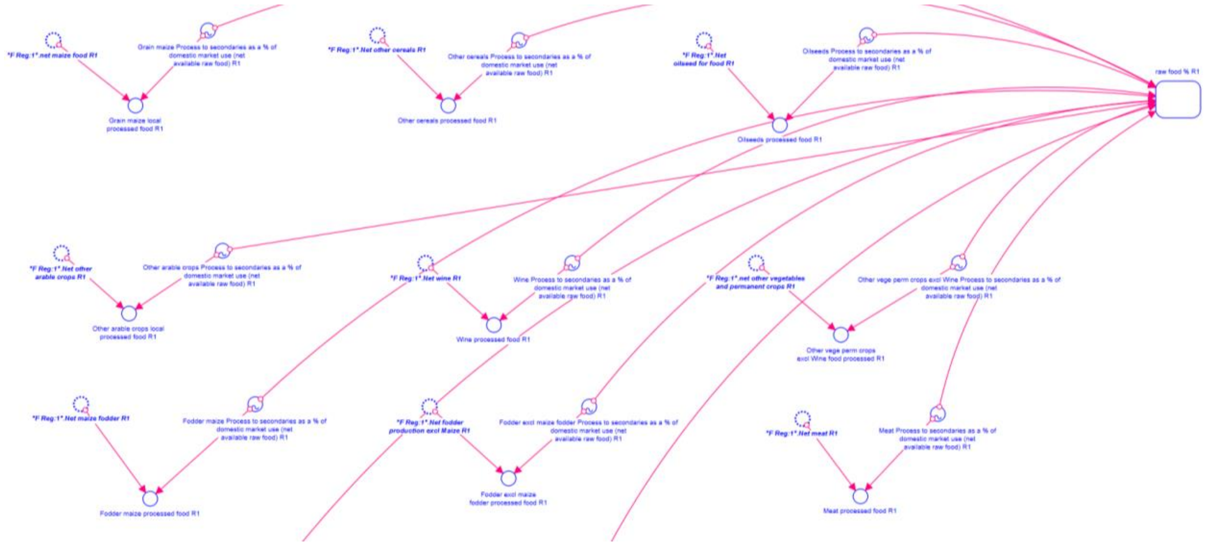

Figure 67: showing detail of part of the sub-module calculating the amount of processed foods. Each food type is multiplied by a specific percentage representing the amount of the raw food that is processed into something else. The amount of processed food for each of the 11 categories is calculated, as well as the total processed food. In addition, the amount of raw food (defined simply as one minus the percentage of food to be processed) is calculated in the sub-module identified by the rounded box in the top right.

On the food consumption side (Figures 68 to 69), this is measured in terms of feedstock consumption for animals (Figure 68), as well as ‘raw’ and processed food consumption by humans (Figure 69), partly modulated by population and consumption factor to estimate the percentage consumption of raw and processed foods respectively. For both, the consumption of each food type is calculated and summed to the regional and case-study levels. Both the food production and consumption sub-groups are summed to give total supply and demand, and are summed with the second region to give case-study totals.

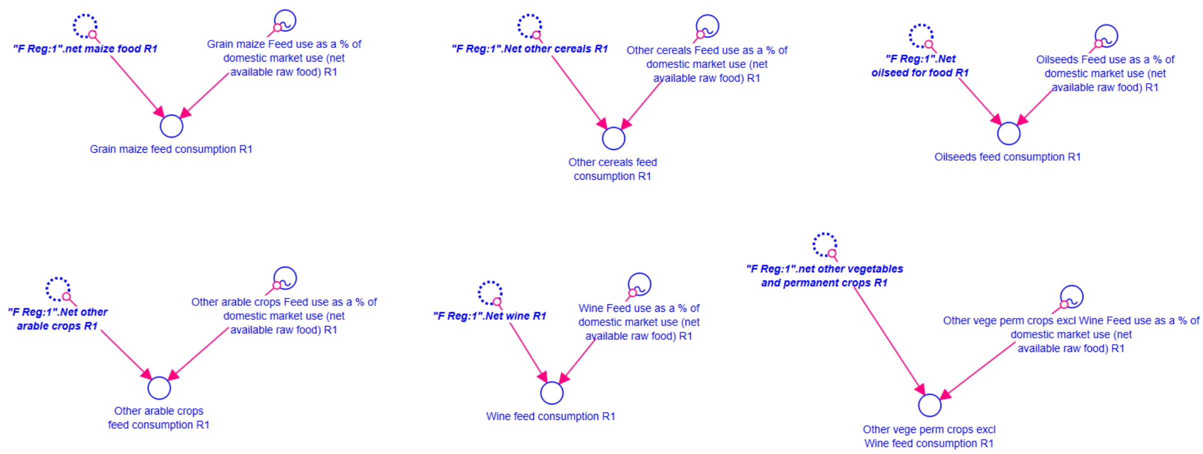

Figure 68: details of the animal feed consumption calculation module. For each food type the structure of the same (i.e. % of food type consumed by animals multiplied by total production of that food type) for all other food types. All food types are summed to give regional and case study totals.

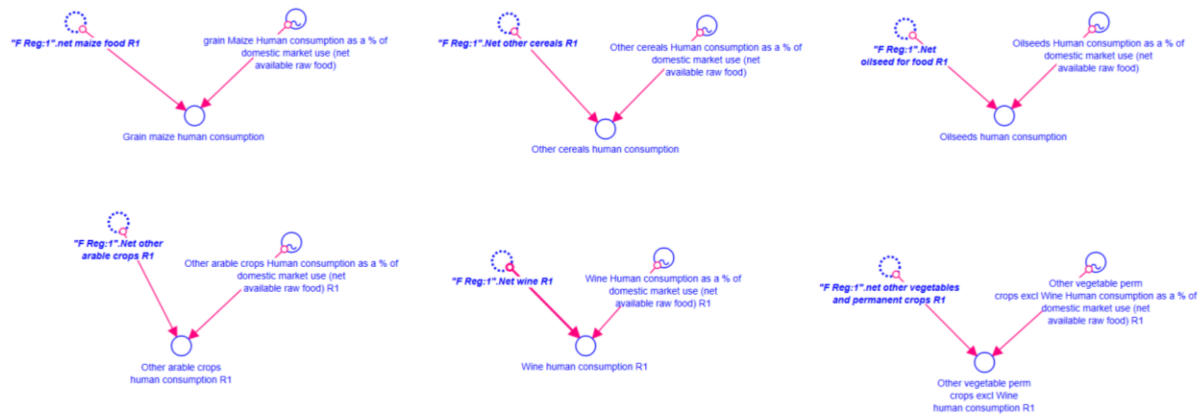

Figure 69: details of the human food consumption calculation module. For each food type the structure of the same (i.e. % of food type consumed by humans multiplied by total production of that food type) for all other food types. All food types are summed to give regional and case study totals.

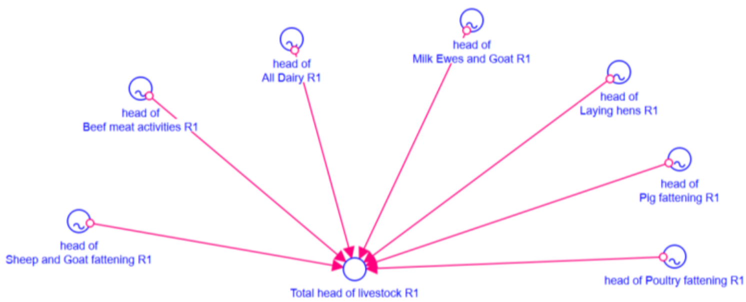

Figure 70: tracking the number of livestock heads produced in the FR-DE case study.

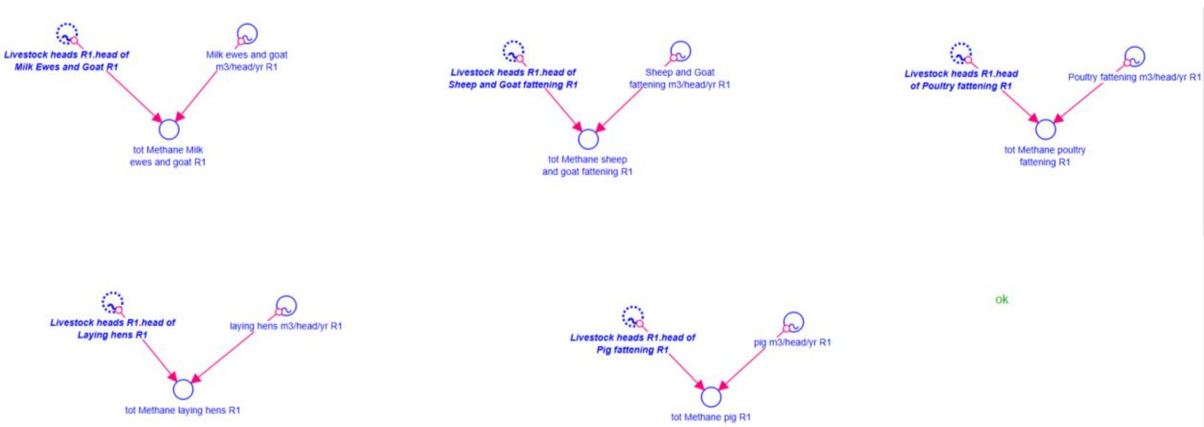

Figure 71: detail of the sub-module calculating methane production from livestock in the FR_DE case study. For all livestock types, the structure is the same. The number of heads are multiplied by a methane release amount, measured in m^3 methane per animal per year.

3.9.1.5 Energy sector

The energy sector considers primary (Figure 72) and secondary (Figure 73) energy production on the supply side, and energy consumption (Figure 74) from a wide range of different sectors on the demand side. A balance between energy supply and demand is calculated for both regions and aggregated to case study level. For primary energy production (Figure 72), oil, natural gas, and other fossil fuels are grouped as fossil fuel sources, while food waste and manure contribute biomass. Wood fuels are also considered. Finally, energy crops consist of sunflowers, rape, maize for biofuels, and other crops.

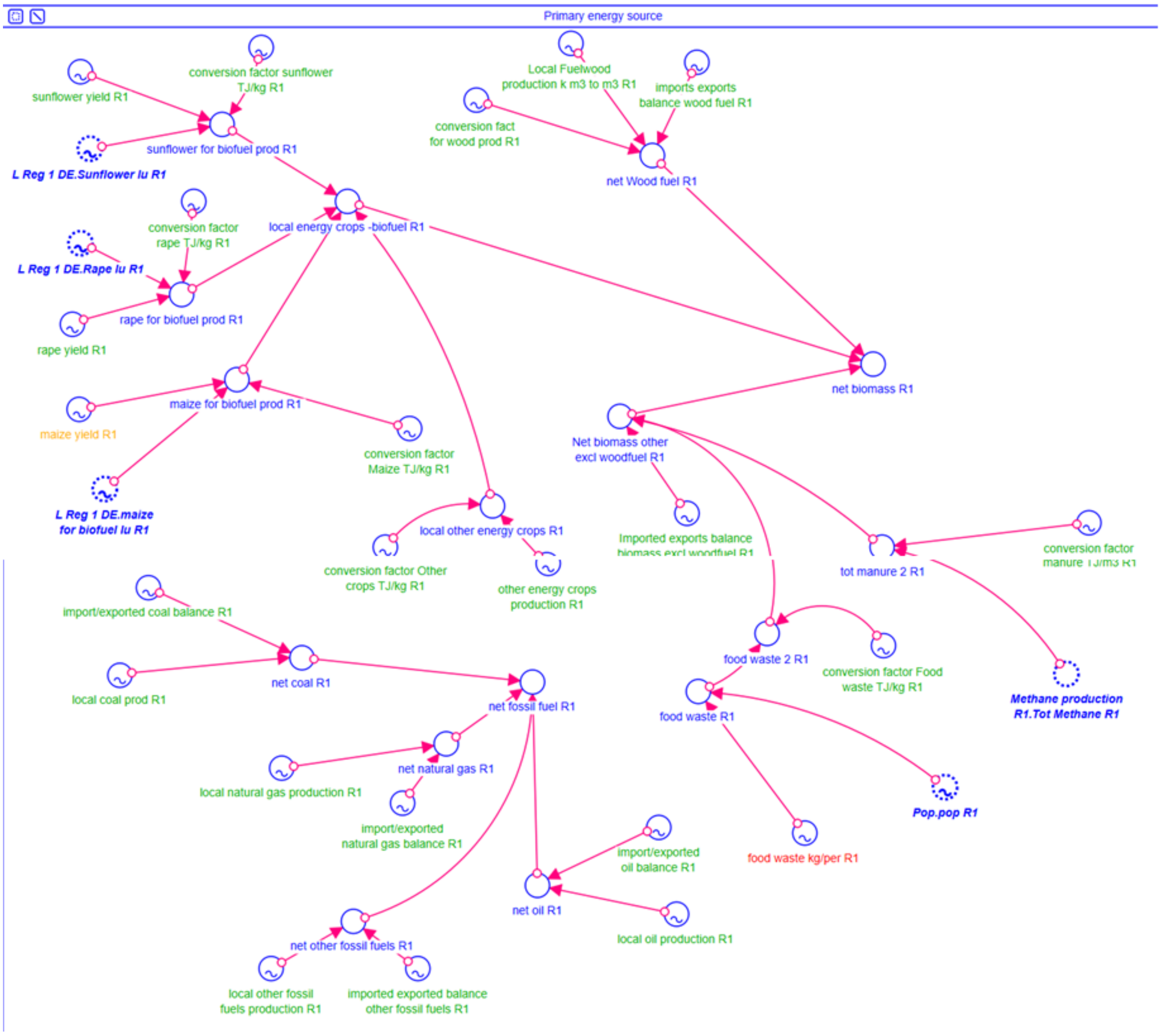

Figure 72: primary energy generation module of the FR-DE case study.

For secondary energy generation (Figure 73), biomass is considered, along with heat and electricity. For heat, solar, thermal from fossil fuels, thermal cogeneration from fossil fuels, thermal cogeneration from biomass, and biomass used for heat production are counted. For electricity, wind, hydropower, nuclear power, solar, biomass, fossil fuels and cogeneration from biomass are taken into account. Imports and exports are considered, so a net generation is given.

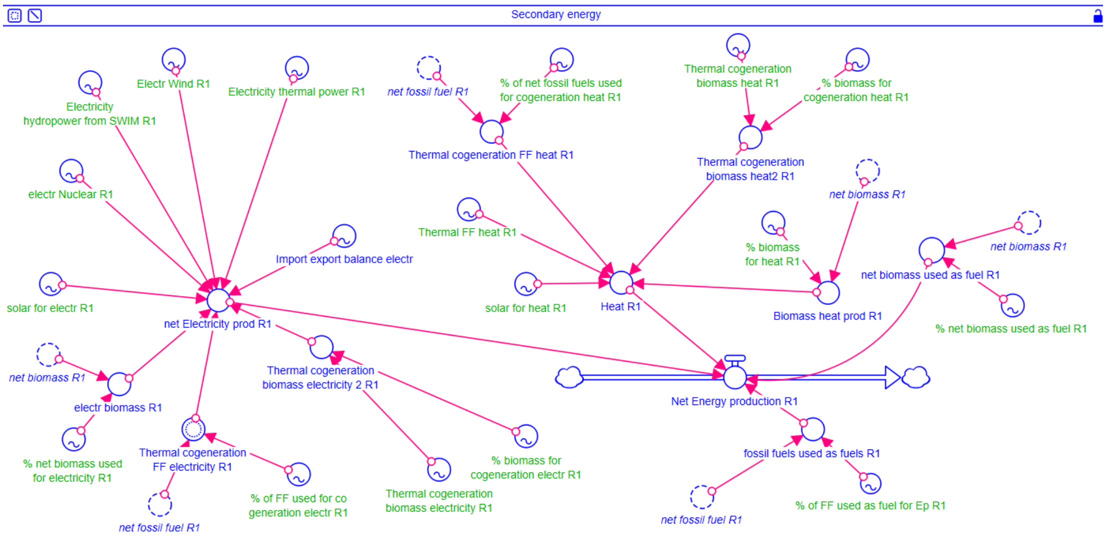

Figure 73: secondary energy computation in the FR-DE case study.

For energy demand (Figure 74), transport, domestic energy use, agricultural demand, industrial use for food processing, energy use for treating potable water, energy use for treating and transporting wastewater, and ‘other’ sectors are accounted for. It is noted that for the two water energy uses, there is a link with the water volumes calculated in the water sector, thus forming a dynamic nexus connection between these two sectors.

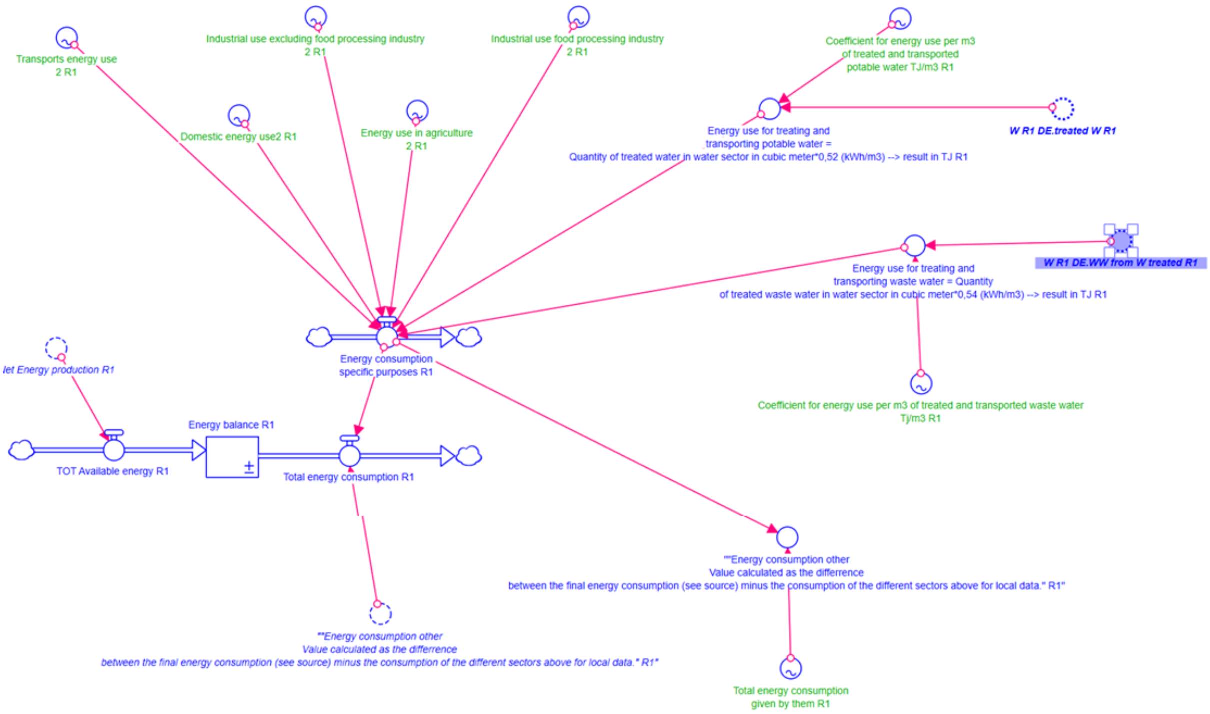

Figure 74: showing detail of the energy sector in the FR-DE case, depicting the energy demanding sectors (circles top and right) and the energy balance (square box on left)

3.9.1.6 Climate sector

The climate sector module is a balance between emissions and sequestration of GHG (Figure 75). Both emissions and sequestration have their own sub modules for the calculations. As with all the case studies, all sources of emissions and sequestration are not taken into account so it is likely that both are under-reported, however the major trends are captured.

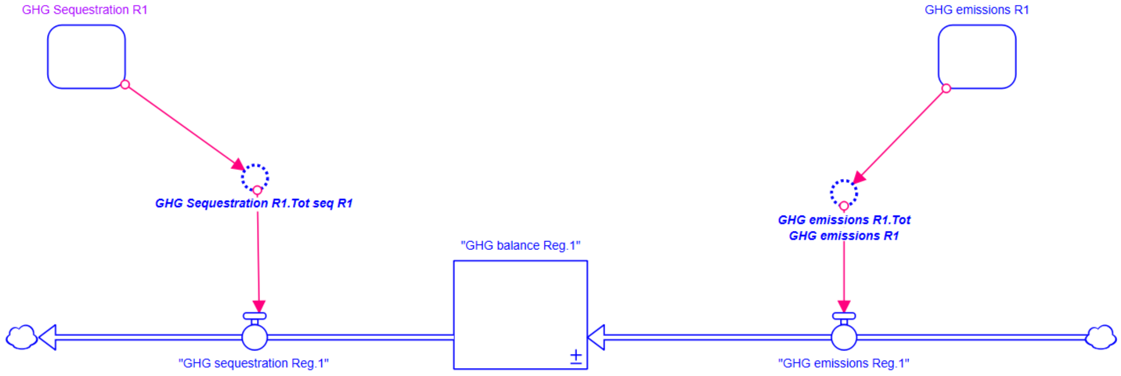

Figure 75: top level of the climate module in the FR-DE case study, showing the GHG balance (square box, centre) between GHG emissions (rounded box, right) and sequestration (rounded box, left).

In terms of emissions, those from manure production and from the energy sector are considered. For emissions from manure production and methane, manure from beef cattle, dairy activities, ewes and goats, sheep, poultry, hens, and pigs are counted. The number of each animal group are multiplied with an emissions coefficient for manure production and methane emissions (Figure 76). All animal types are summed for each region. In the energy sector, emissions from primary and secondary sources are considered (Figure 77). In the primary energy sector, coal, natural gas, wood, biofuels, and oil are considered. In addition nuclear fuels are counted. In secondary energy, wind, solar, and hydropower-related emissions are estimated. Both are summed to give total energy sector related emission for each region, which can be summed to the case study level.

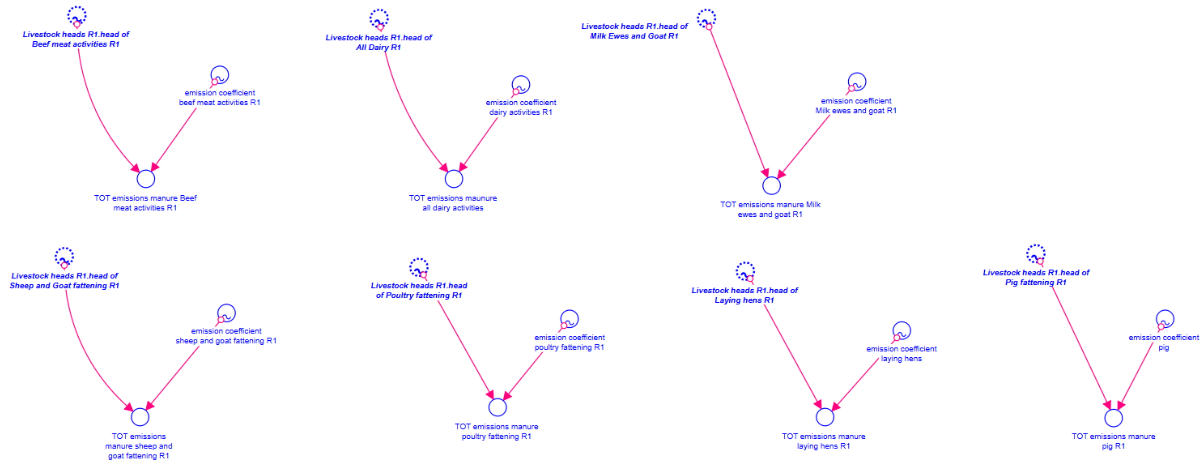

Figure 76: module calculating emissions from manure production in the FR-DE case study.

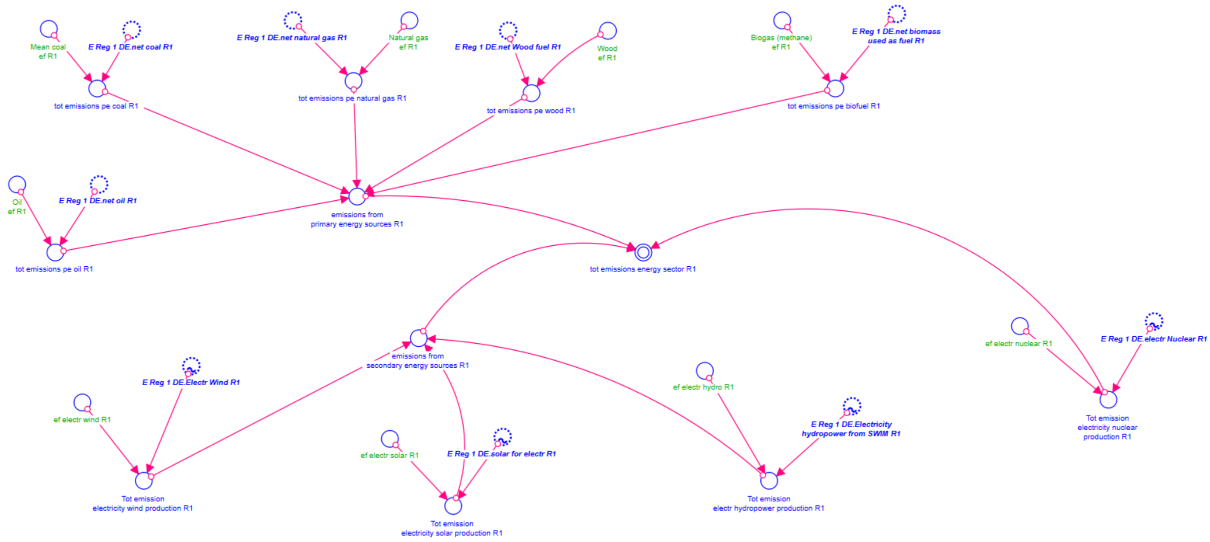

Figure 77: module for calculating emissions from the energy sector in the FR-DE case study.

For GHG sequestration, aquatic ecosystems and agricultural lands are considered as GHG sequestering sectors. In aquatic ecosystems, only wetlands are considered, as the area of wetlands is multiplied with a sequestration factor for wetland carbon stocks. In agriculture, the following land use categories are multiplied with a sequestration factor to give crop-specific sequestration: vegetables, maize (food and fodder), oilseeds, other arable crops, grapes, set aside and fallow land, other cereals, grasslands, forestry lands, green urban areas, permanent crops, and maize for biofuels (Figure 78). Each is summed to give agricultural sequestration potential in each region, and summed to the case study level.

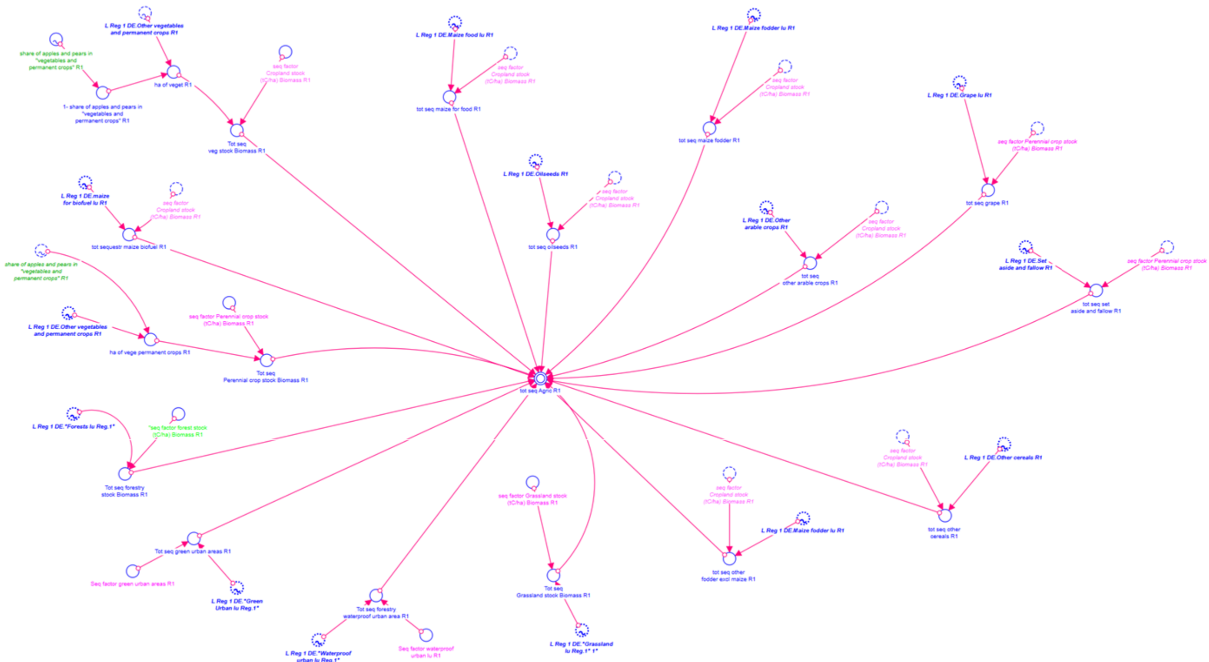

Figure 78: agricultural land GHG sequestration module in the FR-DE case study.

3.9.2 Description of the final results

The datasets and results described here have been built only for the needs of the SIM4NEXUS project's transboundary case study on the Upper-Rhine region. The goal was to put into practice the Nexus approach and contribute to the development and test of associated tools (thematic models, conceptual models, SDM and Serious Game). The goal was not to build a robust dataset to support further research. Therefore, the required reliability of the data and therefore of the results was low to moderate. We recommend great caution in using these results. They are not recommended for decision making purposes.

3.9.2.1 Water sector

The groundwater natural recharge displays an overall downward trend, as a consequence from climate change effect on hydrological patterns. The aquifer recharge is expected to decrease by as much as 50% (from 2011 to 2050).
Water consumption from groundwater resources also shows a downward trend. But the water savings (-9% in Germany and -18% in France) is insufficient to balance the loss of natural aquifer recharge. In the baseline scenario, the depletion of groundwater resources will increase both in France and Germany. Production of drinking water is the largest consumer of groundwater. The volumes will remain stable over the next decades despite the growth of the population.

The surface water discharges are expected to decrease by about 10-15% by the middle of the century. In Germany these lower inflows are compensated by lower water uses, especially for food crops. In France, the water abstractions remain stable over the next decades, possibly leading to water conflicts locally.

Demand from surface water sources shows an initial decrease in demand, followed by a levelling off. Energy sector demand is the largest user, followed by industrial and energy crops water demand. Apart from the energy sector demand, most other sectors show roughly constant demand over time. In terms of total surface water demand to total surface water supply in this region.

Over the next decades, the ecological flows in the MulhouseRhine river discharges section are expected to decline over the course of the simulation (-22% between 2011 and 2050), with the largest declines seen at the start of the simulation. As a consequence, the ecological flow cannot be maintained and the hydropower production is reduced.

3.9.2.2 Land sector

The overall balance between the different land uses will hardly change over the next decades.
Forests expand slightly between 2011 and 2050 (from 35% to 36% of the total land in Germany and from 32% to 33% of the total land in France).
The surfaces dedicated to growing food are reduced a bit between 2011 and 2050, from 16% of the total land in Germany to 14%, and from 28% to 26% of the total land in France (Figure 79).
Urbanisation keeps progressing in France (from 4% of total surface to 5%) and remains stable in Germany. The land occupied by industries slightly grows (from 1% to 2%) in Germany and is stable in France.

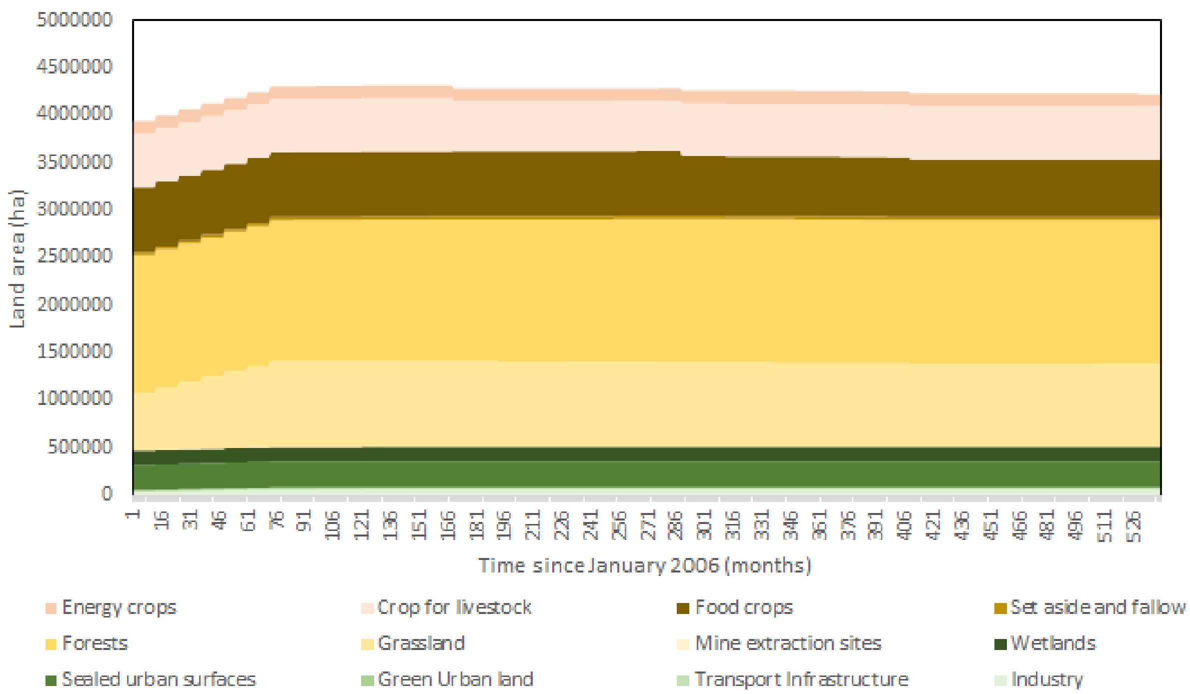

Figure 79: Land use by area for different land use types.

3.9.2.3 Food sector

For the food sector, the total production and consumption in region 1 is shown in Figure 80 and the methane produced in Figure 81. Local food production shows a 26% increase between 2006 and 2050 while feed consumption and human consumption show a 7% decrease and a 14% increase (more than proportionally to the population growth) respectively. As a result, food production exceeds consumption. Methane generation declines throughout the simulation, largely as a result of a decrease in livestock numbers, especially in beef meat and dairy production activities (showing a 29% and 31% decrease between 2006 and 2050 respectively) being the largest emitters.

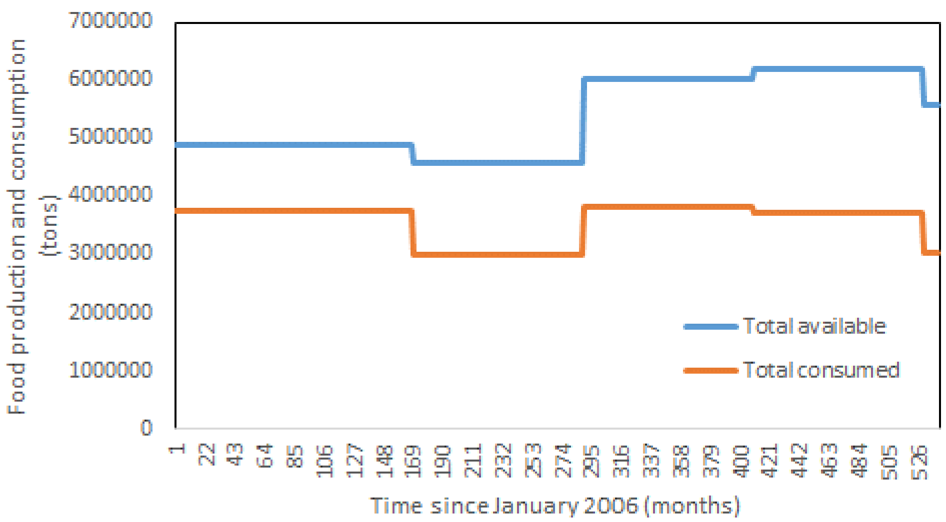

Figure 80: total food production and consumption in region 1 of the FR-DE case study.

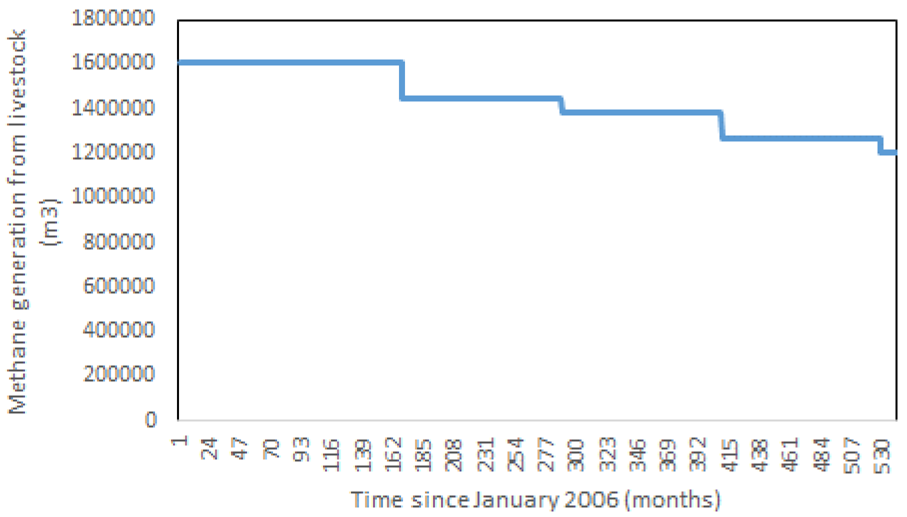

Figure 81: total methane generation from livestock in region 1 of the FR-DE case study.

3.9.2.4 Energy sector

Figure 82 shows primary energy production in region 1 of the case study. The total production is expected to increase slightly initially before showing a gradual decline to the end of the simulation: primary energy production shows an overall 13% decrease between 2010-2050. At the start of the model results, 95% percent of primary energy production is based on fossil fuels (i.e., oil, gas and coal) and the share of primary energy production relying on fossil fuels steadily decreases up 74% in 2050. Thus, fossil fuels still dominate supply by the end of the simulation. While the use of oil and coal for energy production significantly decreases over the study period (47% and 54% decrease respectively) the use of natural gas increases by 4% between 2006 and 2050. Renewable energies show a significant development during the study period (47% and 150% increase in primary energy generation based on biomass and wood energy between 2010 and 2050 respectively), however the relative share of these energies in primary energy production remains modest (from 5% in 2006 to 26% in 2050).

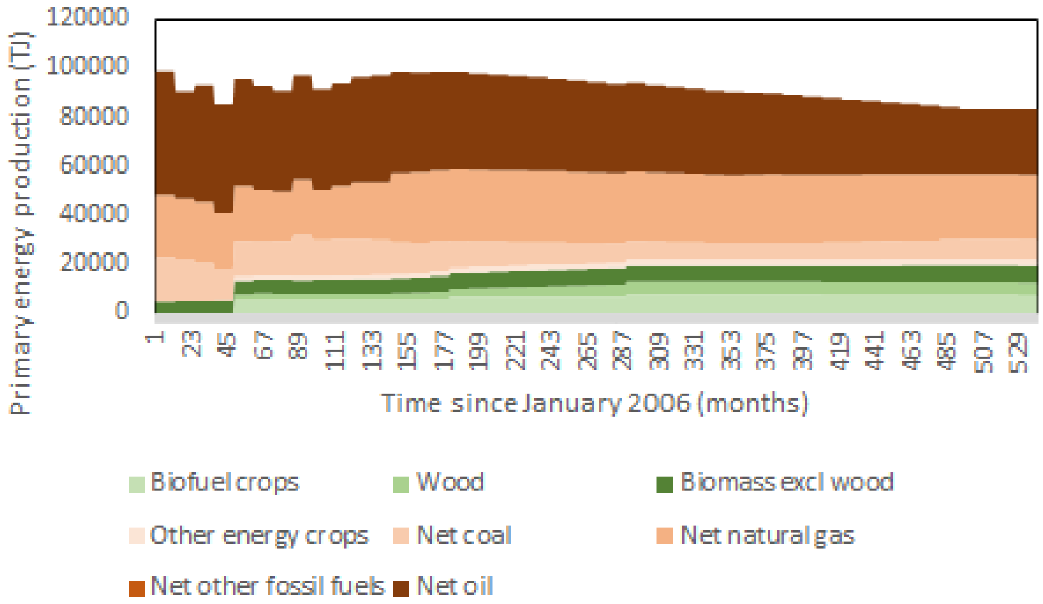

Figure 82: primary energy production by source in the FR-DE case study.

As far as electricity production is concerned (Figure 83), the composition of the energy mix changes significantly between 2006 and 2010: electricity production based on nuclear energy will fall sharply from 2011 until effective denuclearization by 2030. The abandonment of nuclear power is largely compensated by a strong development of photovoltaic, wind and biomass-based electricity (showing a 8,000%, 56% and 380% increase respectively between 2006 and 2010). However, a decrease in hydropower production is observed (-36% between 2006 and 2010), which can be linked with the decrease in the Rhine river discharges discussed previously in Section 3.9.2.1. Besides, a 13% decrease in electricity production from fossil fuels (32% decrease in cogeneration) takes place between 2006 and 2050.

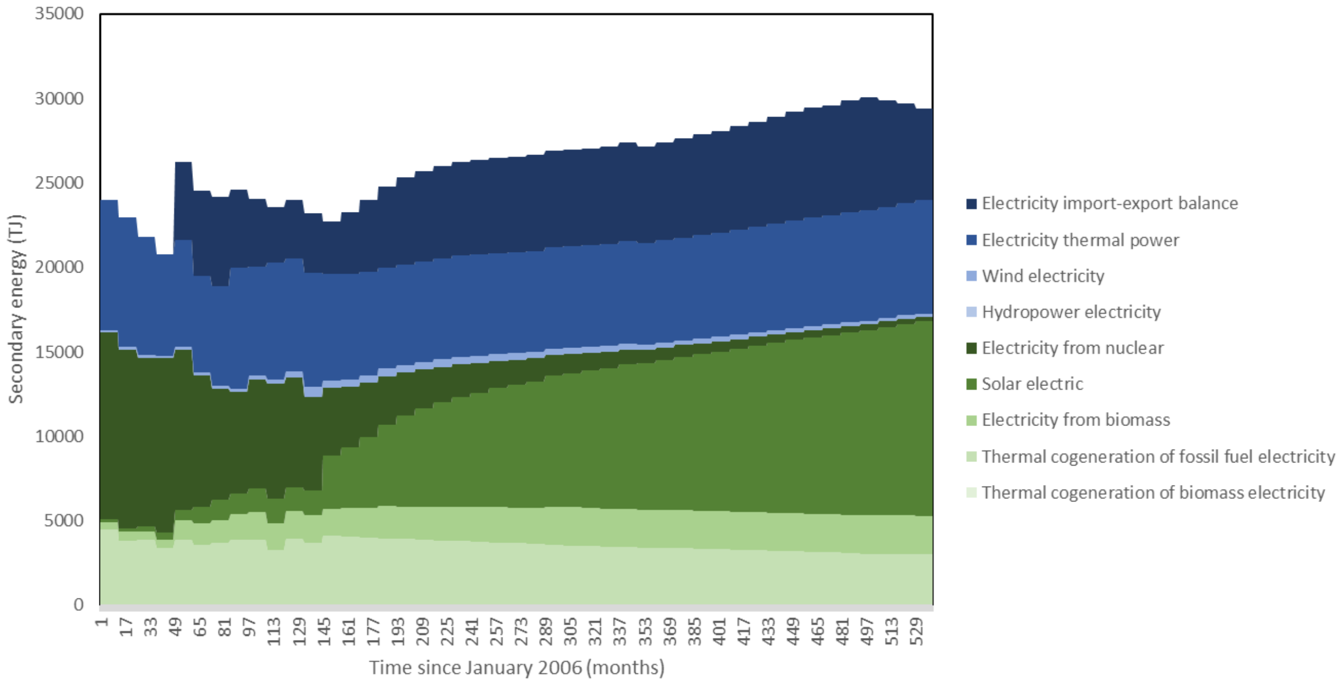

Figure 83: secondary energy generation in region 1 of the FR-DE case study.

On the energy demand side (Figure 84), the overall demand steadily declines over time (22% decrease between 2006 and 2050), which is in line with the objective of the Baden-Württemberg Ministry of the Environment to cut final energy consumption. Four main sectors account for the vast majority of demand and remain roughly constant in proportion over time: transport energy demand, domestic demand, industrial demand, and ‘other’ energy demanding sectors. As a total, energy production is greater than energy demand (Figure 85). While total production slightly increases, total demand is shown to steadily drop during the simulation.

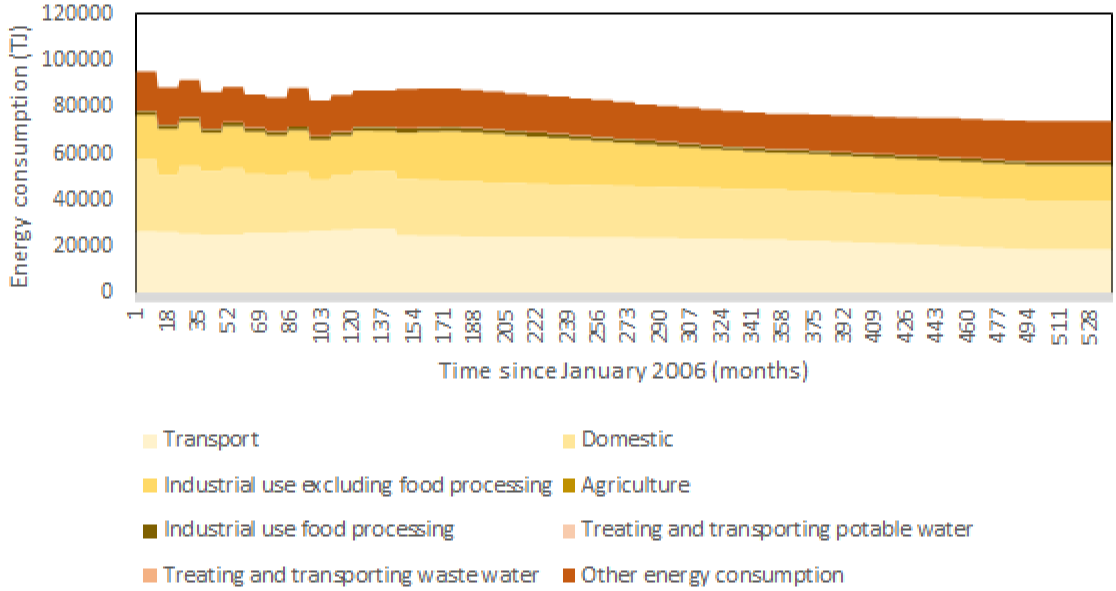

Figure 84: energy demand by different sectors of region 1 in the FR-DE case study.

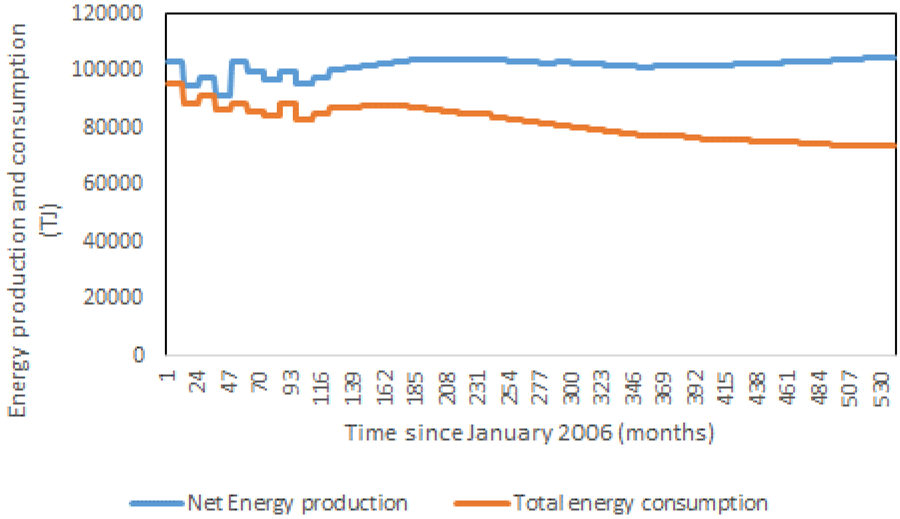

Figure 85: total energy production and demand in region 1 of the FR-DE case study.

3.9.2.5 Climate sector

In terms of GHG emissions (Figure 86), although oil-related emissions remain dominant throughout the simulation, their relative importance does decline steadily over time (47% decrease in oil-related emissions between 2006 and 2050). Likewise, coal-related emissions also drop (54% decrease between 2006 and 2050). Natural gas-related emissions show a slight increase (4%). Emissions from biofuels and wind show small increases over time according to simulation results. In sum however, due to the large drop in oil emissions, total emission levels of GHGs are expected to drop to 2050 compared with recent historical values (30% decrease). Finally, GHG sequestration is far below emissions (Figure 87), however as mentioned earlier, many sequestering factors have not been accounted for.

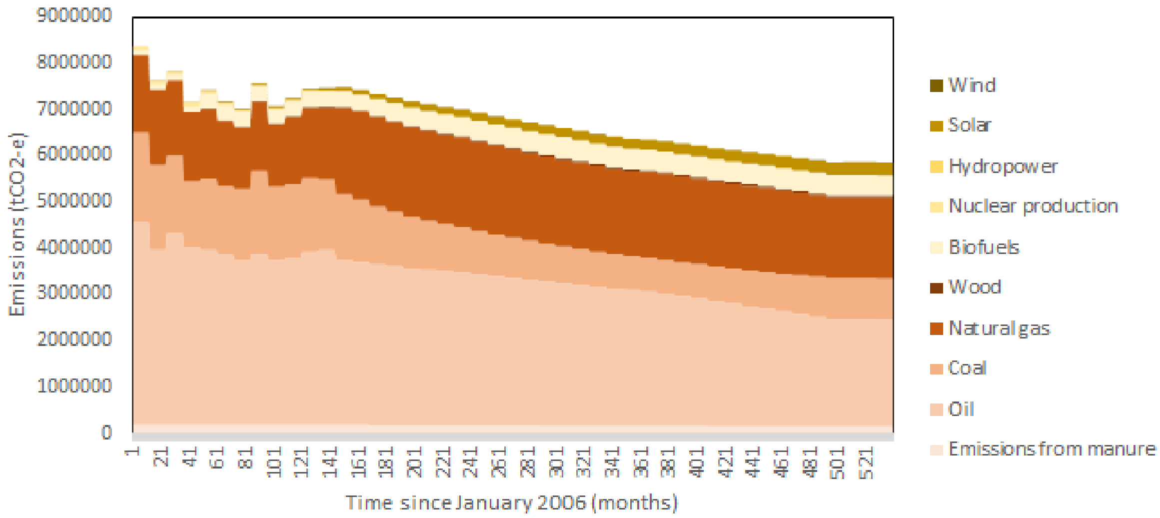

Figure 86: GHG emissions by sector in region 1 of the FR-DE case study.

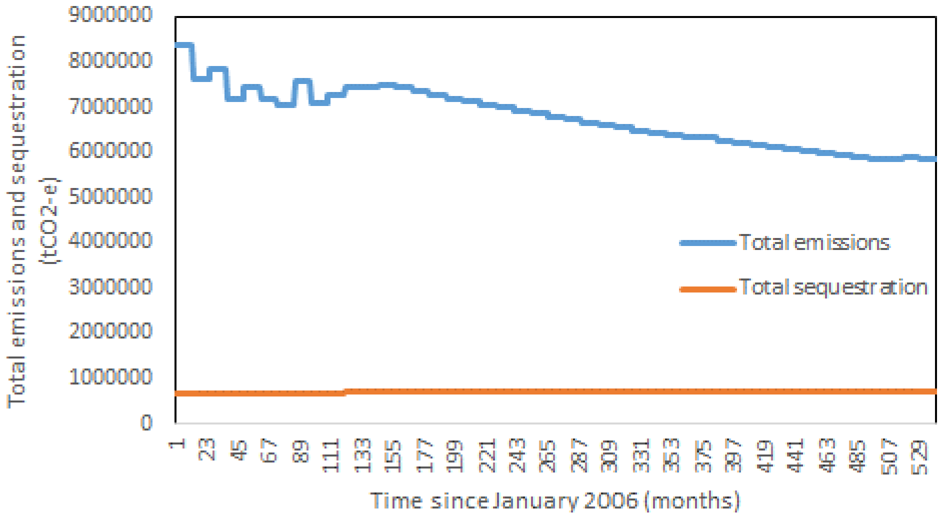

Figure 87: comparison of total emissions and sequestration of GHGs in region 1 of the FR-DE case study. It is noted that many sequestering sectors are not accounted for in this study.

3.10 Transboundary Germany-Czechia-Slovakia case study

3.10.1 Description of the final complexity science model

The transboundary Germany-Czechia-Slovakia (DE-CZ-SK) system dynamics model describes the region along the Elbe shared between these countries. The model is split into 15 regions, five in each country. There is interaction not only between nexus sectors, but also between the regions (e.g. for water flows). In each nexus sector, the same (sub-)model structure is used in each geographical region, allowing replicability and consistency of data and result across the regions (allowing for comparable assessment), and also allows for easy scaling up. As a result of this feature, in the model presentation below, the structure from only one region will be shown, as all other regions are identical in structure, only differing in their data input. The final model consists of 7557 variables in total, with many connections between sectors adding great complexity and depth to the model. The model runs at monthly timestep, starting in January 2010 and ending in December 2050 (i.e. 492 timesteps in total).

Climate is impacted by the land sector, as is the water sector. The food sector is impacted by the land sector and by population. The energy sector is impacted by changes to the water and population sectors. The following sections describe in detail the six model sectors in turn.

3.10.1.1 Population

The population module (Figure 88) estimates each regional population by using a population share in each region relative to the total population in the entire case study. In this way, assuming the shares do not change in each region, the population in each region can be assessed throughout the simulation by having data only for the whole case study area.

Figure 88: structure in the population module of the DE-CZ-SK case study, showing variables to track population shares in the German (left), Czech (middle) and Slovak (right) regions.

3.10.1.2 Water sector

The water sector is represented by 15 interacting sub-modules describing physical water exchanges between the 15 regions in the case study. Within each region, four aspects are calculated in the water sector. First, a soil water balance is estimated, comprising effective precipitation as the supply (with data deriving from SWIM), and actual evapotranspiration, subsurface runoff, direct runoff, and returned water to aquifers as the demand. In addition, the agricultural soil water storage is calculated. Here the supply is effective precipitation over agricultural lands, and is therefore modulated by data from the Land sector. Demands comprise crop water consumption, runoff, subsurface runoff, and recharge to aquifers, all modulated from the land sector. Finally, the surface water resources is the balance between inflows to the region from hydrologically connected regions, outflows to other hydrologically connected regions, and evapotranspiration. Finally in the water sector, crop water consumption for 28 crop types is calculated. For each crop, the actual evapotranspiration per hectare is multiplied by the crop area from the land sector, another nexus connection. Each of the 28 crops is summed to give regional crop evapotranspiration. In turn, the regions can be summed to give case study total crop evapotranspiration.

3.10.1.3 Land sector

The land sector module considers a number of land classes. These include: bare ground, pasture, wetlands and meadows, forests, roads, urban land, water, and crops for food, fodder and biofuels, each of which are further detailed in their own sub-modules. Food crops are composed of other cereals, soft wheat, durum wheat, barley, oats, rye, soya, tomatoes, grapes, other oils, apples, pears, and peaches, other crops, potatoes, other arable crops, vegetables and permanent crops, sunflowers, sugar beets, other fruits, other vegetables, and oilseed crops. Fodder crops comprises of maize, root crops, other arable land, grass and grazing intensive and extensive, and pulses. Biofuel crops comprise maize, rape and ligneous crops.

3.10.1.4 Food sector

The food module calculates the balances (difference between production and consumption) for food crops, feed crops, and biofuel crops for each of the 15 regions. For each of the crop classes, the production and consumption are further detailed. For crop foods, fodder crops, and biofuel crops, the same crops as specified for these categories in the Land sector are accounted (Section 3.10.1.3). On the production side, the land coverage of each crop is multiplied by a time-varying crop yield. Therefore, production is influenced by expected land use changes over time. In addition, policies could also affect the land use of each crop type, and therefore the production. On the consumption side, the time-varying per-capita consumption of each crop type is multiplied by the population in each region. Therefore, as both the population and per-capita consumption change, the total consumption per-crop and overall change in response. Again, policy could act alter both the population and the per-capita consumption values for specific crops (e.g. if emphasis is placed on biofuels in vehicles, the per-capita consumption of these crops may increase in the case study). The demand for each class can be summed within a region, or the demand for a certain type (e.g. food crops) can be summed across regions to give case study totals.

3.10.1.5 Energy sector

The energy sector module focuses on calculating a balance of electricity production and consumption. Demand is a function of per-capita electricity demand multiplied by the population, both of which are time-varying, and both of which therefore influence electricity demand in each region. Supply is considered in more detail. The following electricity production methods are considered: hydropower, solar, biomass, wind, nuclear, coal, lignite, gas, and oil.

3.10.1.6 Climate sector

The climate sector module in the DE-CZ-SK case is unlike any of the others in SIM4NEXUS. The module calculates a few key metrics: 1) the amount of water transported from the ground to the atmosphere in so-called ‘atmospheric rivers’, essentially representing an evaporative cooling potential; 2) the investments in new water retention measures; 3) the volume of new water from measures available for atmospheric cooling potential; 4) the decrease in ‘hot day’ temperature due to different land covers and; 5) carbon sequestration. Initially, the surface and air temperatures are used to calculate the velocity of ascending air. Combined with information on absolute humidity, this is converted into the volume of water released from the land to the atmosphere in the atmospheric rivers. The cost per m3 of new water retention measures over different land use types is multiplied by the volume of potential water retention measures to give total necessary investments in Euros. In addition, via the water retention measures, evapotranspiration is increased, and with this information, the additional water released to the atmosphere (i.e. additional cooling) is calculated. This is then put into practical information by calculating the near-surface temperature reduction on ‘hot days’ over different land use classes, demonstrating the effectiveness of such measures. Finally, carbon sequestration over different land types is calculated. The main outputs from this module are: water transported in "atmospheric rivers"; water transported from the area of landcover in 1 hour; volume of water retention measures; investments in water retention measures; intensity of new water sources created by water retention measures from the area of landcover; new available water for climate cooling released to the atmosphere; increase of agriculture production; sensible heat reduction; decrease of local temperature during heat days; carbon sequestration.

3.10.2 Description of the final results

In these results, only results in Region 6 (out of the 15 regions) will be shown due to space issues. In addition, due to the volume of results, only the most pertinent to the case study will be shown.
The results have been checked and validated by the local case study partners in SIM4NEXUS. On the water sector, while the flow volumes are slightly higher than expected, their trends are consistent with what is expected. However, the soil water outputs are believed not to be representative, possibly due to erroneous data transfer to the SDM. It is suggested that the soil water results are not used for future modelling purposes unless these outputs are updated. In the land and food sectors, the outputs are reporting values from the CAPRI model which closely agree with the SWIM model output. In the energy sector, the simulated output is reasonably well correlated with observed data and are therefore realistic. Further comments on the results are provided under each sector as appropriate.

3.10.2.1 Water sector

Results here focus on agricultural water availability and consumption, and the agricultural soil water balance. Water availability is from effective rainfall, while consumption is from crop water consumption (defined by actual evapotranspiration of the 28 crop types defined in Section 3.10.1.2, runoff from agricultural lands, and recharge from agricultural lands to underlying aquifers. Annual seasonality and inter-annual variability is clearly depicted in all variables. No obvious long-term trend in rainfall or crop water consumption is visible. When inflows and outflows are summed, the net agricultural soil water balance is negative, suggesting longer term soil water depletion, and therefore the potential for increased irrigation water inputs over time, or to increasing competition for water resources with other sectors. This may lead to reduced sustainability and increasing water stress issues over time, or to increasing water-related conflicts (at least in this region of the study area).

Note from Case Study owners:
The results confirm the broad trends of landscape drainage and soil water depletion. However the models cannot distinguish the process of its drainage caused by overheated surfaces and also evapotranspiration cannot be considered always as a water 'loss'. In general, the water and climate nexus is very tight, cannot be separated easily and may be considered as a challenge for climate/hydrology/meteorological models.

In the hydrological balance, evapotranspiration, along with outflow, is classified as "loss" components. Is this really so? Logically considered, a dry harvested field and a paved area do not lose water by evaporation, while the forest, wetland, and especially the water surface, evidently evaporate water and therefore worsen the water balance. However, our logic is tricky: solar radiation reaching 1000 W.m-2 on a clear day heats the surface of the drained areas up to 60 ° C. Air is heated from the overheated surface area and rises upwards. Air at 40 ° C and 20% relative humidity contains 10 g of water (in the form of water vapour) in one m3. Even with a very slow upward flow of 0.1 m/s, it will raise 360 m3 of heated air by 1m2 in one hour, carrying 3.6 kg of water. The overheated surfaces "suck" the air from the surroundings, i.e. from the neighbouring forest, fishpond, or wetland, and the warm air brings water vapour to the upper atmosphere. Evapotranspiration-condensation processes are slowed down in places where there is a lack of water and resulting in an open water cycle. Solar radiation is transformed into sensible heat on areas without vegetation. The sensible heat flux is represented by the total amount of all heat exchanges, which are accomplished by conduction and convection between the Earth's surface and the atmosphere. The overheated surface warms the air layer over it. Warm air raises turbulently upward, causing instability of the atmosphere. In addition, it is able to accommodate a higher amount of water vapour which it draws from the surrounding wet areas. Subsequently, the water vapour is transported to higher layers of the atmosphere where condensation occurs. The landscape is more intensively dried and is gradually causing drying out of areas that have not yet suffered from water scarcity.

Conversely, evapotranspiration-condensation processes work in places where there is enough water and permanent vegetation. In general, vegetation is able to dampen temperature extremes, thereby reducing the temperature of the Earth's surface. The stands with developed vertical structure (especially forest) differ in vertical temperature distribution from simple monocultures (crops, grass). An inverse temperature gradient is created during a sunny day in the forest / under the trees: the temperature in the herb and shrub floor is lower than the temperature in the canopy. Relatively heavier cold air stays on the ground and does not rise. Thus, high humidity is maintained on the lower floors of the vegetation, often in the form of dew. In crops, the vertical temperature profile is reversed. In sunny weather, the temperature at ground level is significantly higher than on the surface of the stand. The soil between the crops is often bare; all vegetation (weeds) is intentionally destroyed by herbicides. Air is heated from the soil surface and rises up through the vegetation. The warm air holds a high amount of water, the soil surface dries quickly, and the crops loose water, while in forest water is maintained due to temperature inversion. Because the surface of the canopies approaches the air temperature, there is not much sensible heat to ascend into the air. Water vapour-saturated air slowly rises and soon reaches dew point, creating local afternoon / evening rainfall, returning some of the evaporated water. A closed water cycle is formed, so evapotranspiration is not a loss. It is necessary to distinguish two processes – drainage of the landscape caused by overheated air which sucks water from the surroundings, transports it into the upper atmosphere with a small chance of precipitation and evapotranspiration with its cooling effect which “recycles” water (Pokorný 2019; Pokorný et al. 2016; Huryna et al. 2014; Hesslerová et al. 2019)[3].

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3.10.2.2 Land sector

In total, the utilised area is c. 900,000ha, of which c. 200,000 ha is food crops, and the remaining 700,000 ha belong to the other categories. In terms of food crops, soft wheat dominates the areal contribution

[3] Pokorný, J., Hesslerová, P., Huryna, H., & Harper, D. (2016). Indirect and direct thermodynamics effects of wetland ecosystems on climate. In: J. Vymazal (Eds.), Natural and Constructed Wetlands. Nutrients, heavy metals and energy cycling, and flow (pp. 91-108). Springer - Cham.
Pokorný, J. (2019). Evapotranspiration. In B.D. Fath (Ed.), Encyclopedia of Ecology,2nd edition, vol. 2 (pp. 292–303). Oxford: Elsevier B.V.
Huryna, H., Brom, J. & Pokorný, J. (2014). The importance of wetlands in the energy balance of an agricultural landscape. Wetland Ecology and Management, 22(4), 363 – 381.
Hesslerová, P., Pokorný, J., Huryna H., Harper, D. (2019): Wetlands and forests regulate climate via evapotranspiration. In. An, S. and Verhoeven J. T.A. (Eds). Wetlands: Functions, Restoration and Wise Use. Ecological Studies 238, Springer, s. 63 – 93.

throughout the simulation, followed by oilseeds and barley. Overall, a decline of about 10% of food crop area by 2050 is expected according to the model results. For non-food crops (Figure 256), fodder, evergreen forests, and pastures make up the majority of the area. All categories are roughly constant over time. There is no appreciable areal change over the duration of the simulation.

3.10.2.3 Food sector

For food crops, production is always greater than local consumption, and this gap grows over the simulation, suggesting possibly greater significance of exports from the region of food crops. Production is estimated to almost double, while human demand grow only slightly. For animal feed the pattern is very similar, with a significant growth in production not matched by the growth in local demand. Finally, for biofuel crops, local demand is negligible, while production more than doubles during the simulation. Again, this could suggest a greater role of exports of these productions from this region in the case study.

3.10.2.4 Energy sector

Consumption exceeds production, implying imports from other regions, or from places outside the case study. Production is expected to increase throughout the simulation while consumption initially drops then starts to rise again. On the production side, solar electricity is expected to rise dramatically, from almost nothing to becoming the dominant source of electricity by 2050. Wind power is likewise expected to rise markedly. Electricity from coal power however is expected to decrease from the most dominant source at the start of the simulation to a relatively minor component of the electricity generation mix by 2050. This implies a greener electricity power mix by 2050.

3.10.2.5 Climate sector

In the climate sector for this case, the focus is on water retention measures implementation, their cost, and their impact on the local climate in the study area. By far the largest volumes are found on crop land, followed by pastures, forests and in urban areas. Other land use types show far less potential. In terms of the associated investment costs, cropland expectedly shows the highest costs, but urban areas (with only the 4th largest volume potential) show costs almost as high as on cropland. This is possibly due to the far greater infrastructure and service disruption in urban areas associated with new developments of this nature. Pastures and forests show the next highest costs, with remaining land types showing the lowest investment costs. It seems that cropland therefore offers good value for money in terms of Euros per volume of retention, especially when compared with urban areas.

Similar to the potential volumes, cropland shows the greatest amount of water available for atmospheric cooling, followed by forests and pastures, with almost the same pattern therefore being seen in the reduction of sensible heat. The measures could offer up to a 1.4°C local temperature reduction over croplands, with lower reductions (0.2-0.5°C) on forest and pastures and in urban areas. These reduction could then lead to lower irrigation water demand, air conditioning requirements, and a more comfortable urban environment.

The greatest potential comes over those lands with the greatest area: crops, forests and pastures. All land classes show roughly constant carbon sequestration over time.

Note from case study owner:
The results confirm the fact that the agricultural landscape has a high potential for temperature reduction after the implementation of water retention measures. The local temperature reduction values were validated with a model of water retention measures for municipalities in the East Slovakia – Trnava region (Kravčík 2020) that uses methodological concept presented in Landscape Restoration Policy Brief (SIM4Nexus project output). Based on both empirical experience and this model, there are discrepancies with the values reported for urban areas, which are probably underestimated. Although these areas often occupy a small area in the landscape, their impact on the local climate and runoff is crucial. They contribute up to 26% to the drying up of the landscape. When implementing water retention measures in urban areas, a reduction in temperature of up to 4 ° C can be expected.

Based on the methodological concept, we present as validation example of one of the municipalities in the Trnava region, for which the benefits of investing in water retention measures were calculated (the land cover types are adapted to local conditions).

Municipality Bučany (SK)	**Crops**	**Vineyards**	**Gardens**	**Orchards**	**Permanent grassland**	**Forest**	**Urban areas**	**Other**	**Total**
Area in ha	**1415,78**	**7,54**	**42,81**	**1,46**	**5,84**	**19,35**	**11,55**	**24,46**	**1658,31**
Runoff [m^3]	**89 422**	**889**	**4 199**	**116**	**573**	**1 222**	**45 496**	**9 634**	**151 551**
Investments €	**447111**	**4444**	**20994**	**581**	**2864**	**6111**	**1273883**	**48172**	**1 804 160**
New water source (l/s)	17,88	0,18	0,84	0,02	0,11	0,24	9,1	1,93	30,31
Increased evapotranspiration m3	59615	592	2799	77	382	815	30331	6423	101034
Increase of crop production €	212366	1131	6422	218	876	2903	17331	3670	248 746
Reduction of sensible heat GWh	62595	622	2939	81	401	856	31847	6744	106086
Decrease of local summer temperature °C	-0,66	-1,24	-1,03	-0,84	-1,03	-0,66	-4,14	-4,15	-0,96
Carbon sequestration (t)	3964	21	120	4	16	54	324	69	4644

The values calculated for forest stands are relevant, however depends on their health status. The results were validated on the basis of the study "Assessment of the condition and function of forests on selected forest property in changing ecosystem conditions" prepared (by ENKI) for the Ministry of the Environment of the Czech Rep. and the article by Hesslerová et al. 2018 . The data show that in the case of deterioration of forest health or complete decay of the stands, their ability to local temperature reduction will substantially decrease, the costs associated with their restoration and loss of climate ecosystem function are in the order of 1.5 million EUR / ha (Seják et al. 2018)[4] that exceed the cost of restoration the agricultural landscape.

[4] Kravčík, M. (2020). Ozdravovanie klímy Trnavského kraja – I. Etapa (Climate recovery of the Trnava region – I. Stage). In Slovak.
Hesslerová, P., Huryna, H., Pokorný, J., Procházka, J. (2018): The effect of forest disturbance on landscape temperature. Ecological Engineering 120, 345 - 354.
Seják J., Pokorný J., Seeley K.(2018): Achieving Sustainable Valuations of Biotopes and Ecosystem Services Sustainability 10(11), 4251; https://doi.org/10.3390/su10114251

3.11 European case study

3.11.1 Description of the final complexity science model

The European (EUR) system dynamics model describes the entire European continent split into six regions: R1 – Eastern EU; R2 – Eastern non-EU; R3 – Northern EU; R4 – Southern EU; R5 – Western EU; R6 – Western non-EU. In each nexus sector, the same (sub-)model structure is used for each geographical region. This allows replicability and consistency of data and result across the regions (allowing for comparable assessment), and also allows for easy scaling up to continental totals. As a result of this feature, in the model presentation below, the structure from only one region will be shown, as all other regions are identical in structure, only differing in their data input. The final model consists of 1702 variables in total. The model runs at monthly timestep, starting in January 2011 and ending in December 2050 (i.e. 480 timesteps in total).

The top level of the model (Figure 89) shows how the five nexus sectors are related. Climate is impacted by the land, food, and energy sectors, while water is impacted by changes in the land and energy sectors, and by population. The food sector is impacted by changes to the land sector.

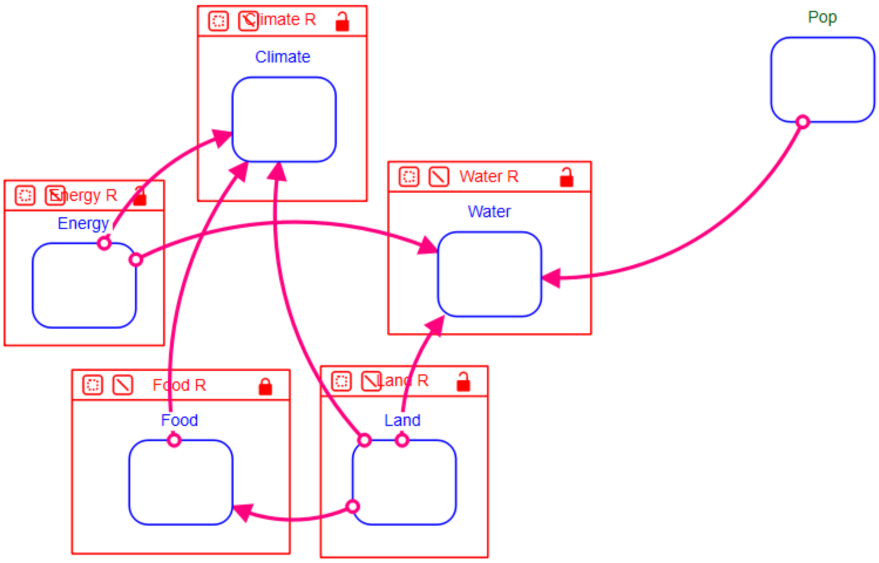

Figure 89: top level model structure of the EUR case study.

3.11.1.1 Population

In the population module, the population for each geographical region, both historically and projected to 2050, is tracked (Figure 90). The regions are summed to continental totals.

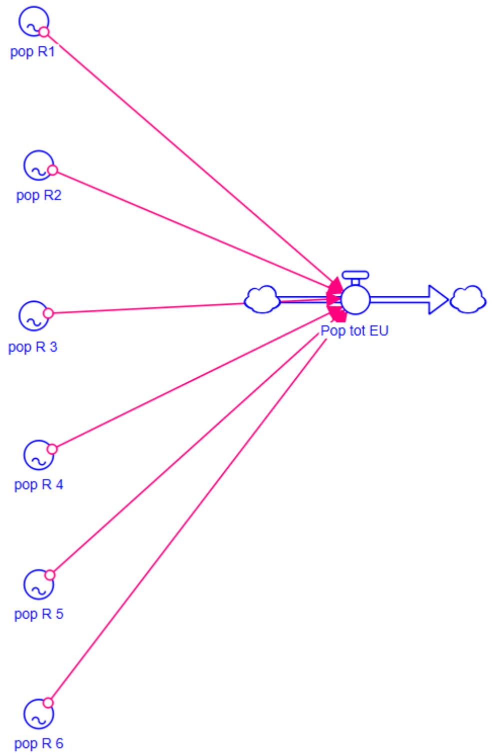

Figure 90: EUR case study population module structure. Each of the six regions is tracked individually (left) and summed to a continental total (right).

3.11.1.2 Water sector

In the water sector, each region is represented separately. At the EUR level, irrigated agricultural water withdrawals and total water withdrawals are explicitly summed to be tracked. All other variables can be aggregated as desired. With each region, only withdrawals are considered, and as such, there is no supply-demand water balance. Water is withdrawn for: nuclear electricity; fossil-based electricity generation; biomass electricity generation; electricity from hydropower; electricity from solar and wind sources; municipal water demand; and irrigated agriculture (Figure 91).

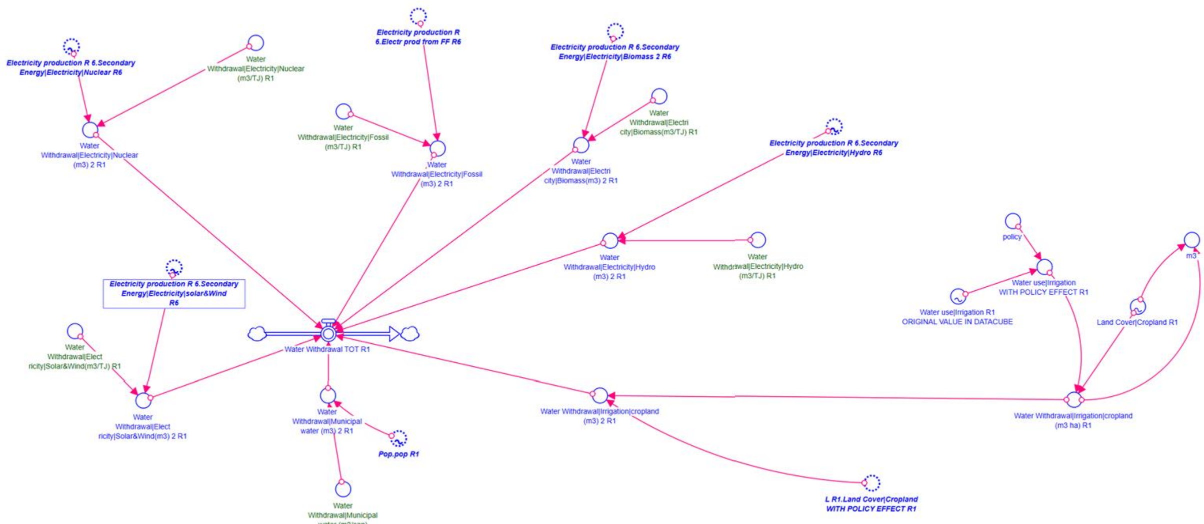

Figure 91: the water sector module for a typical EUR region.

3.11.1.3 Land sector

The land sector (Figure 92) computes EUR land uses split by land use type for each region. In addition, the EUR total land use, as well as the EUR land use per land use type are aggregated (Figure 92). In terms of the land uses counted in the model, the following are included (Figure 93): rainfed cropland; irrigated cropland; energy cropland; pasture lands. Other land use classes such as built up areas, infrastructure, and forests were not included in the computations.

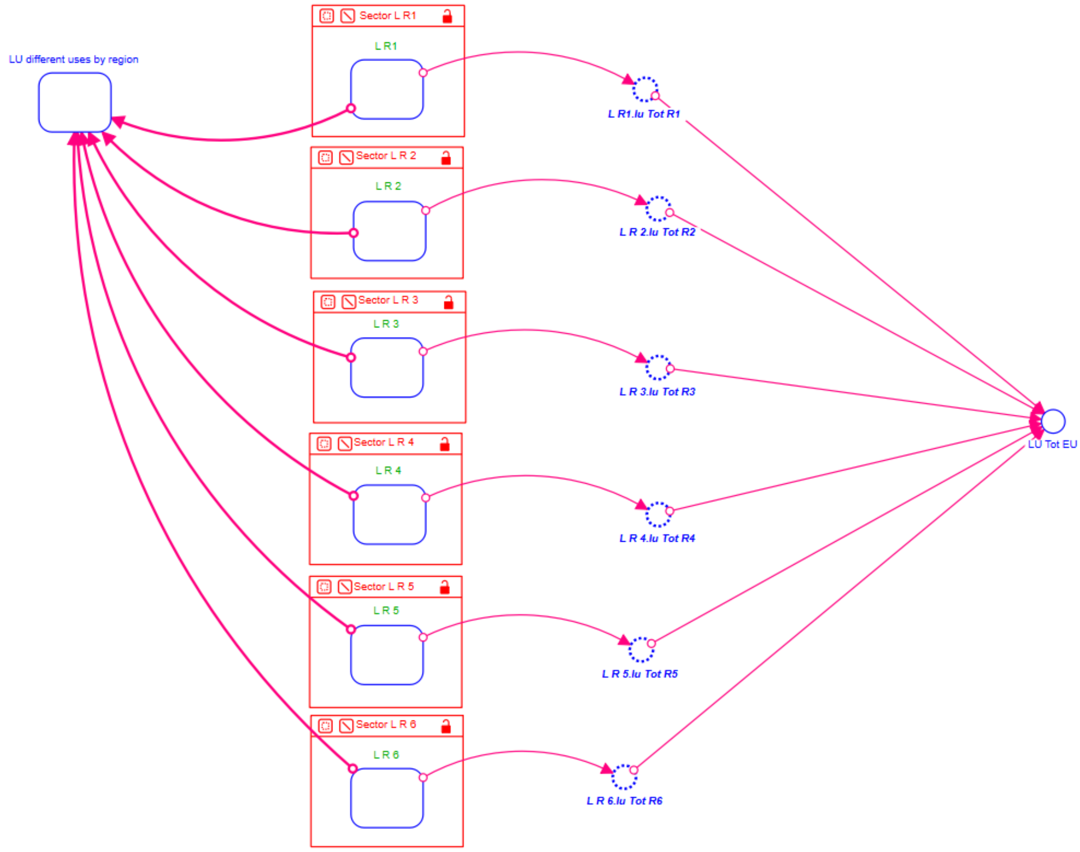

Figure 92: top level of the food module in the EUR case, showing each regional sub-model for land use computations (rounded boxes, centre), the EUR aggregated land use (right) and the EUR aggregated land use by land use type (rounded box, left).

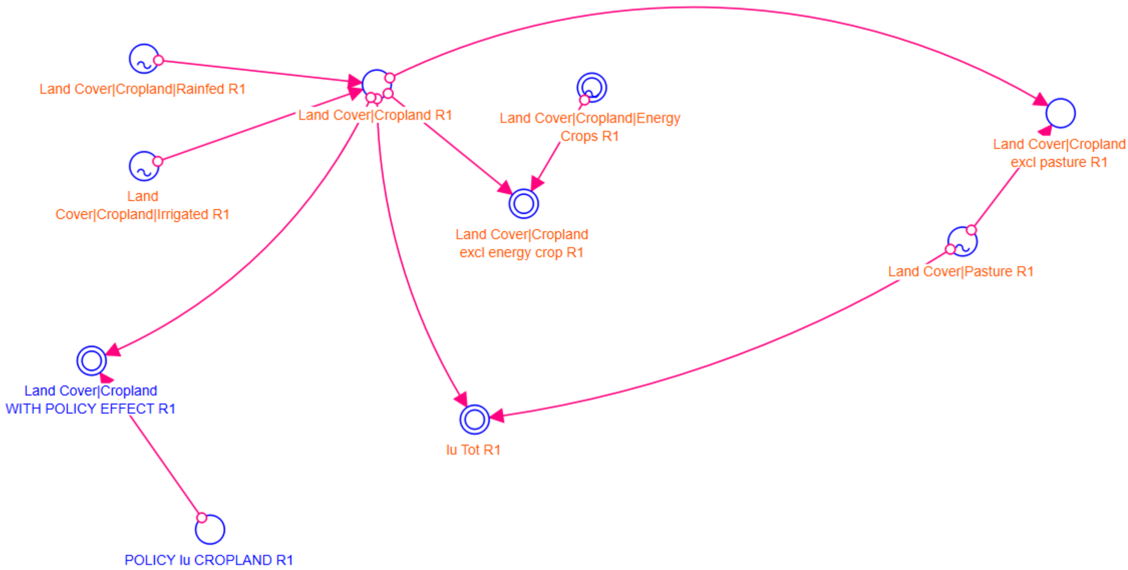

Figure 93: example of the different land use classes computed within each region of the EUR case study SDM.

3.11.1.4 Food sector

As with the land sector, the food sector module computes food availability and consumption in each of the six EUR regions (Figure 94), as well as aggregating European total availability and consumption (Figure 95). On regional food availability (Figure 96), imports and exports are accounted for, as well as regional production of: livestock; fodder; and crops (without disambiguation). Demand is split into the human demand for livestock products and crop products.

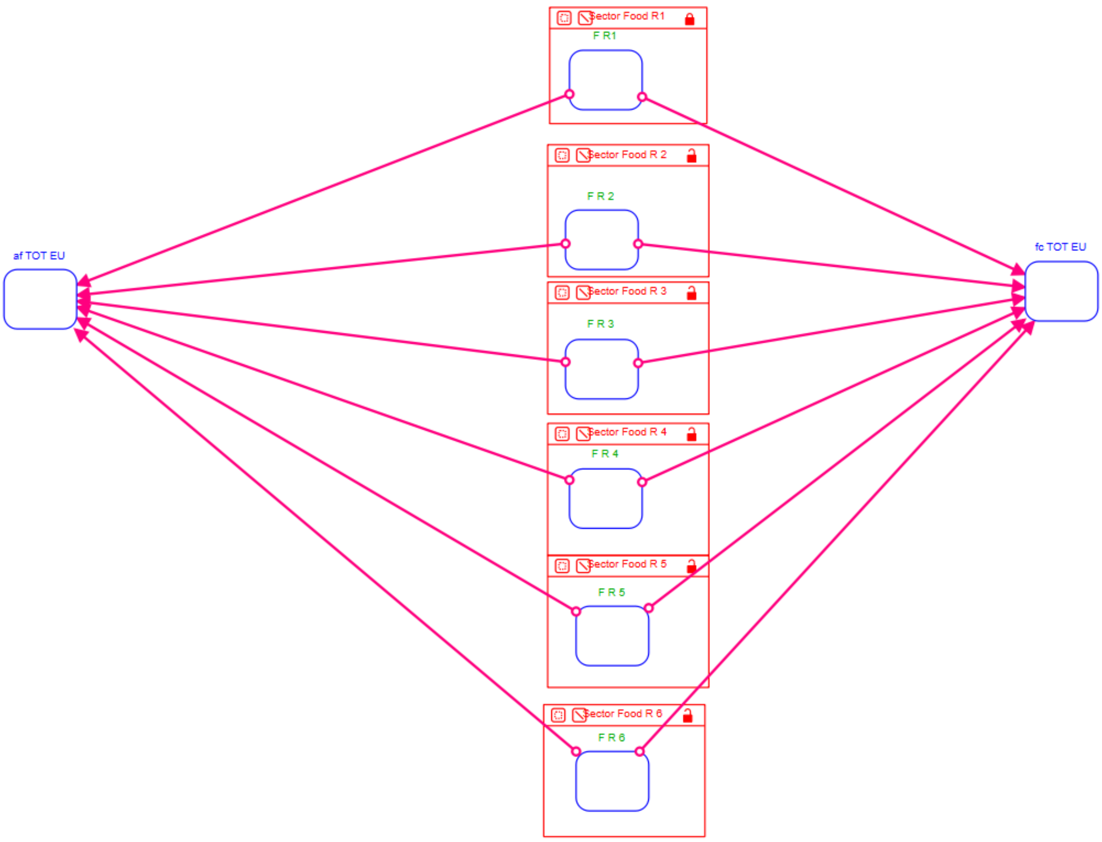

Figure 94: the top level of the food module in the EUR case study, showing sub-modules to compute availability and consumption in each region (rounded boxes, centre), as well as aggregating European-wide food availability (rounded box, left) and consumption (rounded box, right).

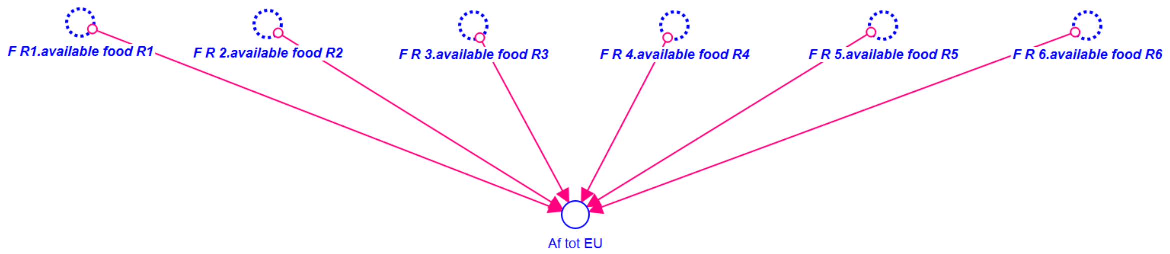

Figure 95: the sub-module aggregating food availability across all six EUR regions.

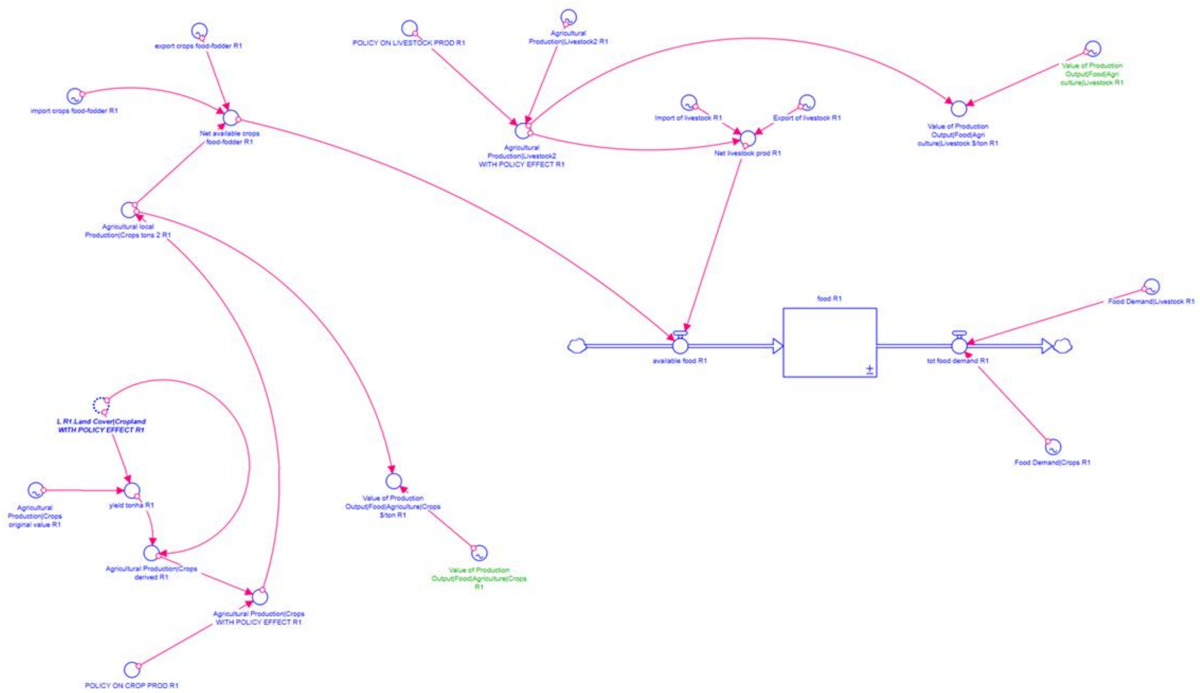

Figure 96: detail of the computation of food availability and demand on one of the EUR regions. A food balance (availability minus demand) is also computed (large square box).

3.11.1.5 Energy sector

As with the land and food sectors, the energy sector module computes energy availability and consumption in each of the six EUR regions (Figure 97), as well as aggregating European-wide availability and consumption (Figure 98). Within each region, energy production comes from primary sources, as well as secondary non-electricity and secondary electricity generation, while demand comes from primary biomass, gas and coal, and secondary liquids and electricity consumption (Figure 99). Each of these is elaborated below.

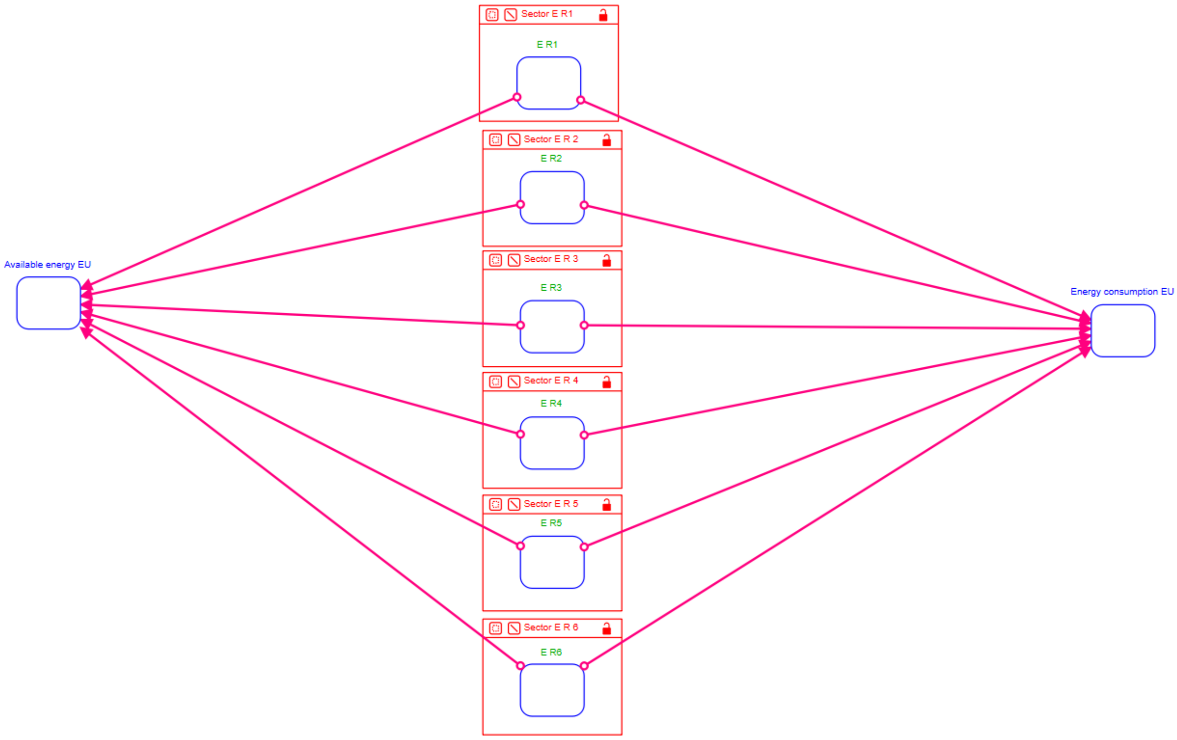

Figure 97: the top level of the energy module in the EUR case study, showing sub-modules to compute availability and consumption in each region (rounded boxes, centre), as well as aggregating EU-wide energy availability (rounded box, left) and consumption (rounded box, right).

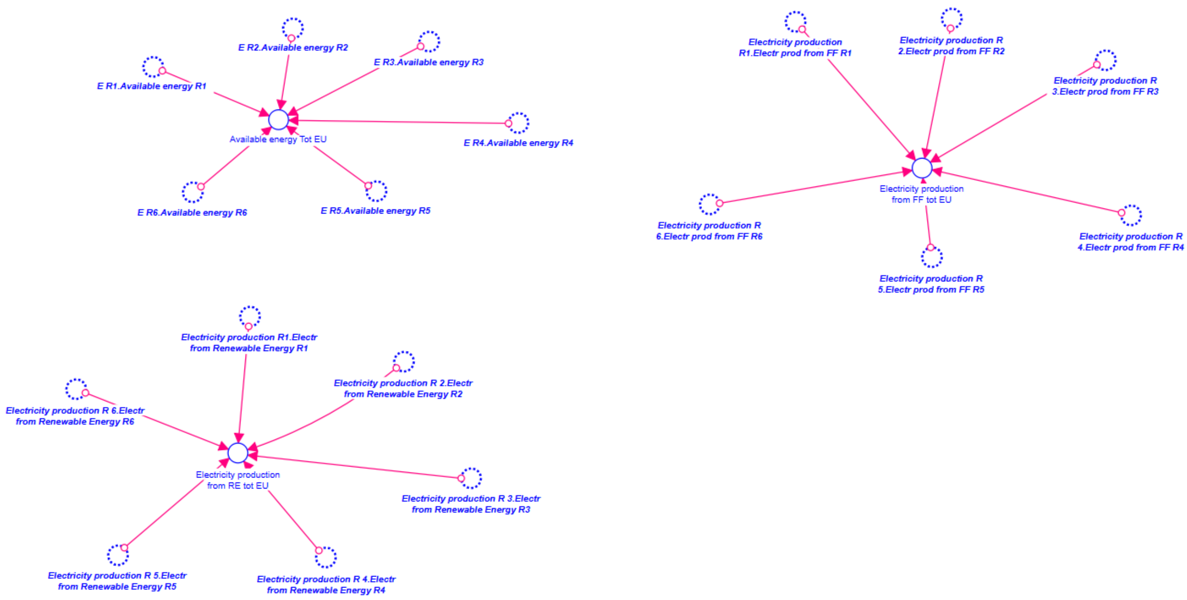

Figure 98: the sub-module aggregating energy availability across all six EUR regions according to total available energy (top left), electricity from fossil fuels (top right), and electricity from renewable (bottom left).

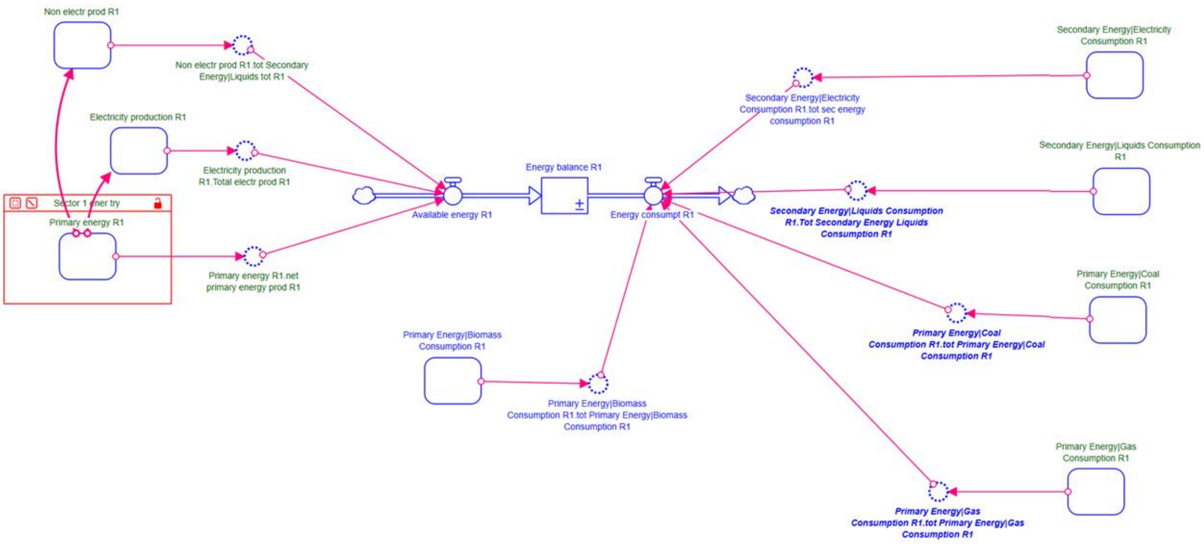

Figure 99: main regional module computing energy availability and demand within a European region. The balance is the difference between availability and demand (square box, centre). Availability comprises primary, non-electric, and electric energy production (left side), while demand comes from primary biomass, gas and coal consumption, and secondary liquids and electricity consumption (rounded boxes, right).

In primary energy production (Figure 100), four main sources are identified: oil, gas, coal and biomass. The production within each region, as well as the import and export to/from each region is captured, giving calculations for total local production (gross) as well the net production after import and exports. The total imports and exports, as well as the import and exports of each fuel are calculated.

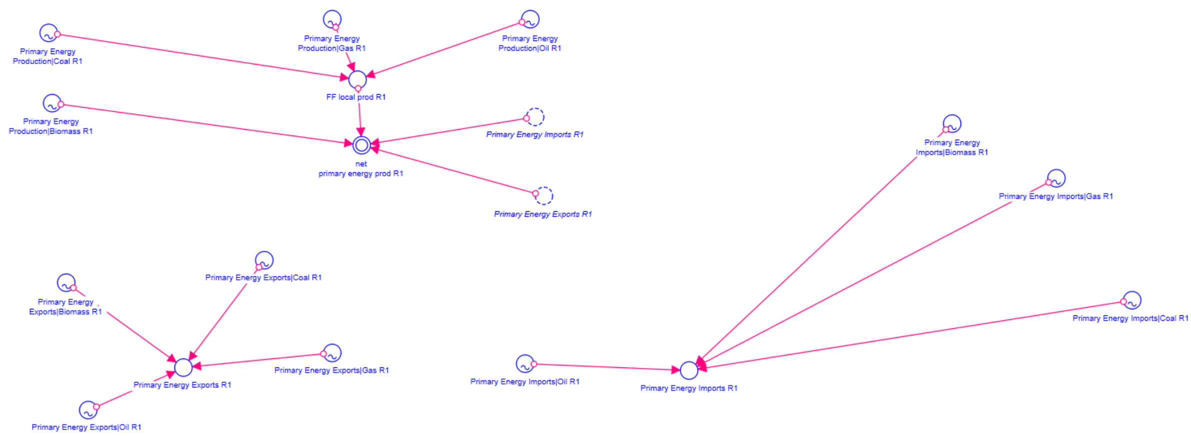

Figure 100: detail of part of the primary energy sub-module in one region of the European case study.

For secondary energy non-electricity production, biofuels (from biomass), as well as oil-based fossil fuels are counted as ‘liquid fuels’, along with their imports and exports to/from a given region (Figure 101). Totals can be summed to give continental detail.

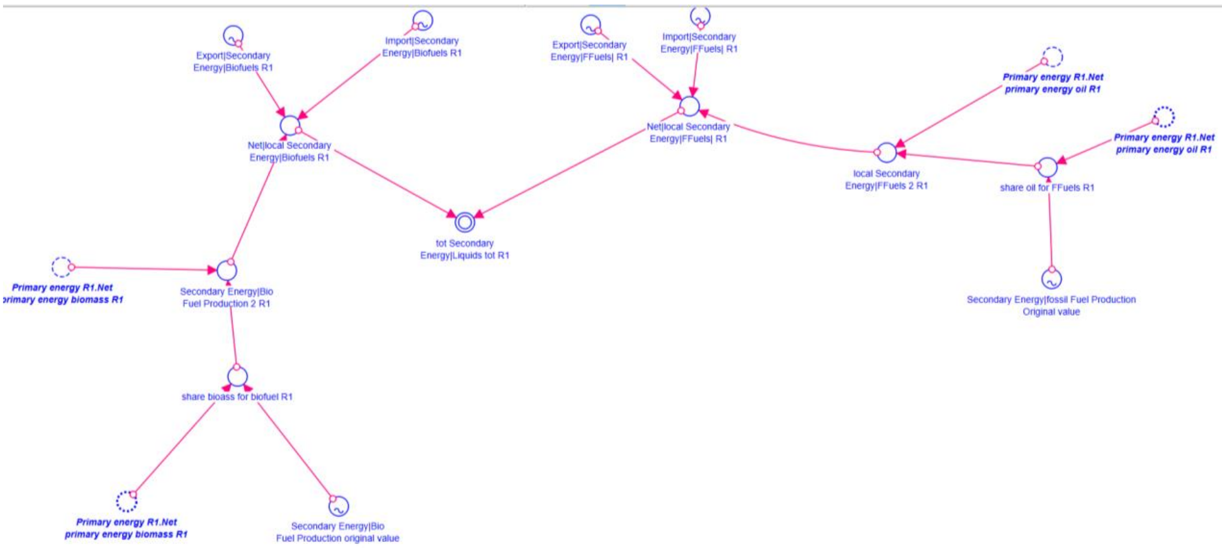

Figure 101: the secondary energy non-electricity energy production sub-module for one EUR region.

In terms of electricity production (Figure 102), sources of power, including their import and export, include: coal, gas (together making fossil based generation), nuclear power, hydropower, solar and wind power, and biomass for electricity.

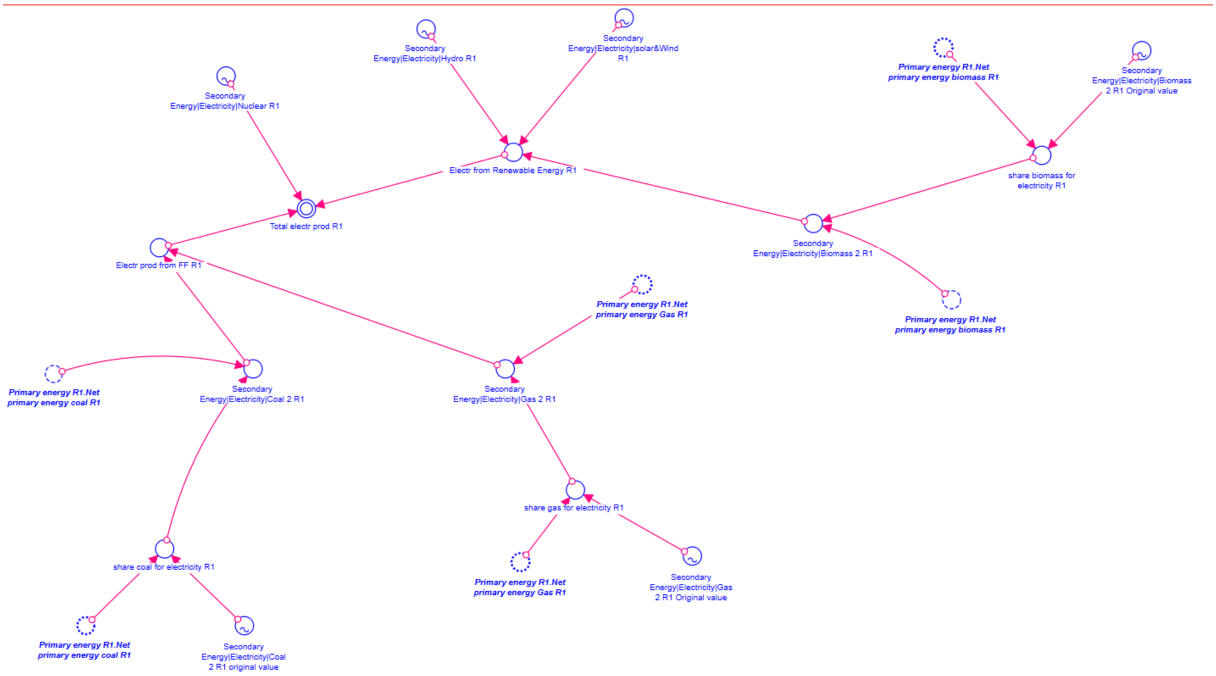

Figure 102: the secondary energy electricity production sub-module in the EUR case study.

Energy demand is broken up into demand for biomass, gas, coal, liquids, and electricity. Biomass consumption accounts for the consumption of primary biomass in terms of use in 2nd generation of biofuels and bio-electricity, biomass use in first generation biofuels and heat are not included. The demand for gas is composed of the agricultural, transport, industrial, electricity, services and domestic sectors (Figure 103). The demand for coal is composed of the same categories as for gas, and as is the also the same demand for liquids (except for electricity generation which is not included in liquid energy demand). Finally, electricity demand is split into the agricultural, domestic, industrial, services and transport sectors. All energy demands are summed to give total regional demand, and summed again to continental level.

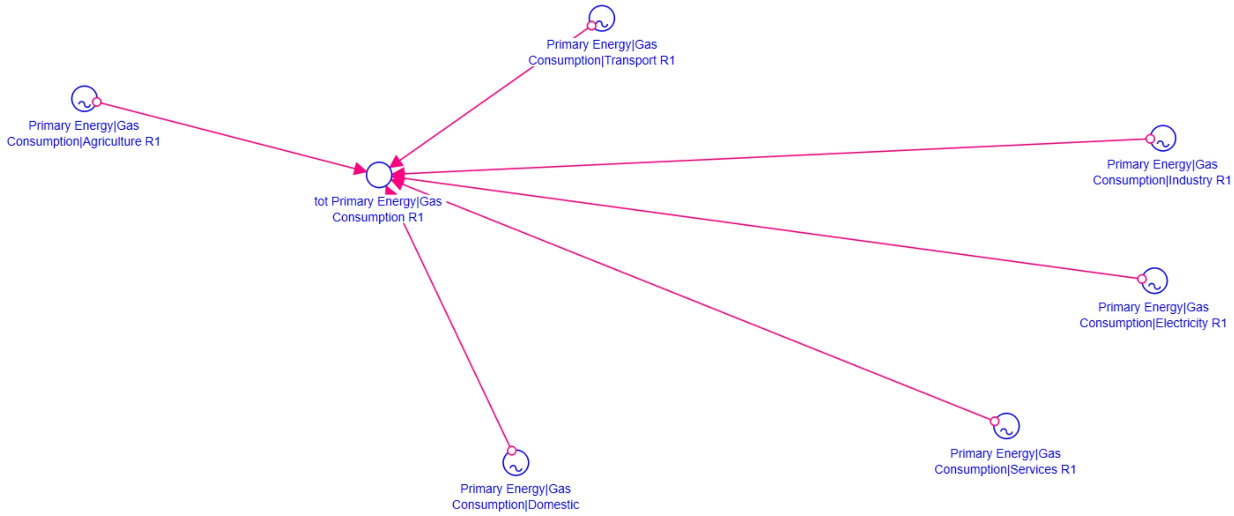

Figure 103: gas demand sub-module for one of the regions in the EUR case study.

3.11.1.6 Climate sector

The climate sector module (Figure 104) accounts only for emissions to the atmosphere within each region, and sums these to continental totals. The composition of emissions is relatively comprehensive, accounting for a wide number of sources (e.g. Figure 105). Emissions are divided into those related to energy consumption which are determined by the type and amount of energy used and those unrelated to energy consumption which simply scale with production (or population in the case of domestic households). For simplicity we refer to the latter source of emissions as emissions from production. On the production side, service, industry, domestic and transport production are quantified, along with agricultural production which is further broken down. In the agricultural production sector, methane emissions, also expressed in CO_2e (CO_2 equivalent units), are calculated for crops and livestock, while N_2O emissions, also expressed in CO_2e, are calculated for crops and livestock. On the energy consumption side, gas consumption comes from domestic, transport, agriculture, service, and industry uses (Figure 105). Coal consumption is comprised of the same categories, as is liquid fuels. Therefore, emissions can be broken down into production and energy consumption, and energy consumption can be further divided by fuel or sector, giving rich information. All regional values can likewise be summed to the continental level.

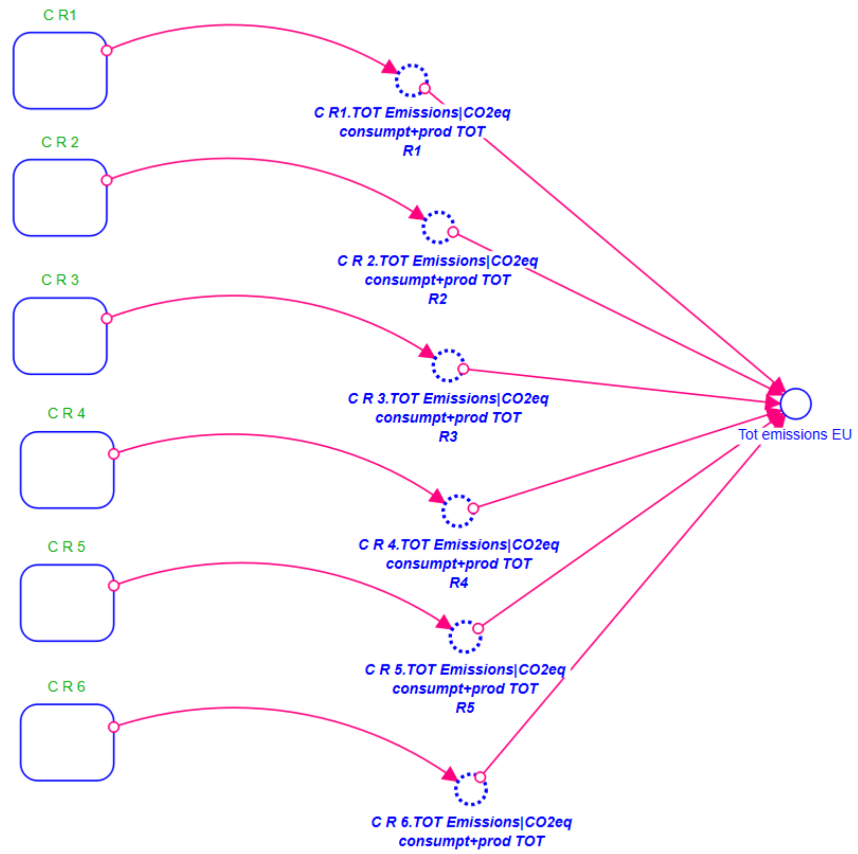

Figure 104: top level of the climate module, showing the regional breakdown (rounded boxes, left) and sum to continental total (right) for the EUR case study.

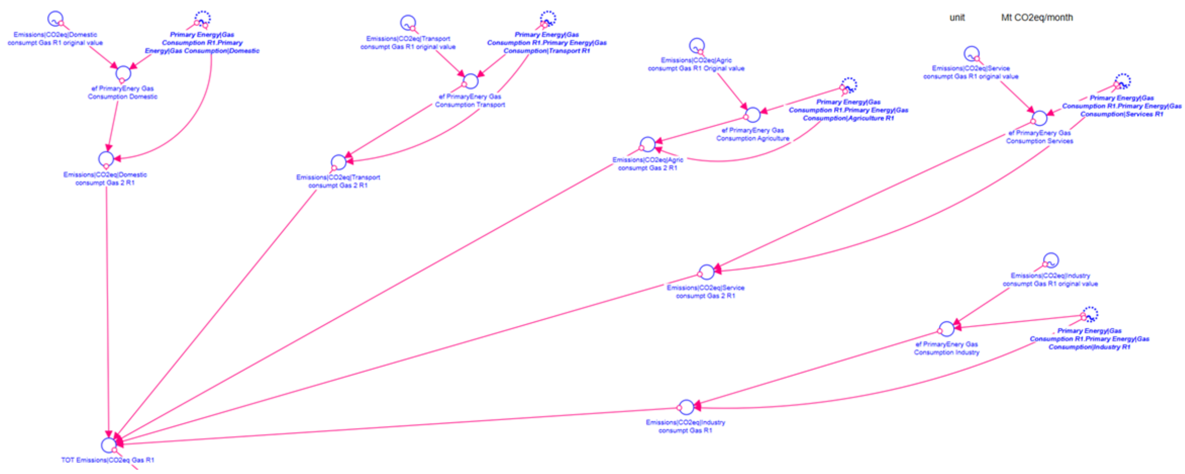

Figure 105: showing only the calculation for gas-related consumption emissions in one region of the EUR case study to demonstrate the complexity of the emissions modules. The coal and liquids sectors are equally complex. The emissions from production are also assessed separately to those from consumption.

3.11.2 Description of the final results

3.11.2.1 Population

Figure 106 shows the results for the population to 2050 in the six EU regions. Overall, a small increase in population is expected European-wide. The northern and southern EU regions (NEU and SEU) show the largest relative increases. Some regions such as eastern EU (EEU) show expected decreases over time. The total level of growth is very moderate, being about 300,000 more people by 2050.

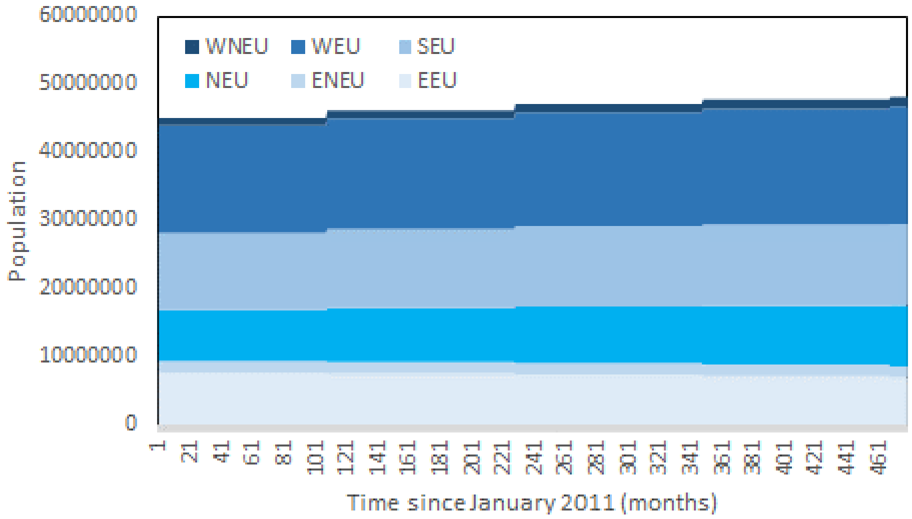

Figure 106: population in each of the six EUR regions.

3.11.2.2 Water sector

In the water sector, water withdrawals are only accounted for irrigated agriculture. For other sectors, insufficient data were available at the regional level. For irrigated agricultural withdrawals, Figure 107 shows that overall, a general decrease in withdrawals is expected over time, largely due to a significant expected decrease in demand in the southern EU (SEU) region. In most regions this is largely due to a combination of irrigation and land management efficiency increases, which allows for a decrease in irrigated area and an even further decrease in irrigated water withdrawals while still maintaining an increase in crop production over time. However this is also due in part to limitations on water availability and pressure on land from other uses particularly in the SEU region. In terms of water resources, a decrease overall has positive implications for the amount of freshwater available for other uses such as domestic water supply and the environment. This may be particularly important in southern European countries. However, at the same time this shows the dependence of European food production on sufficient land and water resources. Proper management of these resources is important for food production levels to continue to increase, otherwise there could be issues surrounding the security of internal (i.e. European-based) food supply. If less food is produced in Europe, the implication is that more is imported from outside, increasing European wide vulnerability to international food markets. Therefore the irrigated agricultural water withdrawal decreases potentially have both positive and negative implications. However as irrigation water withdrawal decreases are also in large part due to efficiency gains while maintaining production, the situation appears to be more 'win-win', saving resources, and maintaining food security in Europe. The southern EU (SEU) region dominates the withdrawal volumes, and the western EU (WEU) is also important in this regard. Other regions have relatively small water withdrawal demands throughout the simulation. For example the northern EU (NEU) has a very small irrigated water demand, largely because of the abundant rainfall in this region, making irrigation supplements mostly unnecessary.

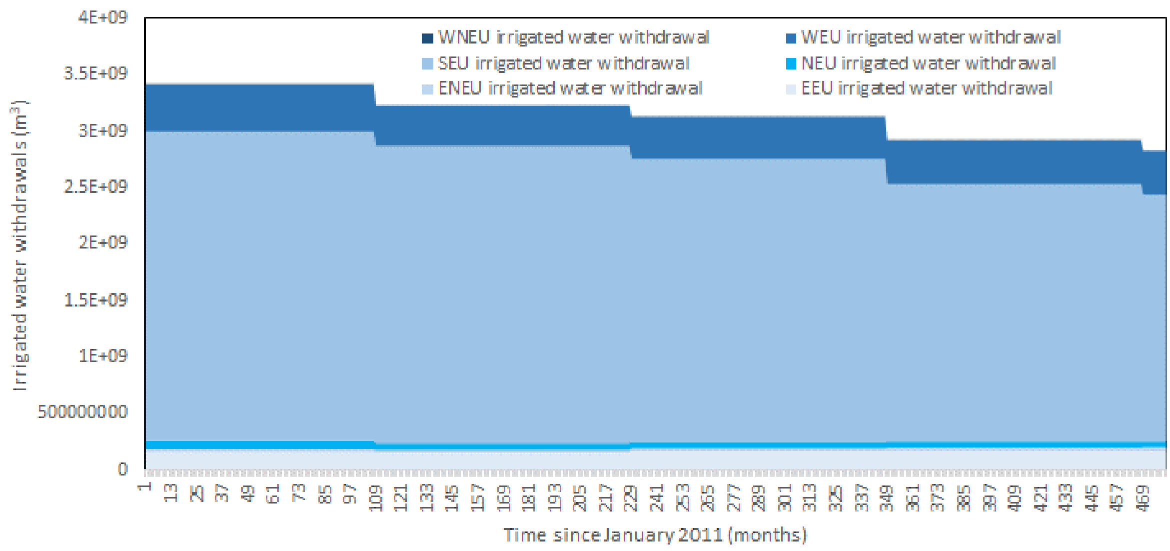

Figure 107: irrigated agricultural water withdrawals over time in the six EUR regions.

3.11.2.3 Land sector

Land sector results are shown for rainfed agricultural land (Figure 108), irrigated agricultural land (Figure 109), and pastures (Figure 110) for each of the EUR regions. Rainfed land (Figure 108) shows only a small expected increase over time, although the increase is marginal. The eastern, southern, and western (EEU, WEU, SEU) regions dominate rainfed agricultural areas. It is within these areas that the small increases are expected to be seen. The other three regions show negligible rainfed agricultural area.

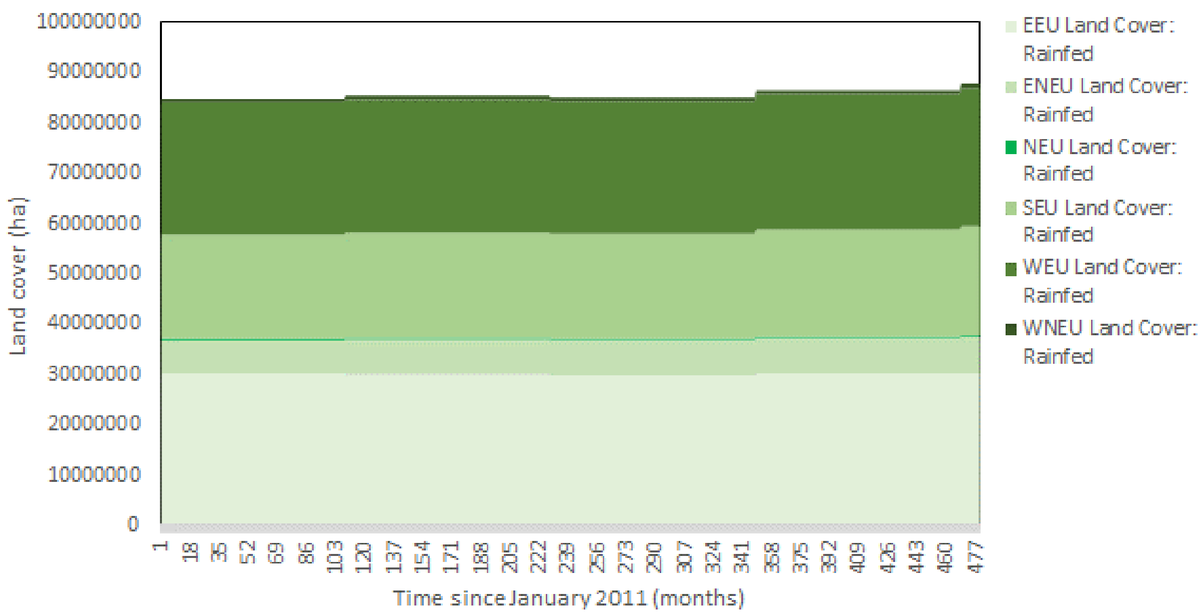

Figure 108: rainfed agricultural land in the EUR case study.

Irrigated land (Figure 109) shows a decline in area over time, contributing to the reduction in irrigated water withdrawal demand shown in Figure 107. The southern and western EU (SEU, WEU) regions dominate irrigated area, however it is in the southern EU region that the largest areal decrease is expected, lending support to the idea that irrigated agriculture area decrease in this region contributes to the decreasing water withdrawals, and may lead to food security issues in the future. On the other hand, the irrigated areas are expected to grow in the western and eastern EU (EEU) regions.

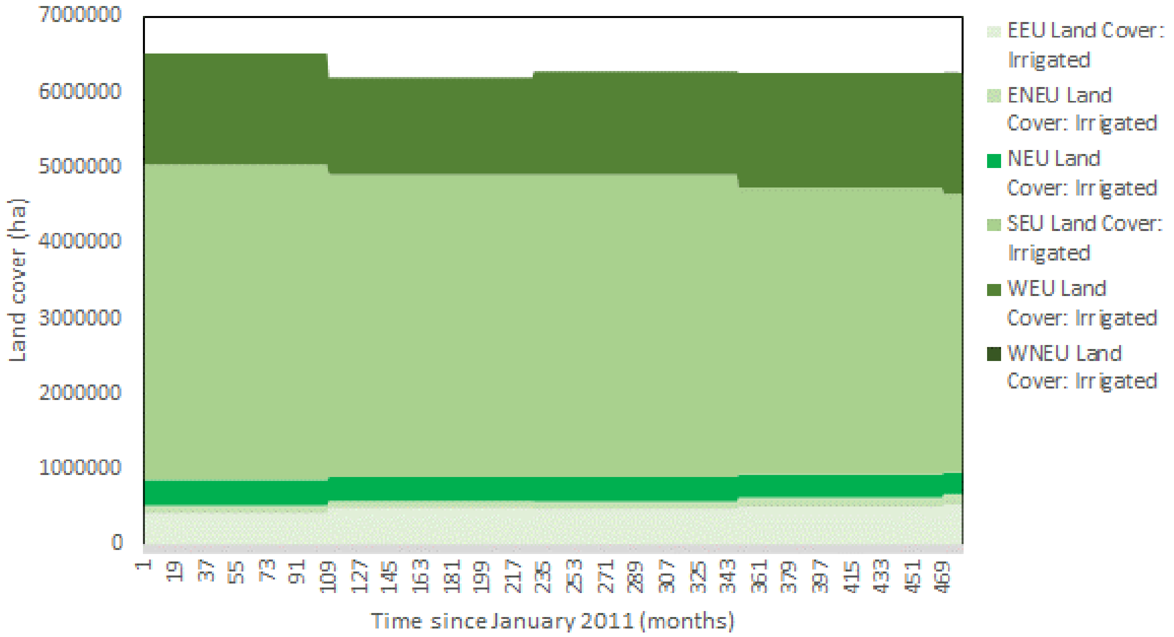

Figure 109: irrigated agricultural land in the EUR case study.

In terms of pasture land (Figure 110), a general decrease is expected across Europe, possibly driven by increases in irrigated agriculture land in the EEU and WEU regions. The total amount of decrease is relatively minor however, and other land use types not tracked here may be more at risk to decline.

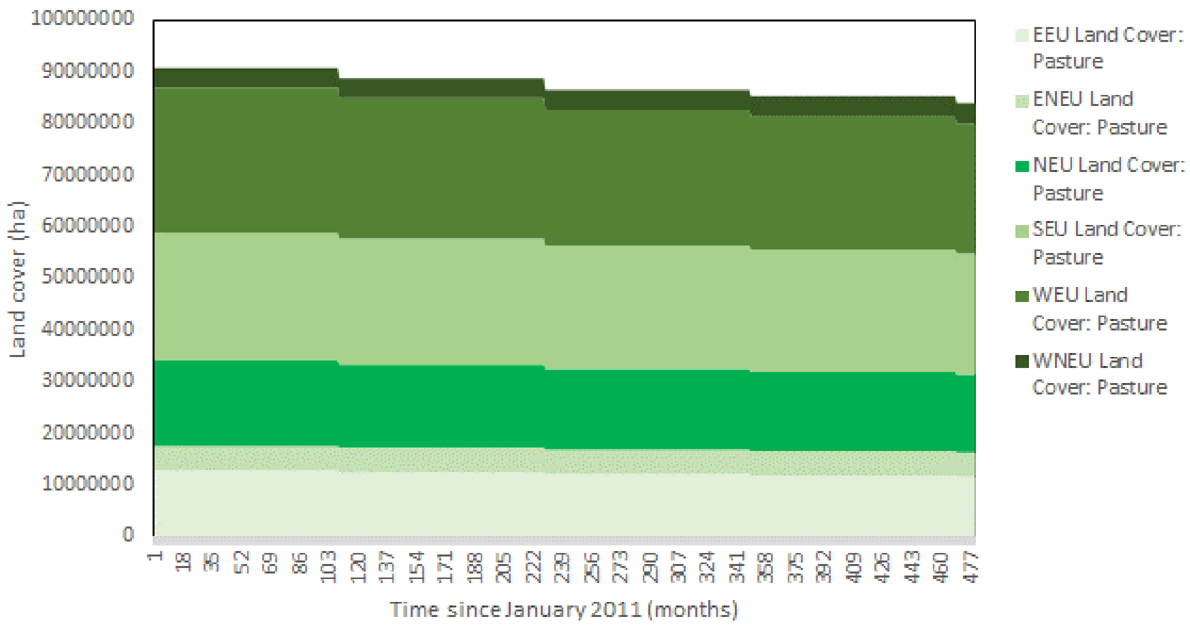

Figure 110: pasture land area in the EUR case study.

3.11.2.4 Food sector

In the food sector, the net production (domestic production plus imports less exports) of food and fodder crops (Figure 111) and livestock (Figure 112), and the consumption of crop based food (Figure 113) and meat (Figure 114) for each EUR region are modelled. For food and fodder net production

(Figure 111), a marked increase over time is noted, especially in the western and southern EU. This is in apparent contradiction to both the decreases in irrigation water demand and the constant rainfed areas and decreases in irrigated areas. This is due to expected increases in yield through the EUR regions as farming methods continue to improve. Overall, the western EU has the largest share of production.

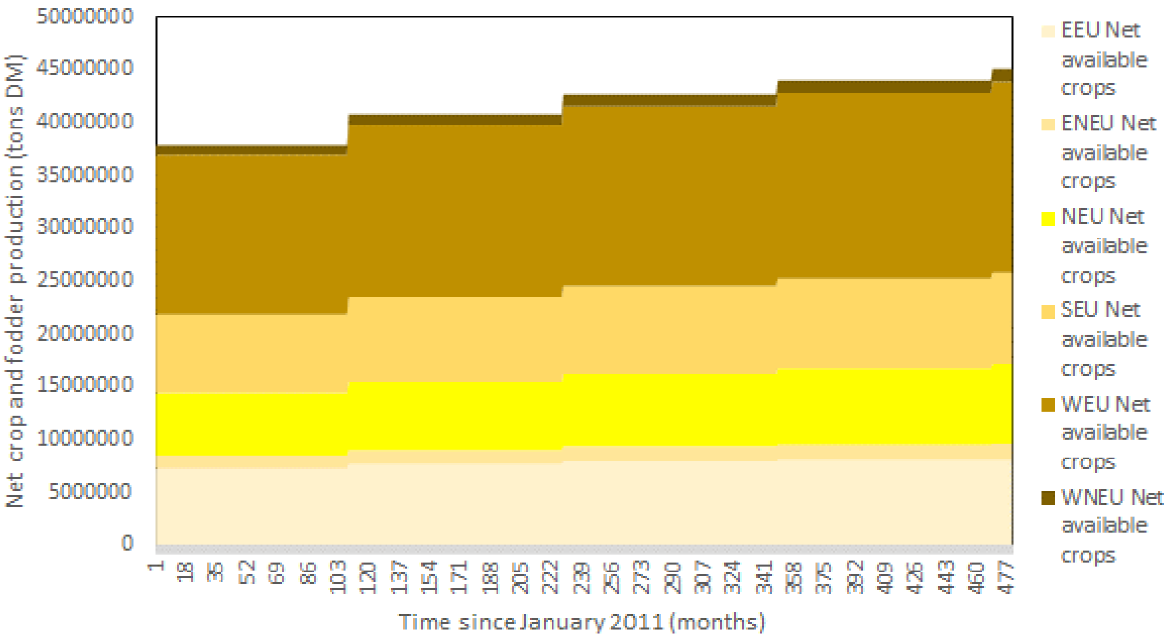

Figure 111: food and net fodder production in the EUR case study.

For livestock net production (Figure 112), again, an increasing trend is shown. The decrease in pasture land suggests an expected intensification of production. The western EU dominates, and shows increases over time. The southern, northern, and eastern regions are also responsible for considerable livestock production, and remain so over time.

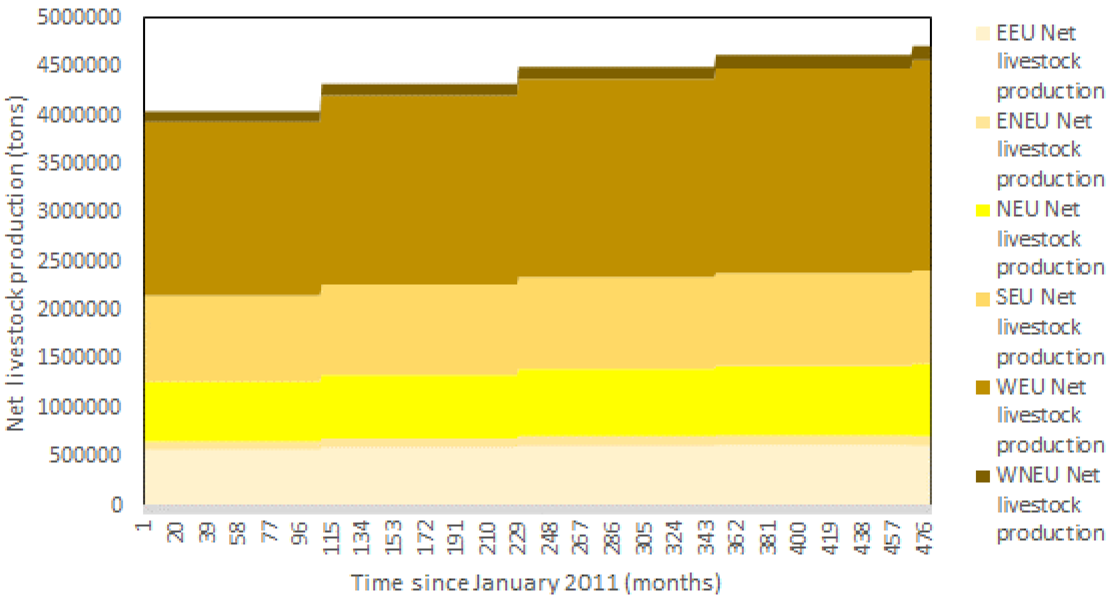

Figure 112: net livestock production in the EUR case study.

On the food demand side, the demand for crop food (Figure 113) is expected to increase across Europe. The scale of growth is less than the expected growth in the net production of primary agricultural products. This is because a significant portion of food consumption in Europe is from processed foods, so the relationship between net production of primary agricultural products and total food consumption is not one to one. The western, eastern, northern and southern regions dominate crop food demand, although the eastern EU and eastern non-EU do show small declines over time, possibly related to population decreases.

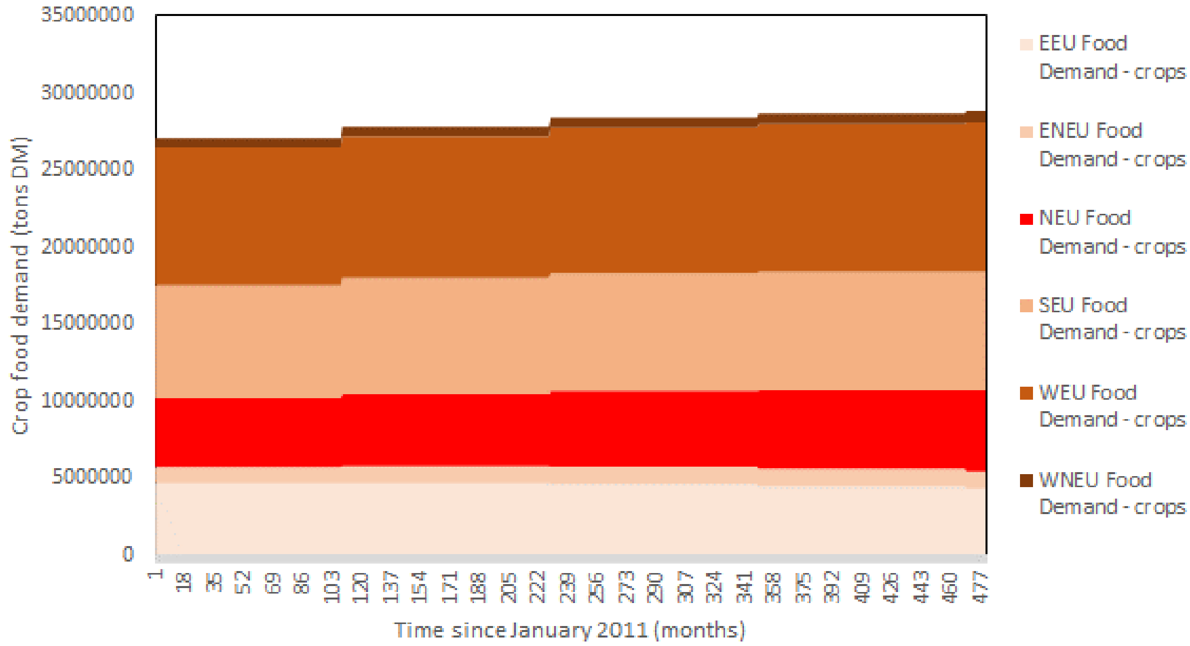

Figure 113: crop based food demand in the EUR case study.

For livestock demand (Figure 114), the pattern is extremely similar to food crops. Overall increases are expected, but with small decreases in the eastern EU and eastern non-EU regions. The growth in food demand is less than the growth in production.

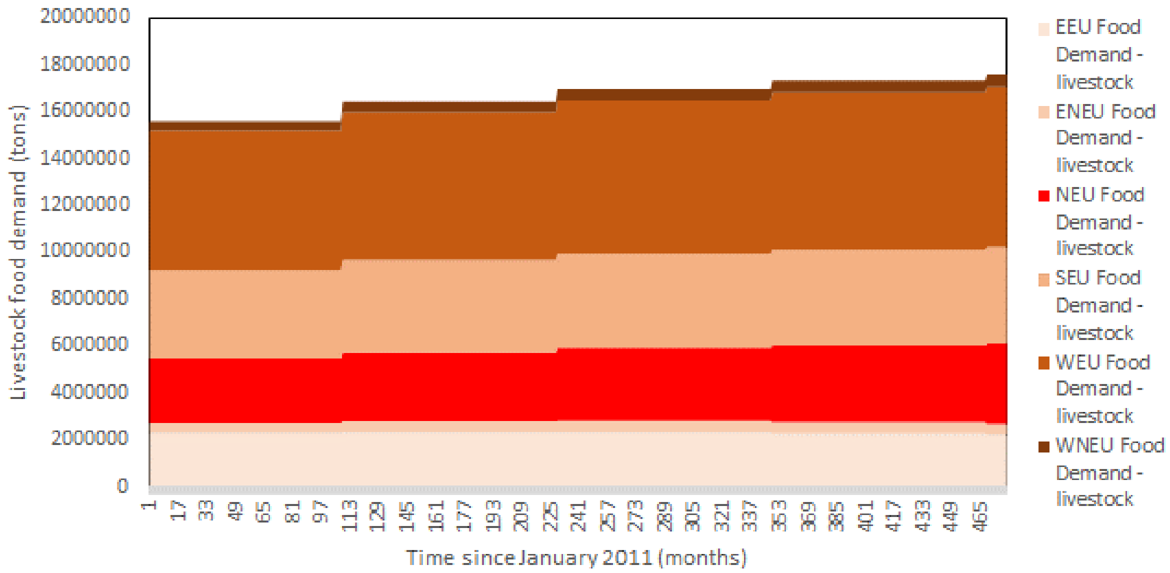

Figure 114: livestock based food demand in the EUR case study.

3.11.2.5 Energy sector

In the energy sector, production for the eastern EU region (Figure 115) is expected to see an increase, owing largely to an increase in production, which remains dominant through 2050. The EEU region remains dependent on imports for a significate amount of its primary energy use through the simulation period. Due to issues with disaggregation, data on primary energy from biomass was not included. Secondary energy from bio-mass as well as impacts on land use and agriculture are included, although the agricultural impacts remain small. Results for the other five regions are available, but not shown due to space.

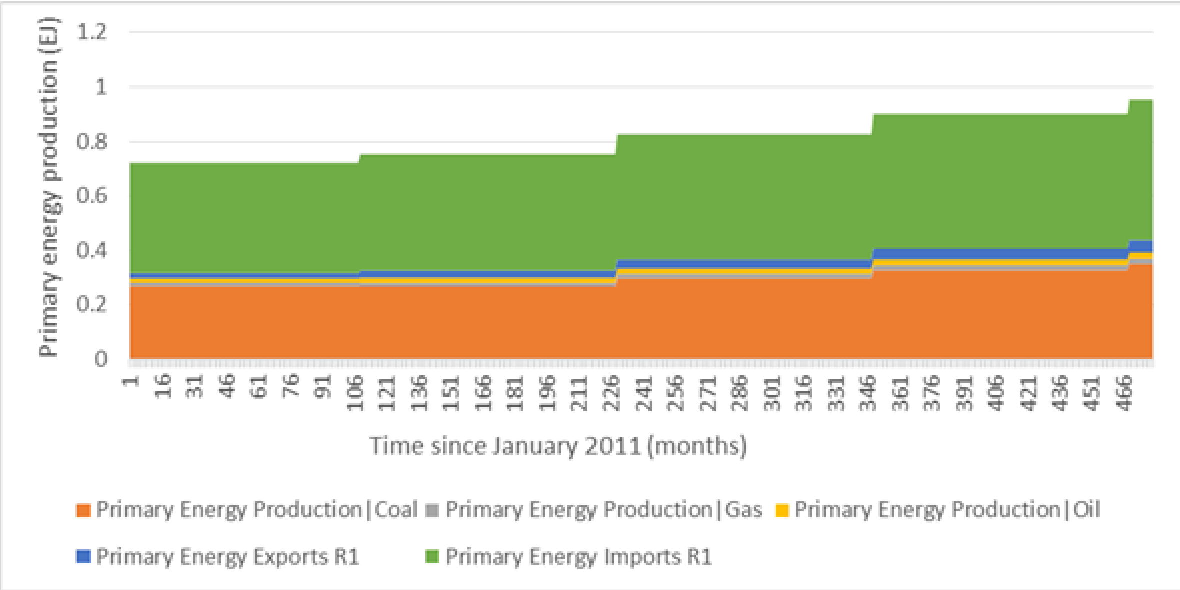

Figure 115: primary energy production in the EEU region in the EUR case study, broken down by energy production source. Similar results are available for the five other EUR regions.

In secondary energy electricity production, again results for the EEU region are shown here (Figure 116). Electricity from coal remains the main energy source in this region throughout the simulation, but the contribution of nuclear energy is expected to become increasingly important. Together with smaller increases expected in electricity from hydropower, solar and wind, and biomass, an overall significant increase in electricity production is expected in the EEU region.

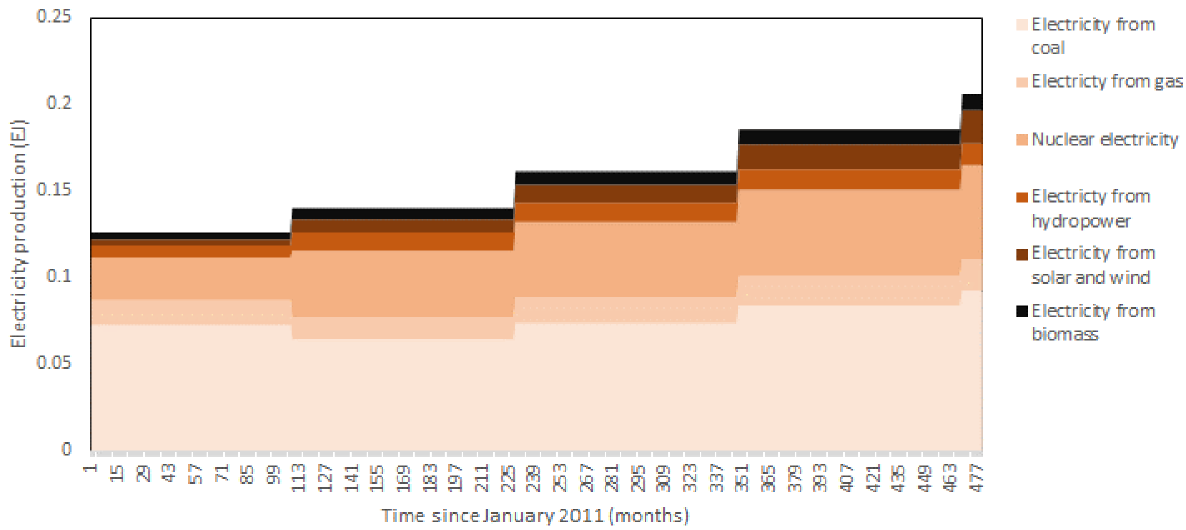

Figure 116: secondary energy electricity production broken down by source for the EEU region in the EUR case study. Similar results are available for the remaining five EUR regions.

Figure 117 shows energy consumption in the EEU region. For completeness secondary and primary energy consumption is shown. This leads to some double countering as secondary energy producers are also consumers of primary energy, but there is no double counting in the model itself. In terms of primary energy consumption, coal for electricity dominates, and remains roughly constant over time, although is shrinks initially around 2020 as renewable sources of electricity gain traction. Indeed, most consumption classes are shown to be roughly constant over time although several sectors also show small demand increases. In terms of secondary energy consumption, electricity consumption in services, industry and for domestic use show roughly equal shares in 2050, and while electricity consumption in services shows the largest increase over time. The transport sector show the largest increase in the consumption of secondary energy liquids while consumption in the remaining sectors stays relatively constant. The expected demand increases match with the projected increases in supply. Results as shown in Figure 117 are available for each EUR region, and at the continental scale.

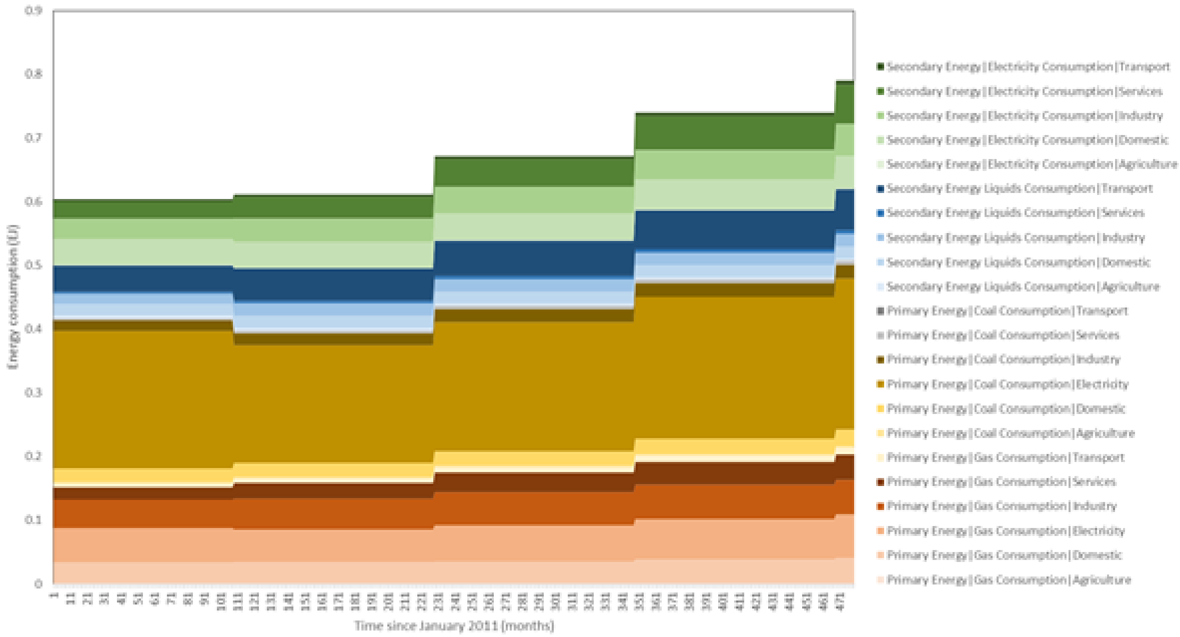

Figure 117: energy consumption in the EEU region of the EUR case study, broken down by fuel type and industry. Similar results are available for the other five EUR regions, and as a continental total.

3.11.2.6 Climate sector

In the climate sector, emissions from energy consumption (Figure 119) and remaining emissions directly tied to sector production (Figure 118) for the EEU region are shown here. For emissions directly related to sector production (Figure 118), the service and agricultural sectors dominate throughout the simulation, with both these sectors expected to contribute greater production-related emissions over time. The transport, and industry sectors play a relatively small role in non-energy related GHG emissions. In total, a growth of about 40% from 2011 is expected by 2050.

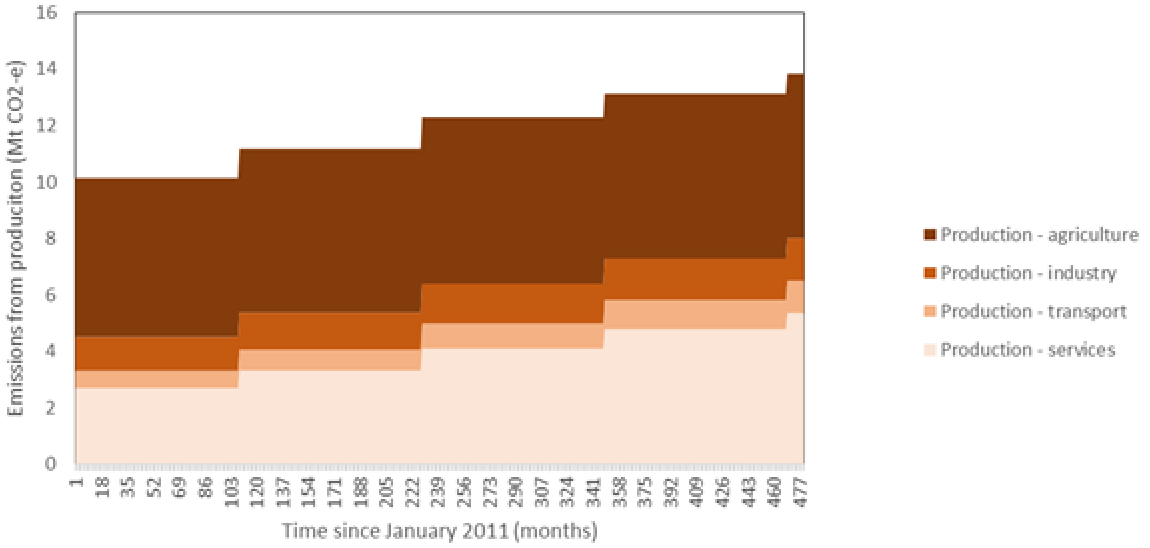

Figure 118: GHG emissions from production in the EEU region of the EUR case study. Results are available for the other five EUR regions, and at the continental level.

Figure 119 shows energy consumption-related emissions. For clarity Figure 119 excludes emissions from electricity generation which account for approximately 75% of energy related emissions in 2011 and 55% of energy related emissions in 2050. Aside from emissions from electricity generation the single largest contributor in the EEU region is liquids used in the transport sector. Domestic gas consumption is expected to play an increasingly important role in consumption-related emissions by 2050, as are emissions from gas in the service sector. Other important energy consumption related emissions are liquids use in domestic households, coal in the domestic households, and coal for industry. Between 2011 and 2050, the largest growth is expected in emissions from the use of gas in domestic households and liquid use in transport. Total energy consumption-related emissions grow by about 30% by the end of the simulation including emissions from electricity generation. Results in other regions are similar, and this suggests that without action, the EU is on course to miss its climate-related policy ambitions.

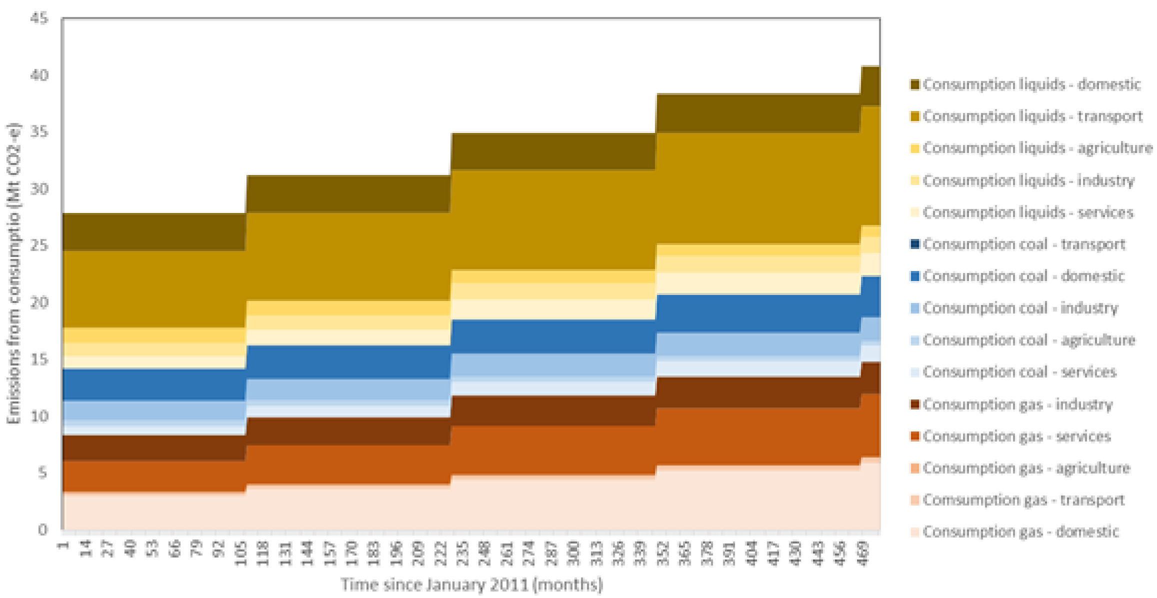

Figure 119 GHG emissions from energy consumption in the EEU region of the EUR case study. Results are available for the other five EUR regions, and at the continental level.

3.12 Global case study

As described in D3.4 and subsequent deliverable D5.5, the Global case has followed a different approach than the other cases, for various reasons. Conceptual model drawings were developed (Section 3.12.2 of D3.4) to get started with the development of a system dynamics model (SDM) for the global case. In May 2019, the status of the SDM of the global case was as reported in figures 3.12.5 to 3.12.17 of D3.4. However, during the further process, it became clear that building a SDM for the global case could not be realized. For most other case studies, no quantitative nexus modelling was available at the start of the project. For the global case, however, there was no need to quantify expert knowledge, but very detailed explicit relations were already included in the complex models of the global case (IMAGE, MAgPIE, E3ME, etc.), including complex multi-region relationships. Therefore, in close discussion with the relevant project partners (IHE, KWR-Water, WUR, 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. This interactive visualization of the global nexus system is built in cooperation with UNEXE (Mehdi Khoury) as a product of Task 4.5 and described in Deliverable D5.5 (Section 2.4).