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

D3.5: FINAL REPORT ON THE APPLICATION OF THEMATIC MODELS

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Executive summary

The primary objective of the Deliverable is to report on the application of the thematic models to each SIM4NEXUS case study. The thematic models are applied both to support nexus-compliant decision making in the case studies and as an input for the development of complexity methodologies. First, we describe the process undergone to select the suitable thematic models to be applied in each case study. Next, we define the setup of the simulation exercise, particularly the baseline and simulation scenarios chosen for each case study. Finally, we report on the simulations done for each case study.

Changes with respect to the DoA

Not applicable.

Dissemination and uptake

This report will be released on the project website. The Deliverable has been written to support the development of the SIM4NEXUS project and is open to all stakeholders, including the case study leaders and researchers contributing to the case studies.

Short Summary of results (<250 words)

This report describes the application of the thematic models to the case studies. The thematic models are applied both to support nexus-compliant decision making in the case studies and as an input for the development of complexity methodologies. First, the suitable thematic models to be applied in each case study have been selected and the baseline scenario has been agreed. Next, selected thematic models have been applied to each case study. This report summarises the scenarios selected as well as the main findings for each case study.

Evidence of accomplishment

Submission of report.

Glossary / Acronyms

TERM	EXPLANATION/MEANING
AGMIP	The Agricultural Model Intercomparison and Improvement Project
CAPRI	Common Agricultural Policy Regional Impact Analysis
CORINE	Coordination of Information on the Environment
E3ME	Energy-Environment-Economy macro-econometric model
ETS	Emissions Trading System
FADN	Farm Accounting Data Network
FAO	Food and Agriculture Organization of the United Nations
FTT	Future Technology Transformations for the Power sector
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GLOBIO	Global biodiversity model
GTAP	Global Trade Analysis Project
IAM	Integrated Assessment Modelling
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change (WMO/UNEP)
LPJmL	Lund-Potsdam-Jena managed Land
MAGNET	Modular Applied General Equilibrium Tool
MAgPIE	Model of Agricultural Production and its Impact on the Environment
NUTS	Nomenclature of Units for Territorial Statistics
OECD	Organisation for Economic Co-operation and Development
OSeMOSYS	Open Source Energy Modelling System
RCP	Representative Concentration Pathway
SDM	System Dynamics Modelling
SRES	Special Report on Emissions Scenarios
SSP	Shared Socio-economic Pathway
SWIM	Soil and Water Integrated Model

1 Introduction

The objective of this Deliverable is to report on application of the thematic models to the 12 case studies in SIM4NEXUS. The thematic models have been applied both to support nexus-compliant decision making and to serve as an input for the development of complexity methodologies. The application of the thematic models was carried out in close interaction with Task 5.2. Each case study has reported on the application of the thematic models in a similar way, involving the following steps:

a. The case study in short. Very short presentation of the case study.

b. The simulation scenarios in short. Describe the simulation scenarios selected for the case study, how these scenarios respond to the nexus challenges in the case study, and how the scenarios have been implemented in the thematic models?

c. Results of thematic models, Presentation and discussion of the main results for each of the scenarios simulated.

d. Concluding remarks on the application of thematic models. Presentation and discussion of the contribution of the thematic models to the analysis of the nexus.

The report is organised as follows. First, we present an overview of the available thematic models as well as the process to select the suitable thematic models to be applied to each case study. Next, we describe the setup of the first run of the models, with an emphasis on the selection of the baseline scenario. The following sections present the main features of each thematic model as well as the first application to selected case studies. Finally, the last section discusses some of the challenges to model the Nexus with the thematic models.

2 Mapping of models to case studies

2.1 Pool of thematic models in SIM4NEXUS

Seven thematic models are available in SIM4NEXUS. They are well-known, existing thematic models that will provide detailed outputs for specific aspects of the Nexus. The set includes operational climate-energy-economic-water and land-use models, with most of them considering the interdependencies of only a few sectors and no single one taking into account all five components of the Nexus. The main features of the thematic models are presented Table 1.

The application of these models to the case studies supports nexus-compliant decision making and provides information for the development of complexity methodologies. The advantage of complexity science methodologies is that they can integrate the results of other models and data sources to develop a Nexus simulation capable of addressing the complex interactions between the components in the Nexus in each case study.

Table 1. Pool of thematic models in SIM4NEXUS

Model feature	E3ME-FTT	MAGNET	CAPRI	IMAGE-GLOBIO	OSeMOSYS	SWIM	MAgPIE-LPJmL
Model type	Global macro-econometric energy, environment and economy model	CGE model with a focus on bio-economy and food security	Global agro-economic model with regionalized EU detail	Global integrated assessment model	Global energy modelling system	Eco-hydrological model	Global socio-economic model of the agro-food system and the environment
Main topics	Energy and climate policies	Trade, agricultural and bioenergy policies, climate impacts	Agricultural, trade, bioenergy and water policies, climate impacts	Sustainability, climate change, land use, hydrology, biodiversity, ecosystem services	Energy efficiency, climate change, mitigation strategies; technology transition	Sustainable water and land use management, climate change impacts	Long-term scenarios of agriculture and the environment (land, water, climate, nitrogen)
Nexus components	Energy, land, economy, climate	Food, land, economy, energy, climate	Food, water, bioenergy, environment, climate	Environment, biodiversity, land, water quantity and quality, energy	Energy, land, climate, water, materials	Water, land, climate	Food, land, water, bioenergy, environment climate
Geographic coverage	Global	Global	Global	Global	Global	Several river basins in Europe	Global
Spatial resolution within EU	National	National	National and regional (NUTS2)	Detailed grids	River basin, national, international	River sub-basins (100–1000 km²)	Detailed grids
Application to case studies	Global, European and national	Global, European and national	Global, European, national and regional	Global and European	Global and European	Transboundary	Global and European
Time step	Annual	2030, 2050 (flexible)	Flexible, until 2030/ 2050	Annual	Annual (and sub-annual)	Daily with arbitrary aggregations	5-year steps
Time frame	Until 2050	Flexible, until 2050	Until 2050	Until 2100	Until 2050	Until 2065	Until 2100
Partner	CE, RU	WUR-LEI	UPM	PBL	KTH	PIK	PIK

2.2 Selection of the suitable thematic models for each case study

To achieve a detailed understanding of the scientific interrelationships between the Nexus components, 12 case studies will be analysed, representing different spatial scales (regional, national, continental and global). SIM4NEXUS comprises three regional case studies (Andalusia, Sardinia and Southwest of the UK), five national (The Netherlands, Sweden, Greece, Latvia and Azerbaijan), two transboundary (France-Germany and Germany-Czech Republic-Slovakia), one continental (European) and one global case study.

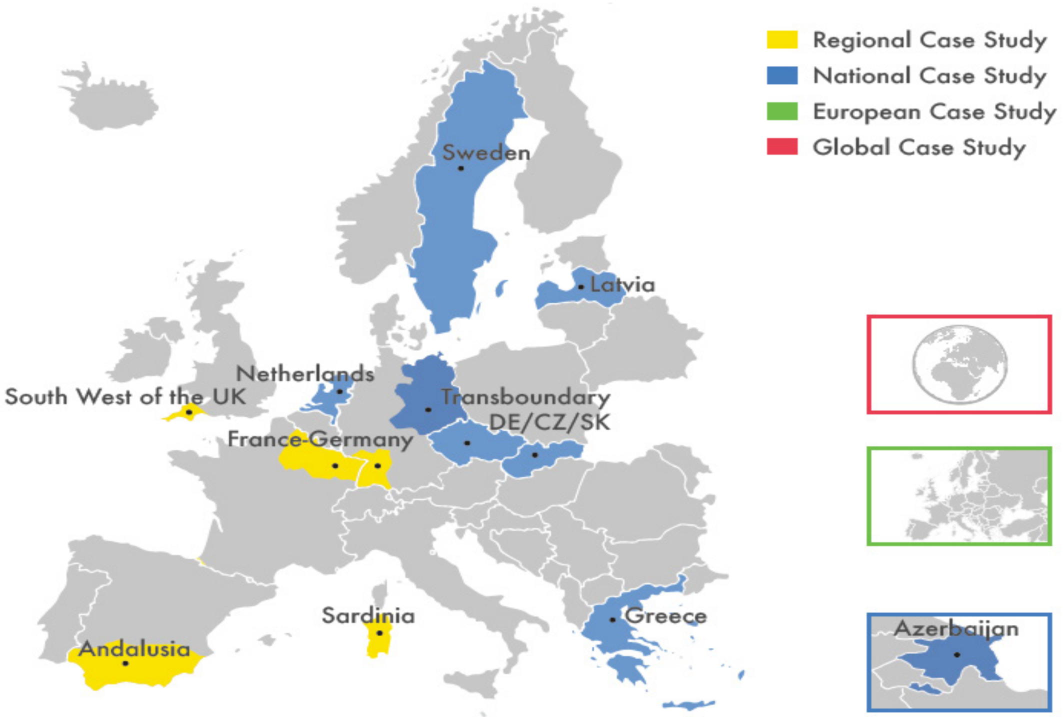

Figure 1. Case studies in SIM4NEXUS

One or more thematic models will be applied to each case study, depending on suitability as well as the main Nexus components to be analysed. The selection of the thematic models to be applied to each case study followed a participatory and iterative process:

- The case studies as well as the thematic models were presented during the kick-off meeting (July 2016). Each case study prepared a poster to outline the Nexus challenges and the policy goals they had drafted during the first weeks of the project. This was the start of interaction between the case studies and the thematic models. The partners who are responsible for the thematic models discussed the capabilities of the models to partly cover the ambitions of each case study.

- A review of the thematic models was developed, giving an overview of each model as well as its coverage of Nexus components. The review report is available in SharePoint: -> WP3 -> Task 3.3 Thematic Models.
- The thematic models were presented and discussed during a tailored workshop in Barcelona (16-17 November 2016). The coverage of each of the thematic models was presented and first conclusions were made in how far the thematic models are able to cover the requirements of each case study.
- Factsheets of the seven thematic models were developed. The factsheets present the model, its spatial and temporal coverage, Nexus coverage, as well as key input and output variables. The contacts of those responsible for each model are included as well. The factsheets are available in SharePoint: -> WP3 -> Task 3.3 Thematic Models -> Model factsheets.
- Case study leaders use the review report, the model factsheets, and the presentations from the Barcelona workshop, to identify suitable outputs and corresponding models.
- Case study leaders contact directly the model developers to explore the applicability of each thematic model to address Nexus components in their case study. Bilateral or group meetings are organized when needed to discuss model outputs.

As a result, each case study selected the suitable thematic models for the first scenario run (Milestone MS31, February 2017). Meanwhile, WP5 together with WP3 developed a note to guide the use of thematic models in the case studies (February 2017). Also, the leads of WP5 had regular Skype sessions with the case study leads and the selection of thematic models was on the agenda in several rounds. Table 2 shows the selection of the thematic models that will be applied to each case study as agreed during the third project meeting (Trebon, June 2017).

Progress in other work-packages has been beneficial to reach agreement. More specifically, D1.1 (Scientific inventory on the NEXUS) was important to address the Nexus challenges in each case study, while D1.3 (A review of thematic models and their capacity to address the Nexus and policy domains – Key Gaps) was important in reaching agreement for the selection of thematic models.

Moreover, the case study leaders are presenting the thematic models that will be used to the stakeholders (during bilateral discussions or workshops). The stakeholders are, thus, informed of the Nexus dimensions addressed by the models, the spatial coverage and time resolution, the necessary inputs and potential outputs. Interaction with the stakeholders does not aim at selecting the thematic models but rather identifying relevant model outputs for the case study as well as gaps in addressing the Nexus issues.

Table 2. Use of thematic models in the 12 case studies

Case study	Thematic model applied						
	E3ME	MAGNET	CAPRI	IMAGE-GLOBIO	OSeMOSYS	SWIM	MAgPIE-LPJmL
Andalusia	XX		XX				
Sardinia	XX		XX				
Southwest UK	XX		XX				
The Netherlands	XX	XX	XX				
Sweden		XX	XX	XX[2]			
Greece	XX	XX	XX	XX[2]	XX		
Latvia	XX	XX	XX				
Azerbaijan	XX	XX	XX[3]		XX		
France-Germany	XX		XX			XX[4]	
Germany-Czech Republic-Slovakia	XX[1]		XX			XX	
Europe	XX	XX	XX	XX			XX
Global	XX	XX	XX	XX	XX		XX

(1) Results available at the national level; (2) Application of GLOBIO; (3) Results available for a group of countries including Azerbaijan; (4) Results available for the Rhine basin.

3 Definition of common simulation scenarios

3.1 Setting up the modelling exercise

The thematic models are diverse and so are their outcomes. Applying one or more thematic models to each case study raises questions about the practicability of combining results from different models. To the extent possible, efforts have been made to harmonize the application of the models by defining a common simulation setting.

To define a common simulation setting, we have selected a base period (2010) and a simulation horizon (2050, with an intermediate time horizon in 2030). Next, we have agreed on a **common baseline scenario** that will be explained below. Finally, we have decided that the first application of the thematic models will consist of running the baseline scenario, with **results for 2010, 2030 and 2050** time horizons.

Case study leaders have been involved from the beginning in modelling activities. Case studies identify the main Nexus challenges and the corresponding output variables to assess them. Modellers provide information about the outcomes available from each model (input variables, output variables). Modellers and case study leaders work together to develop a common reporting format.

In parallel, the Sardinia regional case study was selected as a **fast track case study** to test the whole process, from the selection of the thematic models to the development of complexity models and the integration of modelling outputs.

3.2 Identification of the baseline scenario

SIM4NEXUS will cover pathways to achieving (i) the 2050 vision 'living well within the borders of our planet', (ii) climate and sustainability goals, and (iii) opportunities and limitations of low-carbon options in view of near-term policy initiatives (i.e. IPCC goals from the Paris Agreement, circular economy package).

To define a suitable baseline scenario, we take into account that the scenario analysis will use the set of climate scenarios selected by the IPCC for the Fifth Assessment Report (IPCC 2014). This scenario framework has been developed by the international climate change research community to increase consistency and comparability across climate impact studies (Kriegler et al. 2012, Van Vuuren et al. 2012). It consists of a two-dimensional matrix representing key environmental and socioeconomic drivers of uncertainty in future climate outcomes. Each scenario results from the plausible combination of a Representative Concentration Pathway (RCP) with a Shared Socio-economic Pathway (SSP). The RCPs comprise four trajectories according to different levels of anthropogenic radiative forcing in the year 2100 (2.6, 4.5, 6 and 8.5 W/m2) (van Vuuren et al., 2011). The SSPs consist of five narratives describing alternative socio-economic developments that built on socio-economic drivers consistent with different challenges to adaptation and mitigation: SSP1 (sustainability), SSP2 (middle of the road), SSP3 (fragmentation), SSP4 (inequality) and SSP5 (conventional development) (O'Neill et al. 2017).

For the baseline scenario, we assume the RCP 6.0 scenario for the climate which will only depart slightly from the other RCPs until 2050; the consequences for Europe are detailed in Christensen et al. (2013) and van Oldenborgh et al. (2013).

Regarding the socio-economic drivers, **the baseline scenario corresponds to the middle-of-the-road socio-economic pathway (SSP2)** assuming a moderate capacity to adjust to future mitigation and adaptation challenges in the medium term (O'Neill et al. 2017). The narrative for the SSP2 scenario is explained below. Data for the SSP2 scenario are publicly available through the interactive SSP web-database at https://secure.iiasa.ac.at/web-apps/ene/SspDb, which comprises quantitative estimates for economic growth, demographics, energy, land-use, and emissions projections (Riahi et al. 2017).

Narrative for the SSP2 scenario (O'Neill et al. 2017)

The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing moderate challenges to mitigation and adaptation, but with significant heterogeneities across and within countries.

4 Application of the thematic models to each case study

4.1 Andalusia case study

4.1.1 Short description of the case study

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

Figure 2. Location and regions of Andalusia

Source: Junta de Andalucia (2015b)

Irrigation agriculture derives approximately 64% of the agricultural production in Andalusia, and has also high socioeconomic importance (generates 63% of agricultural employment and 67% of farm income) (Massot, 2016). While irrigation agriculture is crucial for Andalusia´s socioeconomic development, it also puts pressure on the limited water resources in the province. Andalusia has a negative water balance and, in some areas, faces problems of erosion (with risk of desertification).

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

This clearly shows that water-agriculture linkage is considered as the most crucial nexus component in Andalusia, where irrigated agriculture provides more than 64% of food production, represents 67% of farm income and accounts for 63% of the agricultural employment (European Parliament 2016). Furthermore, Within the Andalusian case-study, stakeholders have been engaged in identifying the nexus challenges, and emphasized that energy cost is a limiting factor in irrigated agriculture because of increases in energy demand and energy prices. Altogether the stakeholders have identified six general challenges in the nexus domain in Andalusia:

- Sustainable management of water resources
- Mitigation and adaptation to climate change
- Energy efficiency and promotion of renewable energies
- Fight against soil erosion and desertification
- Resource efficient food production
- Sustainable socioeconomic development

The Andalusian case study focuses mainly on the Nexus of water-energy-food. The research concentrates to analyse **food-water linkages** in terms of agricultural water use (irrigation and livestock) and crop irrigation and yields, as well as to analyse the **energy-food nexus** with regards to energy use by the agricultural sector and energy production from biomass and, **water-energy linkages** in terms of hydropower production. In particular, progress has been made by engaging the stakeholders in the research activities. The main goal of the case study is to analyse how agricultural and environment policies can be integrated to deal with the major pressures on water and land.

4.1.2 Description of the selected simulation scenarios

In the Andalusian case study, two pathways have been used. On one hand, for the baseline, the RCP 6.0 has been selected, which implies a continuation of the current trends and the consequent increase of the temperature from 3°C to 4°C by the end of the century. This RCP is consistent with the SSP2 scenario without climate change mitigation. On the other hand, RCP2.6 has been selected for the 2-degree pathway, which is consistent with the SSP2 pathway accompanied by ambitious climate change mitigation (ambition to keep temperature increase below 2°C relative to pre-industrial levels).

The baseline and 2-degree scenarios differ only in the strategy for addressing climate change. The rest of the assumptions used in the 2050 projections, relating to sectoral policies, are common and represent existing or already agreed policies.

The reference scenario represents the foreseeable evolution of agricultural markets until 2050, under a status quo situation. In policy terms, it represents the continuation of the CAP 2014-2020, and of the Uruguay Round commitments on agriculture. In environmental and socio-economic terms, it assumes the combination of the SSP2 and RCP6.0 scenarios and their effects on the agricultural sector.

The year 2010 has been selected as the base year, and simulation results have been reported for the time periods 2020, 2030, 2040 and 2050.

4.1.3 Results of the application of the thematic models

We have applied sectorial models (agriculture and energy) to obtain results on the future trends of different agricultural, socio-economic, environmental and energy variables in the particular case of Andalusia. We have simulated the baseline scenario with which to compare future policy scenarios and, therefore, assumes the continuation of existing policies (e.g. CAP 2014-2020, Renewable Energy Directive) and the most likely scenario of socio-economic and climate projections.

4.1.3.1 CAPRI

In the Andalusia case study, CAPRI has been used to analyse the links between food production, water use and energy requirements. Additionally, it has been used to analyse agricultural production, prices and margins of the different crops. This analysis is carried out within a framework of comparative statics, where the results of simulation scenarios are compared with a baseline or reference scenario (Martinez et al., 2019).
The reference scenario represents the foreseeable evolution of agricultural markets until 2050, under a status quo situation. In policy terms, it represents the continuation of the CAP 2014-2020, and of the Uruguay Round commitments on agriculture. In environmental and socio-economic terms, it assumes the combination of the SSP2 and RCP6.0 pathways (mentioned above) and their effects on the agricultural sector. The following Figure 3 shows the total and irrigated agricultural area for the reference scenario in Andalusia.

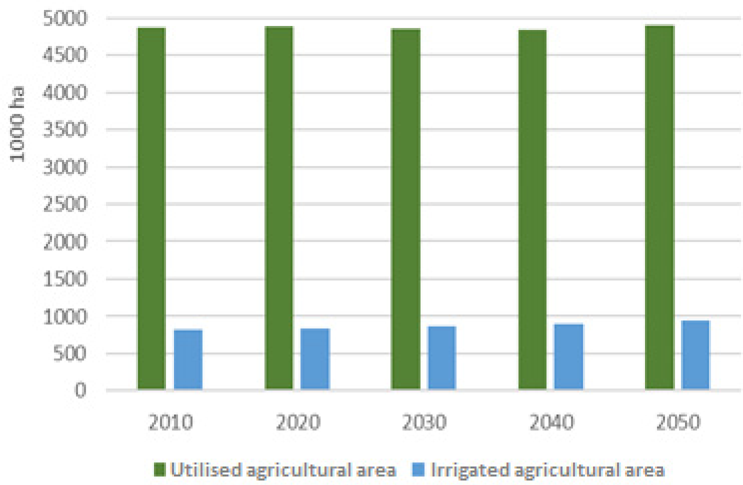

Figure 3. Total and irrigated agricultural area in the reference scenario in Andalusia (1000 ha). Source: Own elaboration based on CAPRI results.

For the simulation of the comparative scenarios, the most relevant variables for the Andalusian case study have been identified according to the evaluation carried out with the main actors and stakeholders in the region. Some of the main variables selected are water availability, improvement in irrigation technologies, and increases in water and energy prices in Andalusia. The following table shows different scenarios analysed regarding the increase in water prices in Andalusia:

Scenario	Definition
WP02	0.02 €/m^3 of increase over the reference scenario
WP04	0.04 €/m3 of increase over the reference scenario
WP06	0.06 €/m3 of increase over the reference scenario
WP08	0.08 €/m3 of increase over the reference scenario
WP10	0.10 €/m3 of increase over the reference scenario
WP12	0.12 €/m3 of increase over the reference scenario

Source: Own elaboration

It is important to mention that the price of each agricultural product is assumed to be the same in all scenarios. Additionally, it is assumed that there are no changes in other regions and that the changes produced in Andalusia will have no effect on other regions. It is therefore important to note that the aim of this exercise is to carry out a sensitivity analysis and that the results should be interpreted in that way. If a scenario of an increase in the price of water at a European level were contemplated, then it would have to be considered that the variations would have consequences for many regions and, therefore, the cross effects should be taken into account.

When analysing the results of the water price increase scenarios, decreases in the use of irrigation water are observed. The decrease is significant for cereal and olive crops. On the other hand, oilseeds are also highly affected; however, fruits and vegetables are affected to a lesser extent. The following Figure 4 shows the analysis.

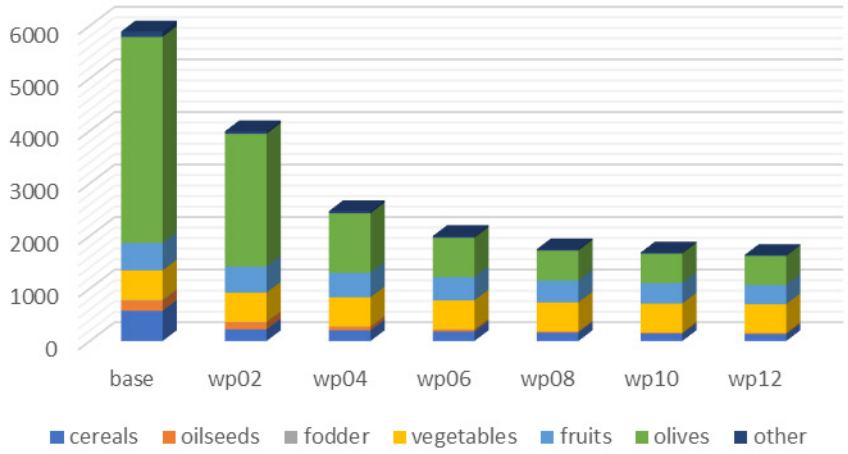

Figure 4. Change in irrigation water use (in hm3) as water prices increase.

Source: Own elaboration based on CAPRI results.

On the other hand, as a consequence of the increase in the price of water, the irrigated area decreases significantly and consequently the dry land area increases, as can be seen in the following Figure 5.

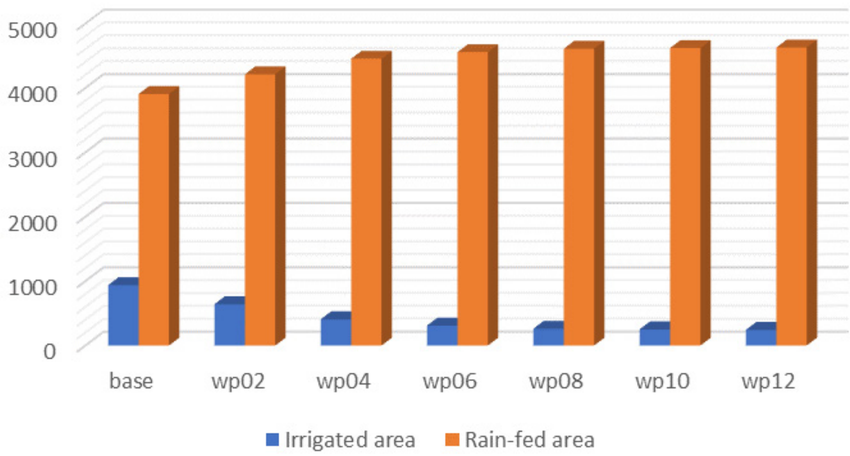

Figure 5. Change in irrigated and dry land area (in 1000ha) as water prices increase.

Source: Own elaboration based on CAPRI results.

In terms of the irrigated area by type of crop, the olive grove, which represents the largest irrigated area in Andalusia, is the most affected. Cereals also experience a strong decrease, however, fruit and vegetables show less variation as the price of water increases.

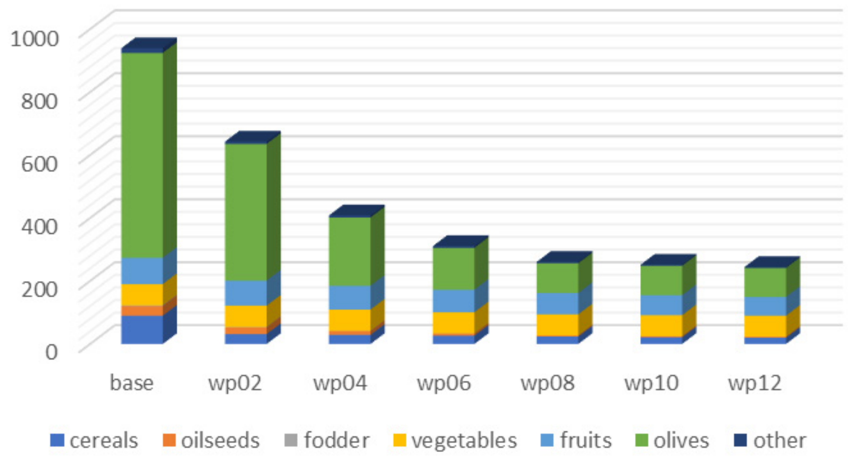

Figure 6. Change in irrigated area (in 1000ha) as water prices increase.

Source: Own elaboration based on CAPRI results.

The results of this sensitivity analysis highlight the importance of having adequate projections for each scenario. In the Andalusian case study, only the water price parameter has been modified as mentioned above, so the results will be interpreted accordingly. Water availability, water prices and irrigation technologies are interconnected, and therefore defining a water pricing policy implies taking these interrelations into account.

4.1.3.2 E3ME model

The E3ME has been applied to the Andalusia case study to analyse the energy-food nexus in relation to energy use by the agricultural sector and energy production from biomass. Furthermore, the E3ME has been very useful to explore the links between water and energy in terms of hydropower production. Other variables provided by the model are GHG emissions by sector and employment.

E3ME provides annual data until 2050 for different variables, such as energy production and consumption by source and GHG emissions at the national level. Within the framework of SIM4NEXUS, the data for Spain has been broken down at a regional level for Andalusia. The following figures show the preliminary results of renewable energy production by source and CO2 emissions by sector in Andalusia.

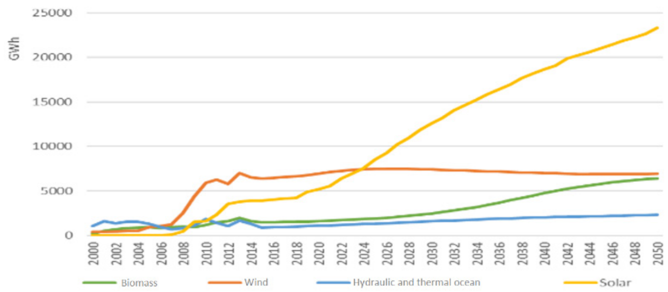

Figure 7. Production of renewable energy by source in Andalusia (GWh). source: own elaboration based on E3ME results.

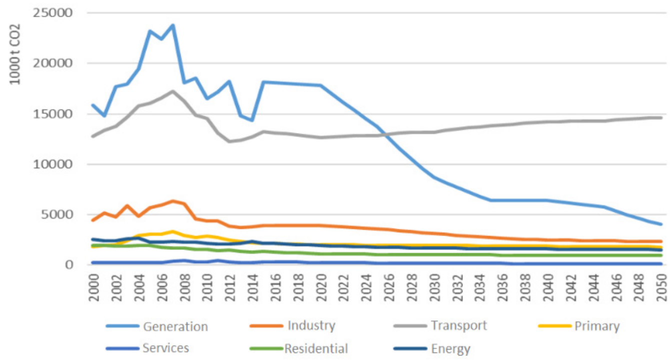

Figure 8. CO2 emissions by sector in Andalusia (1000 t CO2). Source: Own elaboration based on E3ME results.

4.1.4 Concluding remarks on the application of thematic models

The results of the thematic models mentioned above have been validated by the stakeholders during the second workshop of the Andalusian Case Study. The workshop gathered stakeholders from the water, energy, and food sectors. First, the event provided a forum for the presentation of the preliminary results derived from the thematic models (CAPRI and E3ME), applied to the case study. Furthermore, a round table provided a fruitful environment for identifying the main policy objectives to address the Nexus, which will form the basis of the scenario analysis with the System Dynamics Model. Thereafter, the thematic model results and future trends were extensively discussed with the stakeholders with the aim of identifying gaps and selecting suitable future scenarios.

4.2 Sardinia case study

4.2.1 Short description of the case study

The main economic sectors of the island are industry, agriculture and tourism. Industry accounts for a large share of the regional GDP mainly because of a petrochemical industry of national relevance. Agriculture and tourism account for a much smaller share of the GDP, but provide a large share of the employment.

As for the energy sector, total energy consumption in 2012 was of 3M TOE. Electricity production is in the order of 14000 GWh/y with a RES share that increased form 9% in 2009 to 26% in 2013. However, due to the closure of a high power demanding industry in 2012 and global economic crises, export of electricity has increased from 3000 GWh/y to 8200 GWh/y. Energy costs in Sardinia are the highest in Italy. The high cost for energy combined with transport costs make the region of low interest for investors and pose a strong barrier to economic development. Presently, the region does not have access to methane which would strongly reduce energy costs (and emissions). Building the necessary infrastructures to bring methane to the island is an on-going debate. Many consider that investing on the necessary infrastructures could not be the best option in view of the zero carbon emissions to be reached by 2050 and that investments should rather aim at promoting RES, energy accumulators and electricity for transport. Presently, the electricity of the region is mostly provided by two power plants running mostly on coal and, while the government declares that all coal power plants should be closed by 2025, the owners of the power plants declare that such objective is not an option. The economic development, nexus efficiency and reaching CO2 emission targets are strongly linked to these choices.

Sardinia has a very low population (1.6M), with trends that clearly indicate a possible decline to 1.3M by 2030. 50% of the region is covered by forests that provide biomass for domestic heating which mostly uses low efficient technologies, while biomass for energy production is mostly imported.

As in many Mediterranean areas, the balance between water demand and availability has reached critical and unsustainable levels of exploitation. A sharp increase in agricultural productivity over the last 50 years has been associated with both intensification and mechanization of agricultural processes, with a strong adoption of irrigation practices. Currently, agriculture reaches a share of about 70% of total water consumption in Sardinia, due to a strong dependence on irrigation to support and increase yields of different crops (EEA, 2009). In southern Europe, soil water content will decrease, while saturation and runoff be limited to winter and spring periods (GarcíaRuiz et al., 2011). This translates into a reduction in the flow of rivers and surface and ground water resources (Senatore et al., 2011), with negative impacts on various ecosystems. A reduction in water resources is often associated with deterioration in water quality, because less water is available to dilute pollutants. Furthermore, saline intrusion is affecting coastal aquifers, especially those more overexploited.

Following the Water Framework Directive issued by the European Community, the Sardinia region introduces with the Regional Law 19/2006 the concept of Regional Multisectoral Water System (SIMR) with the aim of achieving management and good status of water resources. The coordinated management of the regional multi-sector water system is entrusted to the Water Authority of Sardinia (ENAS), with a subdivision of the regional territory into seven Hydrographic Districts (Figure 9). The characterization and monitoring of all water bodies was first accomplished in 2009-2010, revealing a high quality of surface water, and somehow lower quality for groundwater. The main causes of water degradation are due to the release of organic substances related to livestock activities and in the use of phytosanitary products, synthetic and organic fertilizers. Furthermore, saline intrusion phenomena can occur due to excessive exploitation of aquifers in coastal areas.

Figure 9. Sardinia Hydrographic districts.

Each of the 7 hydrographic districts consists of an interconnected set of artificial reservoirs (resource nodes) and centers of demand (civil, agricultural, industrial, hydroelectric and environmental), with a set of connection lines between resource nodes and centers of demand. The SIMR include 32 artificial reservoirs (with a total current capacity of approximately 1,865 million cubic meters) and 25 small dams, to which are added 5 hydroelectric plants and 47 pumping plants that convey water over 850 linear km of large aqueducts and just over 200 km of canals. Water distribution serves a population of 1.6 million inhabitants, about 160,000 ha of cropland equipped for irrigation and 11 industrial areas. The Regional Multisectoral Water System makes available 75% of the water resources used in Sardinia for the various uses, mainly using surface water resources, while the remaining 25% is extracted from underground resources and used mostly for localized uses. The system is still subject to a high vulnerability due to strong climatic fluctuations that require careful management. Furthermore, the management plan highlights a low capacity for recovery, given that the water resources in the reservoirs are re-established very slowly over time.

4.2.2 Description of the selected simulation scenarios

Sardinia was divided into 7 districts each shaping self-contained water supply/distribution systems. The nexus analysis is performed at district level for water, food, land use, energy demand and climate. Energy demand is instead considered at regional level since the energy network is consolidated regionally. As far as the thematic models are concerned, the baseline scenarios of CAPRI, E3ME and GTAP were considered (SSP2), RCP 8.5 Climate data from ISI-MIP (made available by PIK) were incorporated in the SDM.

Simulation scenarios are modelled within the SDM through the application of single, or sets of policy cards that modify outcomes of specific processes based also on inputs from the thematic models.

The policy or set of policies allow to respond to main challenges for each Nexus component:

1) Water: water shortages are a frequent issue in Sardinia and worries exist on an increased frequency of droughts under climate change scenarios. Relevant policies affect water management as well as water demand. The key indicator is the water balance for each district.
2) Energy: Sardinia has a high, yet mildly explored potential for producing electricity from renewables while it hosts most of its energy production from 2 large coal powered electricity generation plants. Policies affect the energy mix and the energy demand coming from E3ME. Key indicator is the share of renewables in the energy mix.
3) Food: The importance of agriculture in Sardinia is due to its role in employment and conservation of cultural landscapes. Policies affect irrigated and total agricultural area trends defined from CAPRI. Key indicators are food production per hectare and food production per cubic meter of water.
4) Land use: Conflicts for land use in Sardinia are low because of a low population except for coastal areas where the tourist sector exercises a pressure on land use. The population highly values the landscape in general characterized by mixtures of forests and agricultural land (Agricultural land coming from CAPRI). Policies affect tourist flows (derived from a linear correlation with the value added for "Recreation and other services" form GTAP), and in turn land uses for facilities while other policies affect the mix of forests vs agricultural land. Key indicators are number of hosting facilities and percentage forested land.
5) Climate: Sardinia participates to the burden share framework and aims at reducing its GHG emissions. Policies affect the forested area and others are in common with policies for energy. Key indicator is net GHG emissions.

4.2.3 Results of the application of the thematic models

The following results represent some key indicators for Sardinia that are strongly influenced by one or more of the thematic models. The baseline run of E3ME was used as input for electricity generation mix (carbon intensity) and energy demand. Data was downscaled to monthly values and the final outputs are influenced by the inter-linkages inside the SDM. The Figure 10 shows the change in the share of RES Energy mix in Sardinia from 2010 to 2050.

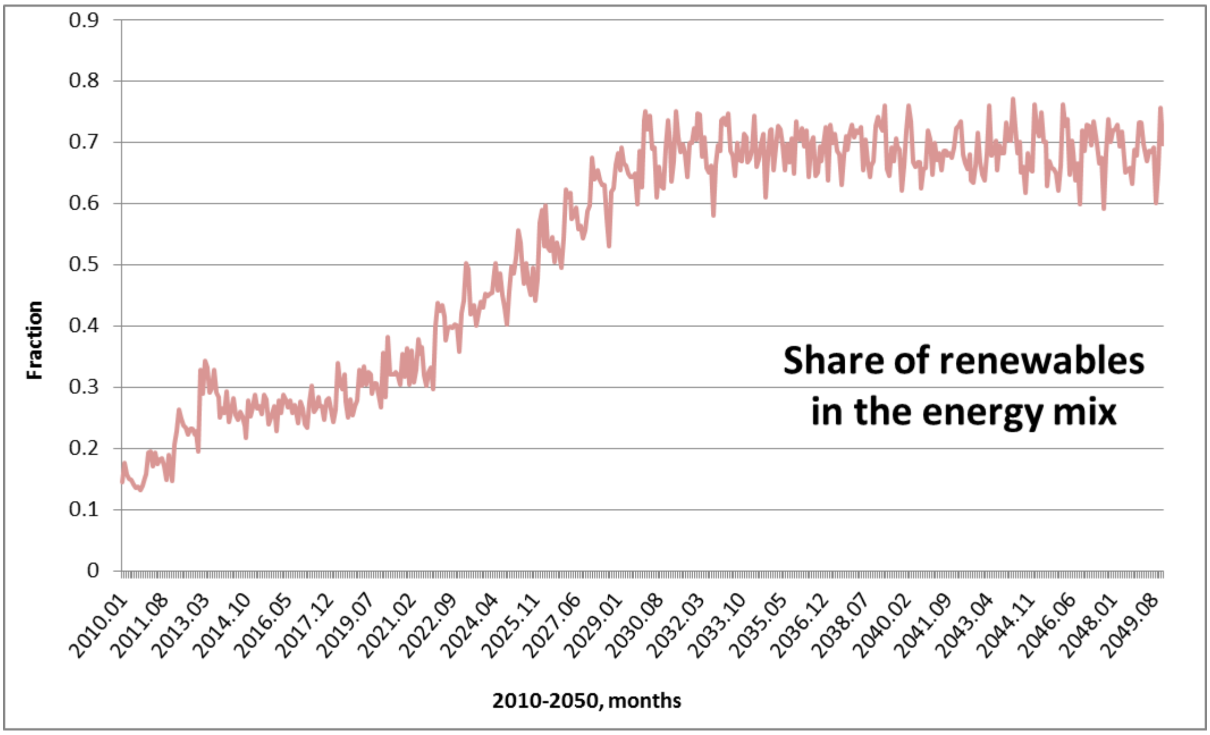

Figure 10. Share of renewables in the energy mix for the whole region of Sardinia, monthly trend from 2010 to 2050.

The Water balance is dependent on climate conditions (RCP 8.5) that affects both water supplies to reservoirs, but also water demand from different sectors. Water for irrigation is accounted for with crop water models (SIMETAW) defining water consumption for the most relevant crop as function of climate but also by changes in irrigated area per crop reported by CAPRI. Water demand for resident population is instead regulated by population trends (GTAP), while tourist water demand (Figure 11) depends in turns on climate (Tourist Climate Index) and economic trends (GTAP).

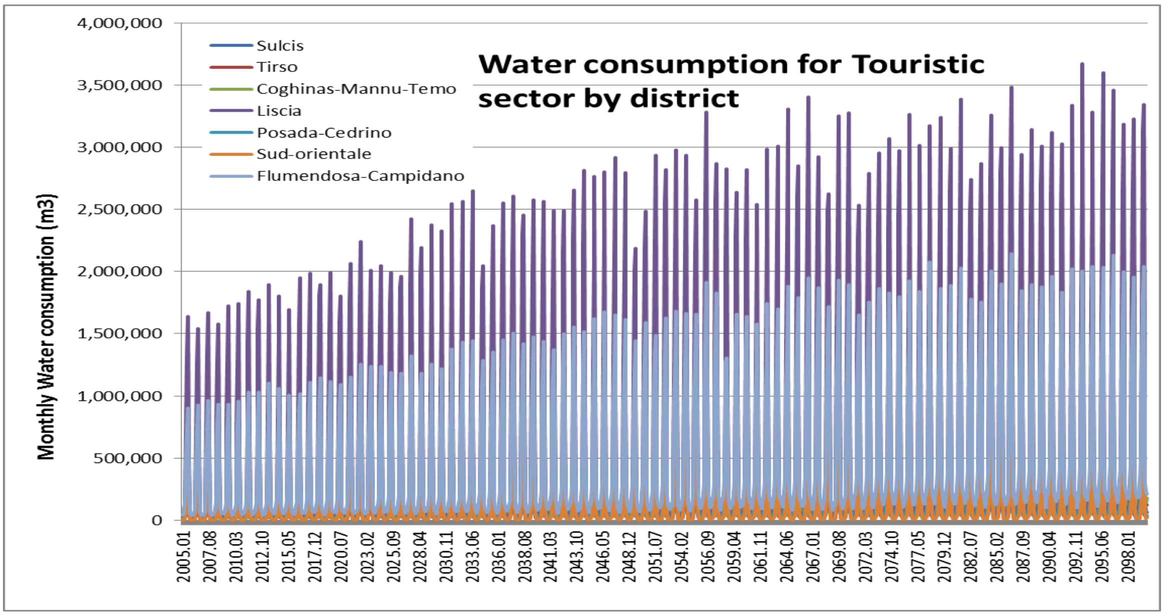

Figure 11. Monthly trends of total water consumption for tourism by hydrographic district.

Figure 12 shows the evolution on an annual base of the percentage water stored in reservoir compared to full capacity for each of the 7 districts, accounting for all the changes in water supply and water demand from different sectors.

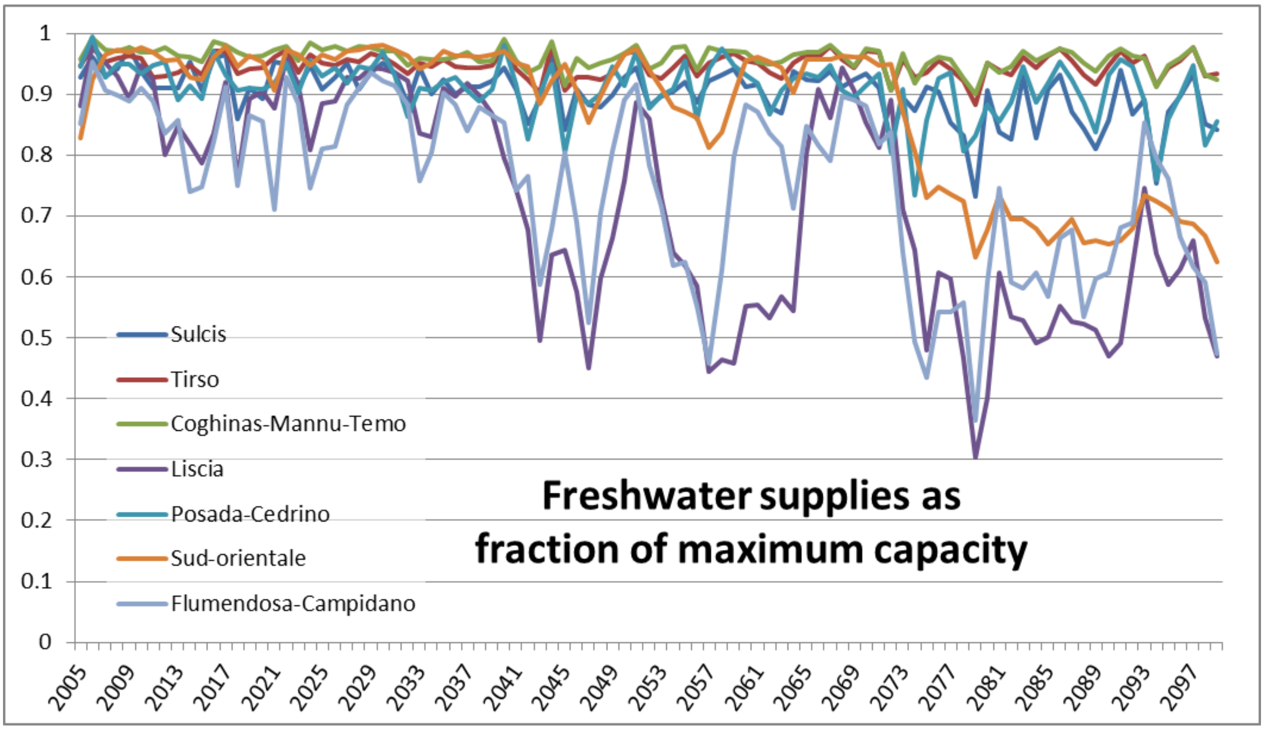

Figure 12. Trends in the baseline scenario of Freshwater supplies as fraction of maximum reservoir capacity for the 7 districts.

The GHG emissions depend on the interlinkages of all NEXUS components and those on the trends provided by all three thematic models. Figure 13 shows the net CO_2 emissions in the baseline scenario.

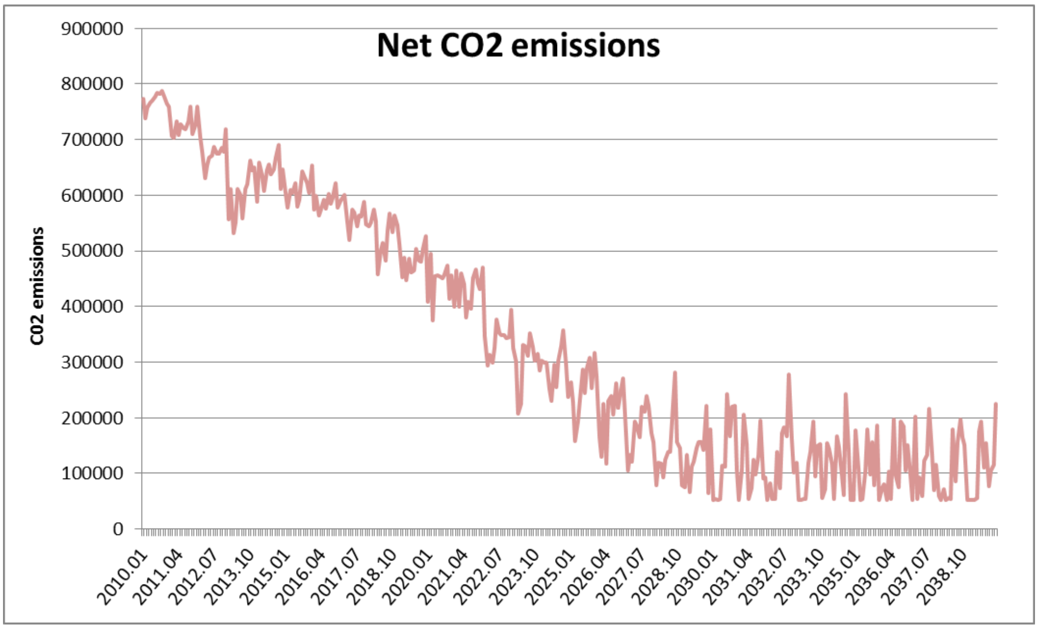

Figure 13. Net emissions integrating energy production and land use, monthly trend from 2010 to 2050.

4.2.4 Concluding remarks on the application of thematic models

The contribution of E3ME was really important and relevant to assess energy production/demand and scenarios. However, most of E3ME scenarios are originally developed at country level, and needed to be scaled down to Sardinia case study by means of proportional scaling based on the actual shares of Sardinia relatively to the national figures. This proportion is then kept fixed through future projections, and does not follow an independent general equilibrium. Further resources should be granted in the future to develop such scenario at regional scale.

Data provided by CAPRI was available instead at regional level, but by comparing the figures with national and regional statistics we have assessed that CAPRI underestimate by almost 50% the extension of irrigated area by crop. Thus, data from CAPRI were rather used to understand the percentage change of irrigated area for the different crops, using regional statistics to define absolute values for current conditions.

GTAP provided data at regional level and was very relevant to define socio-economic trends.

4.3 UK case study

4.3.1 Short description of the case study

The UK Case Study covers the region of the South West of England which is under the operational control of South West Water Ltd. The area roughly approximates to the UKK30 and UKK43 NUTS boundaries Devon and Cornwall, covering an area of approximately 10,300 km2. There are 1.7 million residents in the region, with the majority of the population (45%) located in just 13 urban centres.

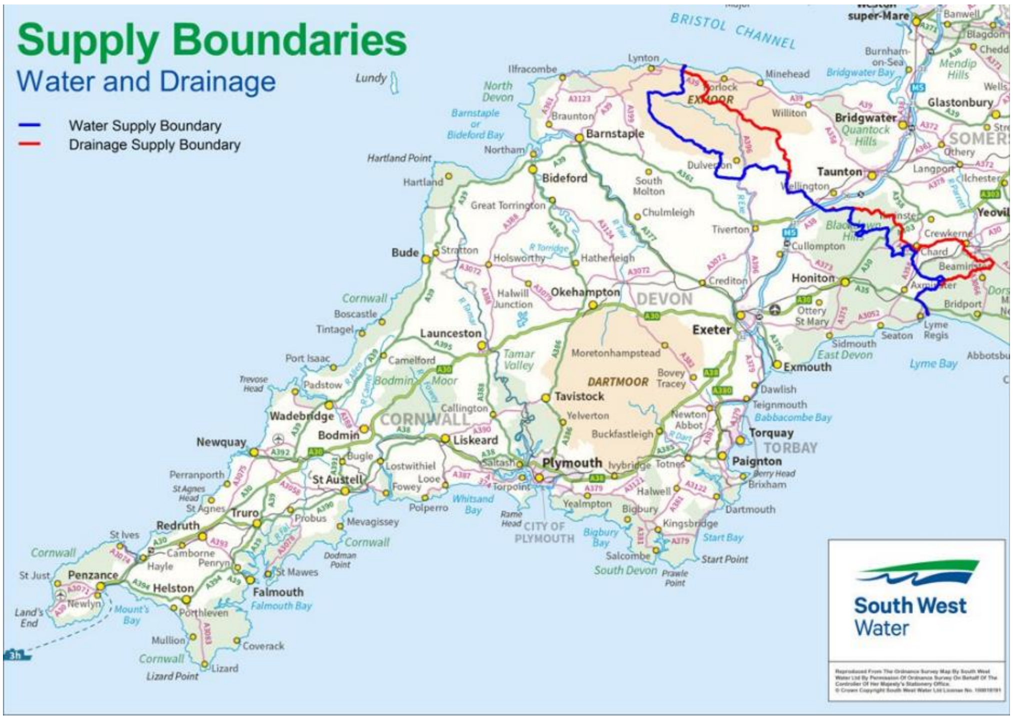

Figure 14. Southwest water operational area

The main aim of the project is to better understand the complex interactions of the Nexus components in the South-West region and develop a decision support framework to facilitate integrated resource management.

The UK case study has been prepared in partnership between South West Water Ltd (SWW) and the University of Exeter (UNEX). Both partners have a strong interest in water and energy. As a water services provider, SWW has a special interest in the influencing factors on the water sector. It is, therefore, the resource and policy interactions between water and energy which form the focus for investigation.

4.3.2 Description of the selected simulation scenarios

The baseline scenario was the only simulation run in the thematic models, CAPRI and E3ME, all other scenario analysis is conducted directly within the SDM. The user is empowered to explore narratives of interest, by selecting any combination of 55 policy interventions (policy card) in each policy setting interval. Scenarios are therefore created by the user and can be made appropriate to unique research objectives. Furthermore, the addition of an economic analysis layer makes it possible to evaluate the economic feasibility of key policy decisions, potentially helping to identify least cost solutions.

The selected approach to scenario analysis was driven by the relatively large number of policy interventions, and in recognition that affordability is the determining factor where multiple solutions to an objective are found. The flexibility of this methodology also supports the approach of the UK's Government, energy and water sector, which have independently identified plausible future scenarios. To illustrate how these high priority stakeholders, utilise future scenario analysis some key examples are given.

The UK Government annually publish projections of GHG emissions arising from energy (Department for Business, Energy & Industial Strategy, 2018). Seven policy scenarios are used to identify possible pathways to 2035. These scenarios are;

1. Reference case, which is based on central assumptions for the key drivers of energy and emissions, such as fossil fuel prices, Gross Domestic Product (GDP) and population.
2. Baseline, which excludes the impact of all climate change policies.
3. Low and high fossil fuel prices.
4. Low and high economic growth.
5. Existing policies, which only includes policies that have been implemented or adopted

National Grid, the owner and operator of the UK's electricity transmission network prepare an annual report on the long term development of the UK energy sector (National Grid plc, 2019). Four scenarios are used to identify plausible pathways to 2050.

1. Community renewables, which focuses on decarbonisation by 80% of 1990 levels by 2050, through a highly decentralised model with strong consumer engagement and focused energy efficiency.
2. Two degrees, which also achieves the 80% decarbonisation, but with the focus on large scale centralised solutions, such as carbon capture and off shore wind.
3. Steady progression, the closest scenario to the current situation, largely maintaining the centralised energy model with slow uptake of low carbon alternatives.
4. Consumer evolution, which assumes strong consumer engagement and an effort to select low carbon alternatives, but progress is limited by poor policy support.

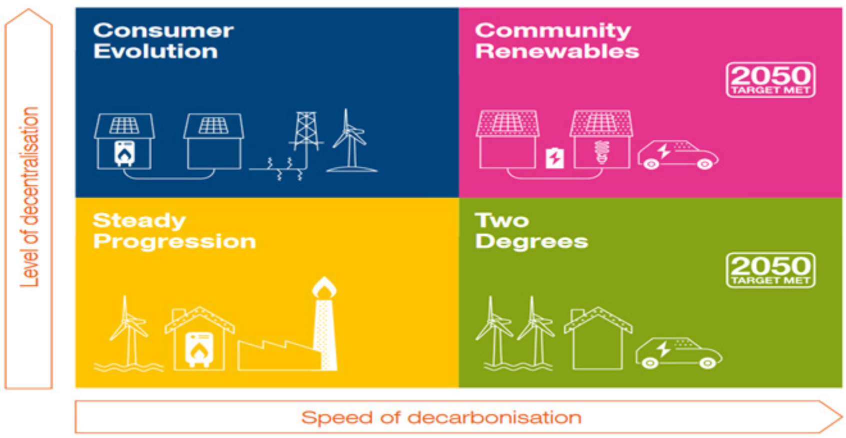

Figure 15. Scenario matrix, National Grid 2019

As part of their work toward developing sustainable river management plans, the Environment Agency who act as the UK environmental regulator have conducted scenario based analysis of potential pathways to 2050 (Environment Agency, 2017). Five scenarios are used for analysis:

1. Uncontrolled demand, which is indicative of a society concerned with self interest and economic growth, to the detriment of environment and social equality.
2. Innovation, which assumes that technological advancement will maintain living standards while preserving natural resource reserves.
3. Sustainable behaviour, which is based on greater alignment of personal and national attitudes toward social and financial equality and environmental sustainability.
4. Local resilience, assumes a weak economic climate where localism and self sufficiency are embraced at community level.
5. Reference, is the mild of the road option, where society is environmentally conscious, but social behaviours are largely driven by self interest.

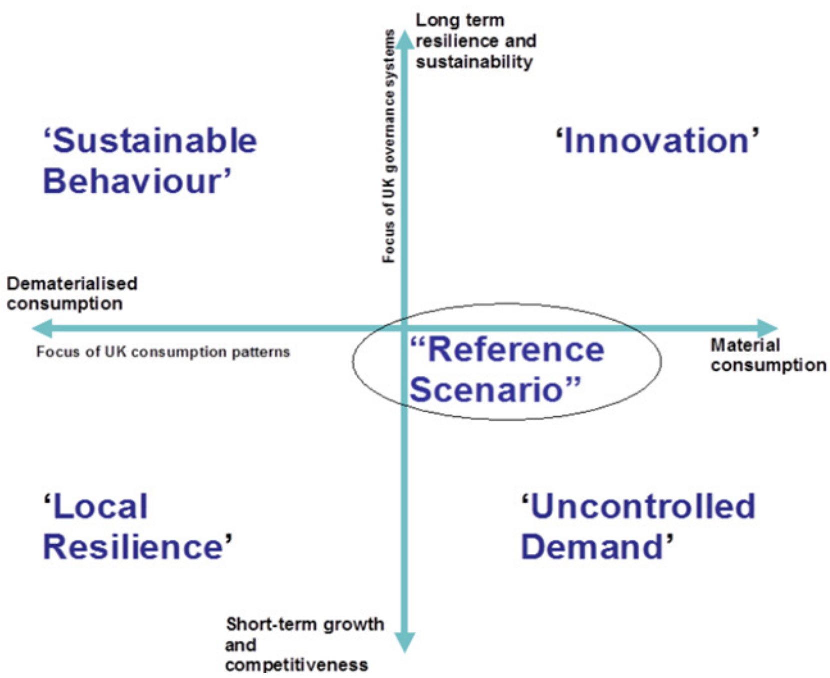

Figure 16. Axis of uncertainty representing the dominant drivers defining the scenarios, EA 2017

OFWAT the economic regulator of the UK water industry frequently publishes scenario based analysis on its proposed changes to regulatory obligations placed upon water companies. In the majority of cases the focus is on economic performance, however with OFWATs remit now including resilience, a relevant scenario analysis was published considering demand reduction (OFWAT, 2018). Five scenarios are used to examine per capita demand reduction to 2065. The scenarios are: DPSIR

1. Current ambition, which is the baseline, showing demand reduction based on existing strategies.
2. Unfocused Frugality, which assumes a poor level of public understanding/engagement with water scarcity and limited response from organisations to conserve resources.
3. Localised sustainability, which represents society, regulators and water companies positively aligned on the issues of resource management.
4. Technology and service innovation, which assumes water efficiency is achieved via market driven technological solutions.
5. Regulation and compliance

While it is true to say that some parallels can be drawn between the scenarios used by these stakeholders, enough difference exists to suggest a prescribed set of scenarios would be of limited value. The ad-hoc scenario approach will offer greater value to a wider range of users, and enable approximations of the above scenarios to be explored on a common framework.

4.3.3 Results of the application of the thematic models

The baseline run of E3ME provides core data for GDP, electricity generation mix (carbon intensity), electricity price, population and commercial activity. All of these data sets are converted to percentages using 2020 as the reference and are used as coefficients to drive trends within the SDM. Similar data provided by E3ME is also publicly available from UK government databases, while there are notable differences this has minimal impact on the final outputs of the SDM.

The land use and food modules of the SDM rely heavily on date from CAPRI for several functions. Data extracted from CAPRI is restructured using interpolation to provide monthly values for agricultural land use and yield. Each of the land uses is calculated as a percentage of the total Utilized agricultural area and applied as coefficients to the total land area calculated in the SDM. This approach enables the SDM and policy cards to control the gross volume of agriculture land, and CAPRI to forecast the specific more detailed agricultural land uses and yields.

Climate data was initially provided by PIK, however the detailed spatial analysis and hydraulic modelling required to generate realistic river flows from the precipitation data is beyond the scope of this project. Therefore, the forecast river flow data which SWW and other UK water companies use for resource planning provides for an adequate approximation.

The Future Flows and Groundwater Levels project undertaken by the Centre for Ecology & hydrology; Natural Environment Research Council, provides calibrated dataset of forecast river flow in key rivers across the UK. The river flow models are driven by forecast precipitation from based on Hadley Centre Regional Climate Model HadRM3-PPE.

4.3.4 Concluding remarks on the application of thematic models

The role of data provided by the thematic models was highly restricted by the number of policy interventions under investigation and the impracticality of running the thematic for a meaningful number of the policy combinations.

The problem arises from the static nature of the data from the thematic once extracted and the need to rely on a prescribe list of policy scenarios which would give the user very limited scope for investigation. Ideally a lightweight or stripped down version of the thematic would be embedded within the SDM to enable truly dynamic experience, this however would be computationally prohibitive. It is therefore believed that the approach taken to scenario building in a highly dynamic SDM with a light touch on thematic models offers a suitable compromise.

4.4 Greece case study

4.4.1 Short description of the case study

The concept of 'nexus' implies a group of components (elements) that interact with each other through a web of interlinkages. Under such an approach, pressures put on one nexus component entail pressures on the rest. Under the 'nexus rationale' a System Dynamics Model (SDM) was developed aiming at the effective management of five nexus components (water, energy, food, land use, climate) in Greece, in accordance with relevant nexus-related policies.

Greece is located in the South-Eastern part of Europe (Southern part of the Balkan Peninsula) in the Mediterranean Sea. According to the Hellenic Statistical Authority (http://www.statistics.gr/en/home/), its area is about 131,957 km^2 and its population has been estimated to 10.8M inhabitants. As projected by Eurostat, it is expected that by the year 2030 the Greek population will continuously decline (about 9,9M inhabitants) while by the year 2050 it is estimated to 8,9M inhabitants. Approximately 35% of the Greek population lives in the metropolitan area of Athens. Greece consists of nine geographic regions in the mainland and four insular regions/complexes. The Aegean Sea, eastern embayment of the Mediterranean Sea, lies to the East of the mainland and the Ionian Sea to the West. Greece has the longest coastline in the Mediterranean Basin, approximately 16,300 km in length, and more than 5,000 islands (227 inhabited). The natural environment of Greece is of exceptional importance as its biodiversity – flora and fauna- is very rich. More than 25% of its total area is registered as 'NATURE 2000 area'.

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

In the nexus analysis performed in Greece in addition to the five nexus components, agriculture and tourism were also investigated as the two prevailing economic sectors that put extra pressures to the 5 nexus components in order to properly accommodate their needs. Among the main issues explored are the sustainable management of water resources (surface water and groundwater), the management and regulation of land uses, the sustainable development of agricultural sector (including: certification of agricultural products, food quality and food safety), the management of conventional and renewable energy resources, the existing climate change adaptation and mitigation strategies, the sustainable development of the tourist sector, etc.

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

As for the energy sector, the total energy consumption was about 16M TOE in 2012. Public Power Corporation (PPC) supplied 77.3% of electricity demand, while 61% of Greece's energy needs are covered by imports, mainly petroleum products (44%) and natural gas (13%). The remaining 39% is covered by lignite (77%) and Renewable Energy Sources (RES), mainly photovoltaics, wind parks, small hydro-power plants, and biomass (22%). In 2015, the share of wind power for electricity production was about 9%. The highest percentage of electricity produced in Greece comes from lignite exploited within the Greek territory. RES follow with a total share of 29%, percentage that is constantly developing in the Greek energy market. The energy sector follows the general principles having been determined by the European Union and has been totally reconciled with the respective European policy priorities. The national goals set for the year 2020 in combination with the 20-20-20 European Energy Policy are (Ministry of Environment and Energy, 2017):

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

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

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

4.4.2 Description of the selected simulation scenarios

The simulation scenarios selected for the case study were modelled through the use of Policy Cards. No simulation scenario was modelled, other than the baseline. The main thematic model that was used in the case study was **E3ME**. The E3ME baseline for the EU is calibrated to the PRIMES Reference scenario 2016. The PRIMES Reference scenario focuses on the EU energy system, transport and GHG emission developments, including specific sections on emission trends not related to energy, and on the various interactions among policies in these sectors. The Reference Scenario is used by the European Commission (DG Energy) as a benchmark of current policy and market trends. For non-EU regions the E3ME model uses the International Energy Agency's *World Energy Outlook* (IEA WEO) Current Policy Scenario (CPS) for 2016. The CPS takes into account only those policies for which implementing measures had been formally adopted as of mid-2016. In the construction of the baseline, E3ME matches energy balances and emission values from the sources outlined above and this means that the same policies that are included in the sources above, are implicitly including the baseline. So, while some policies may not be explicitly presented in the E3ME model, they are implicit in the baseline numbers that are being used. In addition to the baseline run, E3ME has provided the case study of Greece with a run with most of the policies "turned off", so that they could be used with the policy cards in the serious game. The 2-degree scenario was provided by E3ME as well.

Additionally, data from **OSEMOSYS** were provided for the construction of the baseline in the SDM, only in the form of a database for power plants in Greece. OSEMOSYS provided a detailed list of all power plants in Greece, along with their capacity (in MWs) and the different fuel type (coal, oil, gas, biomass, renewables). Runs from **MAGNET** were provided and were used to estimate the Virtual Crop Water Export for the Case Study of Greece for all RBDs. Results are presented in Mellios et al. (2018)[1]. **IMAGE/GLOBIO** has provided a baseline run for Greece and reports on Nitrogen levels and Biodiversity metrics; it is incorporated in the SDM at the National level scale. 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[2]. **CAPRI** provided data, but the results were not matching for the most part the data from the National Statistical Authority, so the ELSTAT data were used instead. The outcomes worked fairly well with the other trends we have for the country, so we could proceed without the CAPRI data.

4.4.3 Results of the application of the thematic models

Results of the application of the thematic models are incorporated in the Nexus_SDM, the System Dynamics Model developed for the case study of Greece. All data provided by the thematic models, along with data from published databases have been disaggregated and processed to produce the 2010 baseline. All data are included in the published data set (Mellios and Laspidou, 2020[3]), while results from the case study of Greece that includes all thematic model data are published in Laspidou et al. (2020[4]).

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[1] Mellios, N., Koopman, J. F., & **Laspidou, C.** (2018). Virtual Crop Water Export Analysis: The Case of Greece at River Basin District Level. *Geosciences,* 8(5), pp. 161, doi:10.3390/geosciences8050161

[2] Ritchie, J., 1972.Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* **8** **(5)**, 1204–1213.

[3] Mellios, N., Laspidou, C., 2020. Water-Energy-Food-Land-Climate Nexus Data for the CaseStudy of Greece: National and River Basin District Scale. V1. Mendeley Data.https://doi.org/10.17632/9x7wn24rrp.1.

[4] Laspidou, C., Mellios, N., Spyropoulou, A., Kofinas, D., Papadopoulou, M. (2020) Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions, *Science of the Total Environment* **717**, 137264, doi:10.1016/j.scitotenv.2020.137264

4.4.4 Concluding remarks on the application of thematic models

The contribution of Thematic Models was relatively limited. Out of all thematic models, E3ME was proved to be the most robust and provided data that were critical to the modelling of the case study. **CAPRI** provided data, but the results were inconclusive for the most part and did not match the data from the national statistical authority. Thus, a decision was made to rely on the National Statistical Authority data and extract meaningful information for the model from that source. Massive effort was dedicated from the Greek team to collect reliable data and the importance of data availability and data sharing in a Nexus context was made emphatically clear to the researchers.

4.5 Latvia case study

4.5.1 Short description of the case study

Source: http://latvijas-karte.lv/

The Republic of Latvia lies in Northern Europe, on the eastern shores of the Baltic Sea. It is bordering with Estonia, Russian Federation, Belarus and with Lithuania. The total length of its maritime boundary is 498 km. Latvia covers the area of 64 573 sq.km. About 36% of area is agricultural land and 47% is covered by forest land. At the beginning of 2019 population of Latvia accounted for 1.9million people (Central Statistical Bureau of Latvia 2019).

The economic structure of Latvia is based on services, industry, and agriculture. Exports contribute to more than half of GDP. Latvia mostly exports wood and wood products, wood charcoal, electrical machinery, equipment, as well as mineral products. Due to its geographical location, transit services are highly developed, along with timber and wood-processing, agriculture, food products, manufacturing of machinery and electronics industries (IndexMundi, Latvia Economy Profile 2017). Latvia has a high potential for renewable energy but remains largely dependent on imported fossil fuels and electricity. Thus, energy security is of a key concern and ensuring the energy supply, competitiveness, energy efficiency and the use of renewable energy is the target set for 2030. The dependence on imported energy resources is steadily reducing due to the increased gross consumption of renewable energy sources (RES). Wood fuels and hydro energy, along with the oil products and natural gas imported from various countries play the most important role in the energy balance of Latvia. Energy, transport and agriculture are sectors are of the highest concern with respect to the greenhouse gas emissions (GHG). Having achieved significant reduction of total GHG emissions since 1995, the current level of emissions in Latvia remains high.

Latvia case study is focusing on the low-carbon development considering interlinkages between climate, water, energy, land use, and food and identifying potential synergies, trade-offs and possible solutions. In Latvia, low carbon development is getting an increasing attention on various policy levels along with elaboration of the "Strategy of Latvia for reaching climate neutrality until 2050" (to be adopted in 2020). Low carbon development calls for reduction of GHG emissions as well as maintaining or even increasing CO2 sequestration at the same time having positive environmental, economic, and social impacts. The directions of the Latvia case study comprise increasing energy production by RES, reduction of energy demand, decarbonisation of transport, along with sustainable land and water management practices reducing GHG emissions and nitrogen leakage from point and diffuse sources to improve the water quality.

4.5.2 Description of the selected simulation scenarios

Latvia case study focuses on low-carbon economy and resource efficiency to the development path by 2050. Pathways to explore by the simulation scenarios are related to (i) energy (energy efficiency, RES, decarbonisation of transport); (ii) land use (arable land and grasslands); (iii) food and agriculture (food production); and (iv) water quality (relevant to the fertilization practices). Three thematic models: E3ME, MAGNET and CAPRI were used for the Latvia case study. The case study implementers from BEF Latvia were in communication through e-mail exchange and Skype sessions with responsible partners to the thematic models. The actual model runs were performed by the project partners: for E3ME (Cambridge Econometrics), MAGNET (Wageningen Economic Research), and CAPRI (Technical University of Madrid).

The global macro-econometric **model E3ME** was applied to explore a low-carbon transition through different sets of energy and climate policies in Latvia. Two simulation scenarios were selected: **a baseline** to represent the current trends of the systems being modelled and **a 2-degree scenario** with E3ME assumptions on carbon pricing, improvements to energy efficiency in final use sectors (except for road transport), power sector RES support, decarbonisation of road transport, and a biofuel mandate in aviation. E3ME model application to the Latvia case study provided results on energy production by technology, energy consumption by type and sector, GHG emissions (Table 3).

Table 3. Application of E3ME model in the Latvia case study.

Variable type	Variables	Reflection to the pathway
Economy	GDP Output by sector Employment by sector	
GHG emissions	CO_2 emissions by sector	Energy related emissions by industry, households, tertiary sector
Energy demand	For coal, oil, gas, electricity, heat, biomass & combustible waste – by sector	Energy efficiency Decarbonisation of transport
Electricity generation	By technology (nuclear, coal, oil, gas, biomass, hydro, solar, wind, other)	RES for electricity

A general computable equilibrium model **MAGNET,** with an additional focus on agriculture and designed for economic impact assessment was applied to a baseline simulation. The Latvia case has received variables for macro-economic, sector level (incl., food and energy), trade, land, climate and welfare.

The global spatial partial equilibrium model **CAPRI** was applied to explore impacts of agricultural, environmental and trade policies. Two simulation scenarios - a **baseline** and a **2-degree** scenario were selected. The baseline scenario is building upon the medium-term outlook for EU agricultural markets and income and depicting the projected agricultural situation up to 2050 under the SSP2 scenario and a status quo policy setting. The 2-degree scenario is being built on application of policy instruments aiming to reduce the GHG emissions in non-ETS sectors by 30% by 2030 and by 75% by 2050 compared to 2005. CAPRI model application to the Latvia case provided results on crop yields, land use patterns and on income from different types of agricultural areas (Table 4).

Table 4. Application of CAPRI model in the Latvia case study.

Variable type	Variables	Reflection to the pathway
Agricultural production	Crop yields	Promotion of more productive cultivars
Land use	Utilized agricultural area Arable land Cereals Rape Perennial grasslands Meadows and pastures Pulses	Sustainable land use (different choices for land use type)
Economy	Income from agricultural areas	Sustainable land use (arable land and grassland) considering farm welfare

4.5.3 Results of the application of the thematic models

Outcomes from the selected simulation scenarios by the thematic models in Latvia case are applied both, to support nexus-compliant decision making and to provide feed-in for the development of complexity methodology application by a System Dynamic Model to the Latvia case.

Projections delivered by E3ME model the baseline and 2-degree scenario

Key economic indicators and GHG emissions for the Latvia case

The outcomes of the 2-degree scenario are compared with the baseline in order to assess the impacts of a global set of policies that are designed to limit temperature change to 2-degree C. In the 2-degree scenario all baseline policies are included, and the additional energy and climate mitigation policies added. Impact on GDP and output by economic sectors is positive by moving towards the 2-degree target as compared to the baseline (Figure 17).

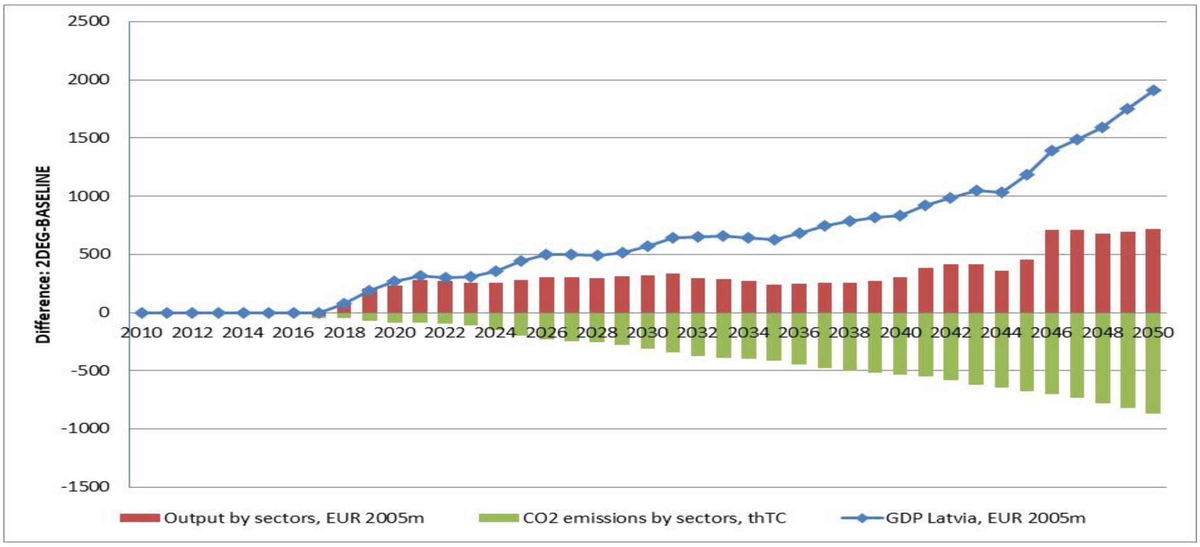

Figure 17. Macroeconomic and GHG emission projections 2010 – 2050 in Latvia (as difference between the 2-degree and baseline scenarios). Data source: E3ME.

GHG emissions are projected to decrease by 2050 both in the baseline as well as in the 2-degree scenario. Application of additional policies in 2-degree scenario result in higher decrease in CO2 emissions (Figure 18). Decarbonisation of road transport sector using policies to encourage the uptake of electric vehicles and introduction of biofuel mandate reaches CO2 emission reduction of 420 thTC by 2050 in the 2-degree scenario compared to the baseline. Another sector benefitting from implementation of additional policies – a combination of feed-in-tariffs and direct subsidies to promote the uptake of renewables, is the power generation sector reaching CO2 emission reduction of 225 thTC by 2050. Less pronounced CO2 emission reduction is projected for households, agriculture and forestry and other sectors.

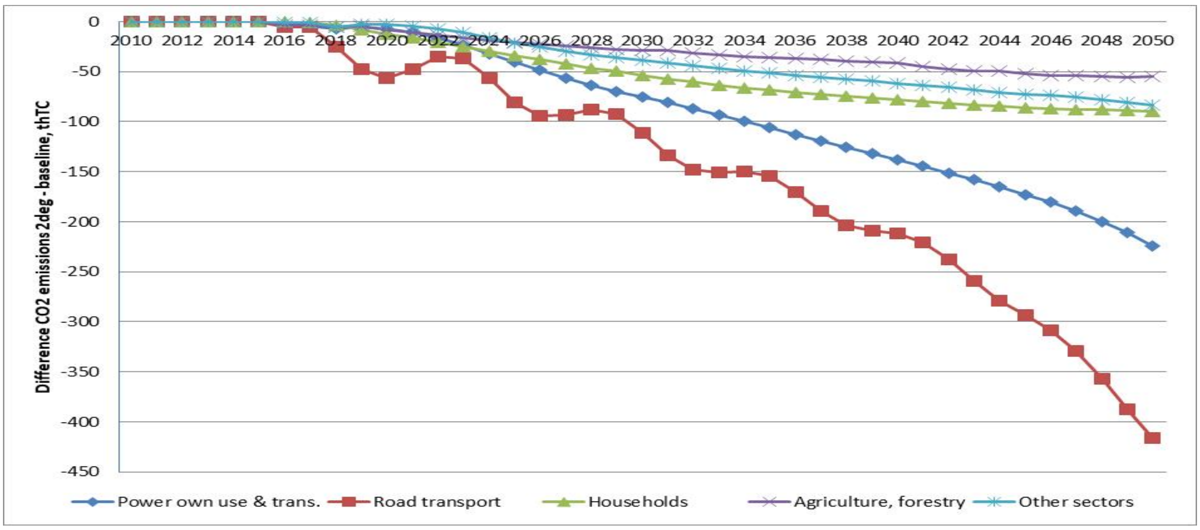

Figure 18. Projected CO2 emission difference in the 2-degree scenario in comparison to the baseline scenario 2010 – 2050 in Latvia. Data source: E3ME.

For the E3ME model calculation, the macroeconomic and energy impacts of the policies implemented in the 2-degree scenario were compared within the three SIM4NEXUS case studies of Latvia, The Netherlands, and the UK. These case studies are of similar objectives (low carbon economy and/or increasing renewable energy use). Results indicate positive GDP effects (as compared with the baseline levels) in these case studies that are expected to benefit from the additional investment in energy efficiency and increased support for renewables as well as lower dependency on fossil fuel imports (Brouwer et al., 2018).

Impact on electricity generation

The policy objective for increasing energy production by RES in Latvia is largely directed to electricity production sector. In the period from 2010 to 2050, the projections by E3ME indicate increased electricity generation by 29% in the baseline scenario and by 59% in the 2-degree scenario. From the electricity generation technology perspective Latvia has suitable circumstances for use of hydropower (share of 53% in 2010). Hydroelectricity is mainly produced in 3 hydropower plants installed on the Daugava River. The already installed electrical capacity most probably will not be changed significantly in the future. During the recent years, gas electricity generation technology has been another cornerstone in the electricity generation in Latvia; however, gas is imported fossil fuel. The modelled policies for the power sector lead to a substantial decrease in the use of gas for electricity generation. Table 5 highlights the changes in share of the electricity generation systems resulting from application of the decarbonisation policies.

Table 5. Share of electricity generation by source in Latvia. Source: E3ME

	2010	2020	2030	2040	2050
Electricity generation baseline, share					
Gas	0.45	0.32	0.29	0.26	0.21
Biomass	0.01	0.07	0.13	0.17	0.24
Hydro	0.53	0.60	0.54	0.48	0.39
Wind	0.01	0.01	0.04	0.09	0.16
Electricity generation 2-degree scenario, share					
Gas	0.45	0.32	0.22	0.13	0.07
Biomass	0.01	0.07	0.19	0.34	0.52
Hydro	0.53	0.60	0.55	0.45	0.31
Wind	0.01	0.01	0.04	0.08	0.11

Increasing electricity production by RES using/ developing new sources: biomass and wind is projected by E3ME (Table 5). Considerable increase for use of biomass in electricity generation is predicted in the baseline scenario (24% in 2050); however, projections in the 2-degree scenario foresee that half of electricity is generated by biomass technologies (52% in 2050). Energy production policy in Latvia support electricity production from wind as an unexploited source: it is projected to reach 16% share in the baseline and 11% share in the 2-degree scenario by 2050.

The policies related to increased use of renewables, technology development and carbon pricing in the 2-degree scenario promotes substantial increase of electricity generation from biomass since mid 20ties resulting in increased production of 3200 GWh/y in 2050 (Figure 19). Opposite trend is indicated for electricity production from fossil fuel (i.e. gas) since mid 20ties due to support for use of RES. Surprisingly energy produced from hydro and wind energy sources decreases since 30ties which is hard to explain in this context.

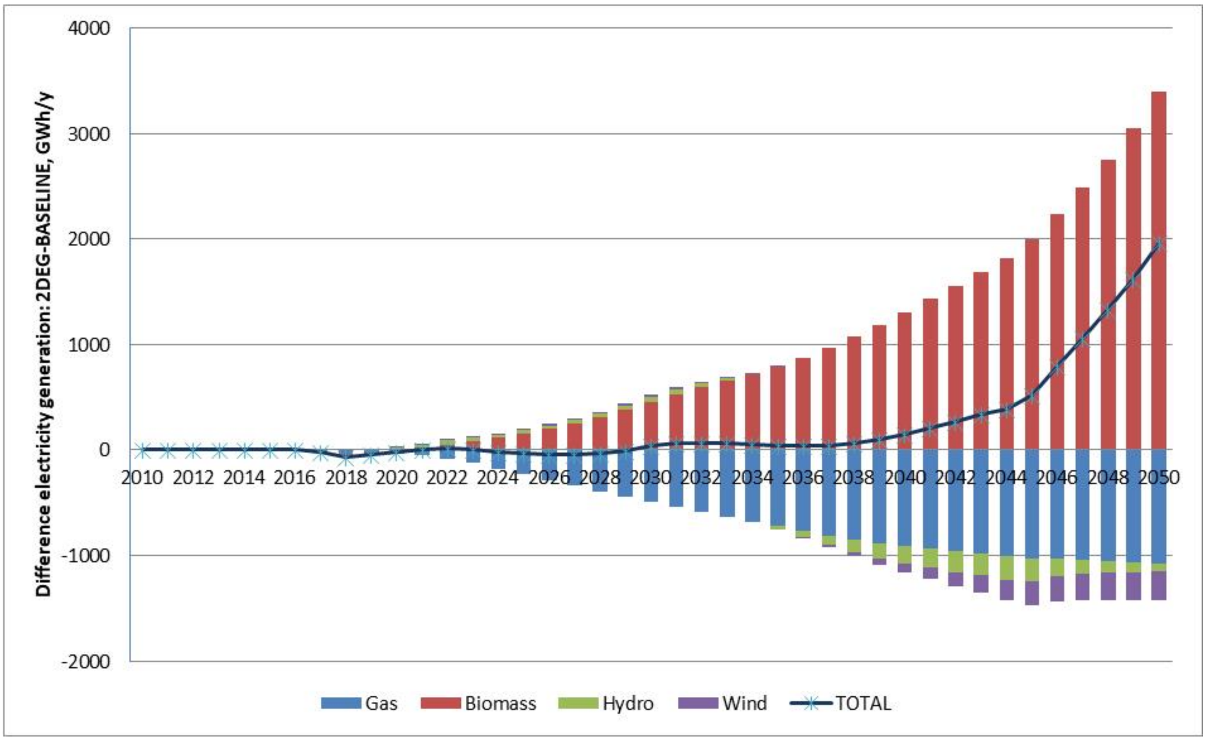

Figure 19. The difference of 2-degree and baseline scenario for electricity generation by technology in Latvia, 2010 – 2050. Data source: E3ME.

E3ME model predicts electricity energy demand increase in Latvia by ca. 50% in the period from 2010 by 2050 by both the baseline and the 2-degree scenario. Comparing these scenarios different patterns in electricity consumption is attributed to various sectors (Figure 20). Electricity demand in households shows increasing trend that can be attributed to the household switch from gas to electricity appliances being more energy efficient and increased uptake of electric vehicles (particularly from 40ties) which is expected to lead to increased demand. In industry, agriculture and other use sectors electricity demand reduces most probably due to higher energy efficiency which contributes to the decrease in demand for electricity.

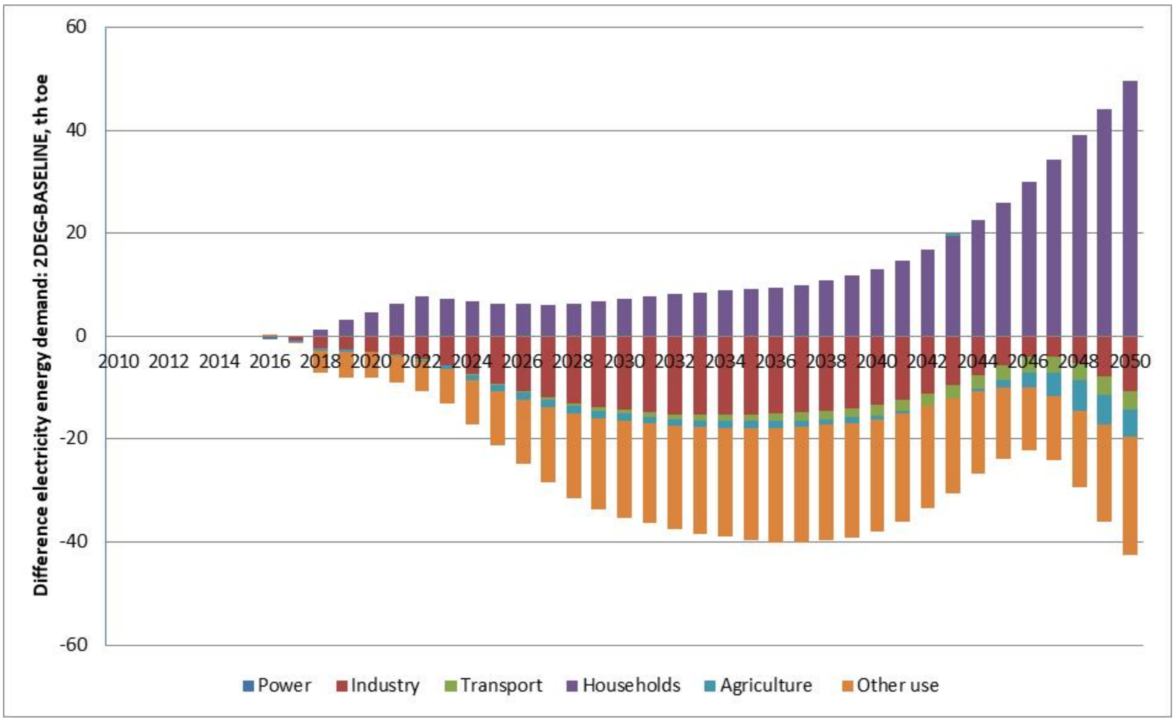

Figure 20. The difference of 2-degree and baseline scenario for electricity demand by various sectors in Latvia, 2010 – 2050. Data source: E3ME.

Energy demand in Latvia

In Latvia slight increase in total energy demand from 2010 to 2050 is predicted by E3ME model baseline scenario. The 2-degree scenario predictions show the decrease in total energy demand by ca. 15% in 2050.

Shares of various energy sources are compared for the baseline and 2-degree scenario in the period 2010 - 2050 (Figure 21). Coal as an energy source is nearly phased out in Latvia. The transport sector is the main user of oil in Latvia and thus the predicted share remains stable throughout the period having slight decrease after 2040 possibly due to uptake of electric vehicles. As expected, demand for gas is decreasing as policy implementation support phase out of fossil fuels in favour to renewable energy sources. Heat demand is reduced in 2-degree scenario mainly due to lower heat consumption in household sector possibly because of implementation of energy efficiency measures (e.g. insulation of buildings) and switch to more efficient electricity appliances. Biomass is continuously a prominent energy source in Latvia. Its dominance is particularly highlighted in the 2-degree scenario prediction where 50% of energy demand is covered by biomass in 2050.

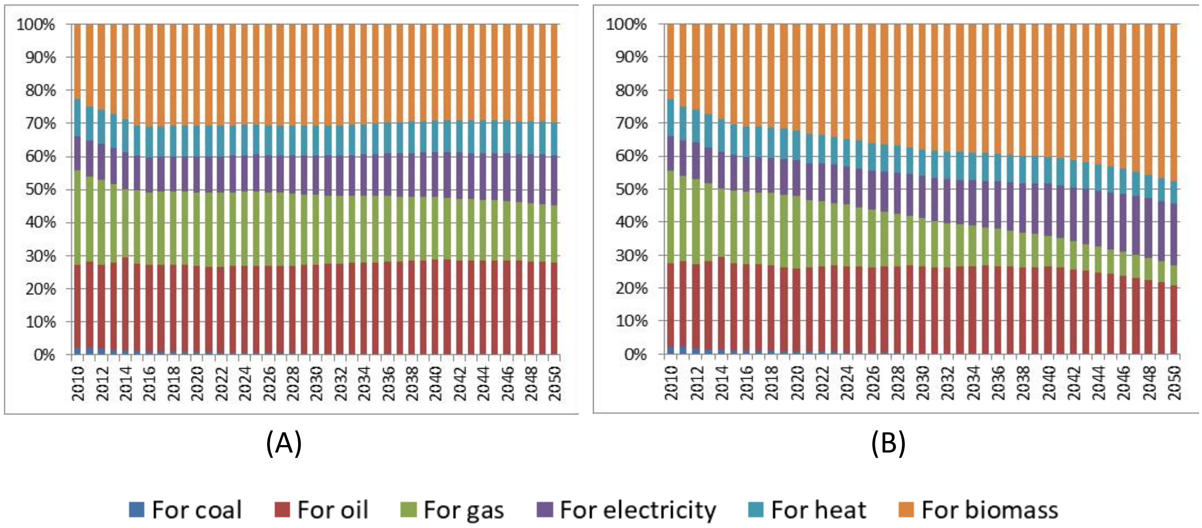

FIGURE 21. SHARES OF ENERGY DEMAND FOR VARIOUS ENERGY SOURCES COMPARED FOR THE BASELINE AND 2-DEGREE SCENARIO IN THE PERIOD 2010 – 2050 IN LATVIA. DATA SOURCE: E3ME

E3ME predictions indicate high biomass energy demand for power generation and households in the 2-degree scenario (Figure 22). Such high demand in biomass for energy production can create a pressure on local biomass resource. Policies concerned with biomass resource maintenance shall be balanced with energy production and demand.

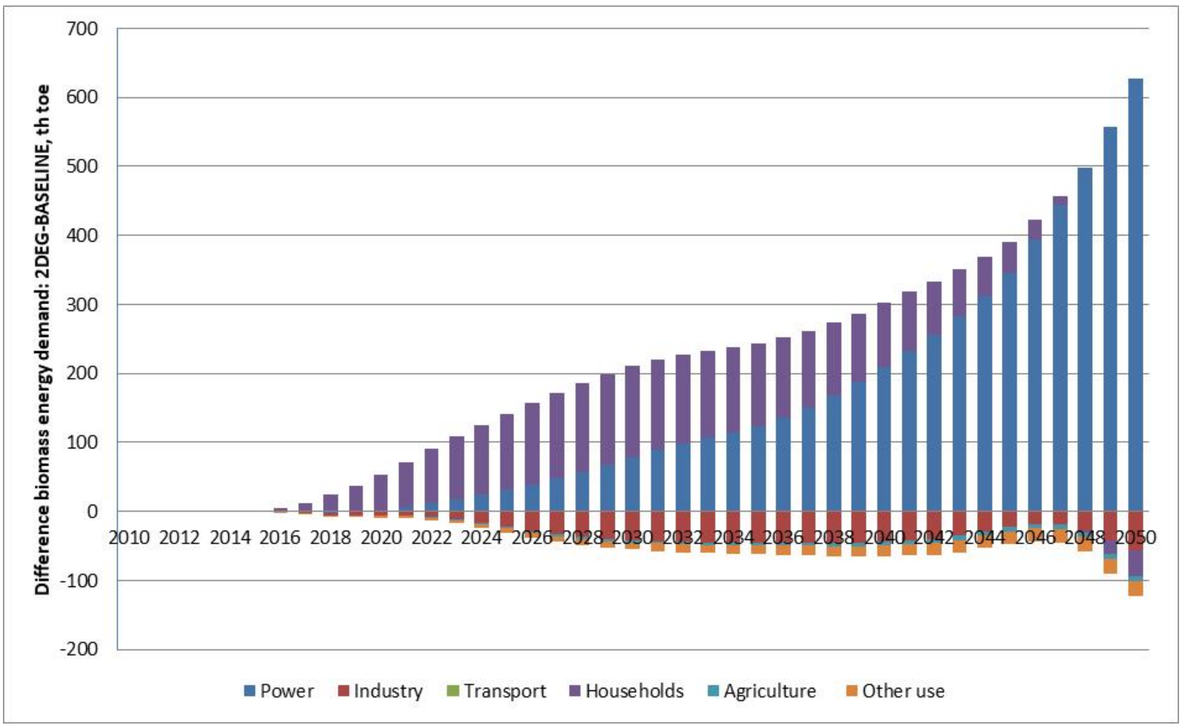

Figure 22. The difference of 2-degree and baseline scenario for biomass demand by various sectors in Latvia, 2010 – 2050. Data source: E3ME.

The policy objective for increasing energy efficiency in Latvia is targeted to reduction of energy consumption in households. In the period from 2010 by 2050, E3ME model predicts decrease in energy demand by ca. 5% in the baseline and 36% in the 2-degree scenario for households. Comparing these scenarios different patterns in energy demand is attributed to various sources (Figure 23). Considerable decrease is indicated for consumption of gas and heat. Slight increase is projected for electricity and oil. Somewhat different pattern is observed from biomass consumption by increase until the 30ties and then reverse to a decrease reaching the lowest level in 2050.

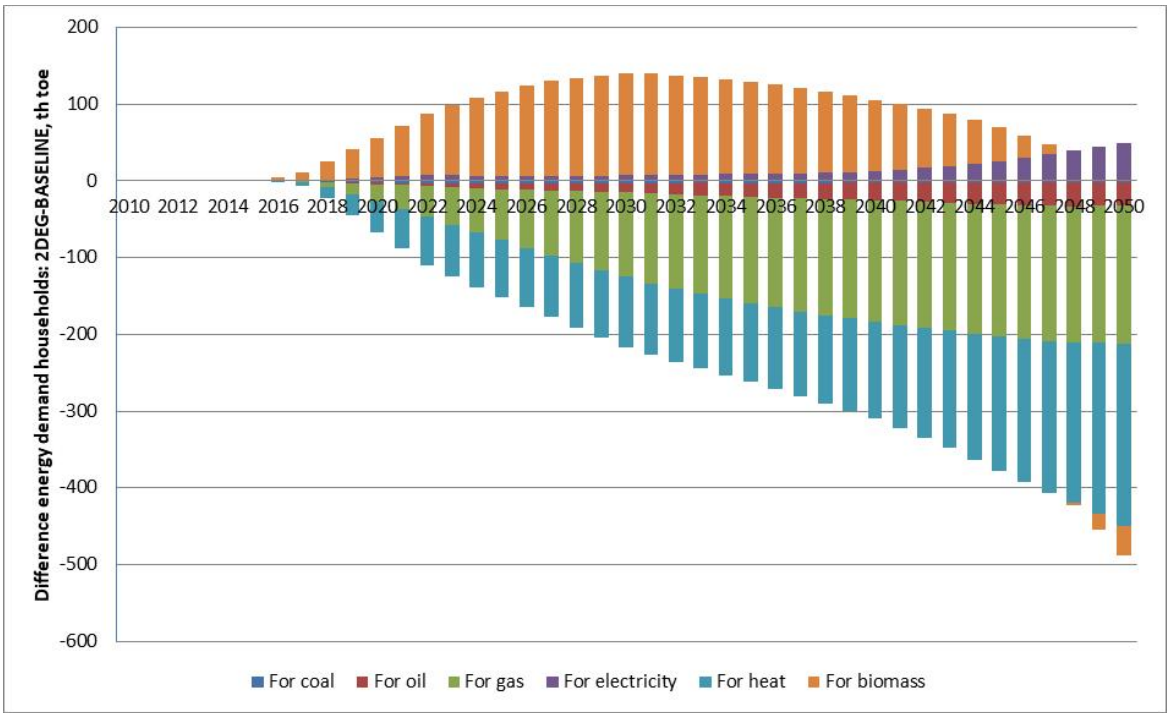

Figure 23. The difference of 2-degree and baseline scenario for demand of various sources of energy by households in Latvia, 2010 – 2050. Data source: E3ME.

Projections delivered by CAPRI model the baseline and 2-degree scenario

In the Latvia case, CAPRI has been used to analyse the links between land use and agricultural production. In the period from 2010 to 2050, CAPRI model results were compared for the baseline and the 2-degree scenario. In the period from 2010 by 2050, comparison of the CAPRI predictions from both scenarios indicate increase in utilised agricultural area and arable land in Latvia by applying GHG emission reduction policies (Figure 24). This increase is predicted on expenses of perennial grasslands, meadows and pastures. Surprisingly the area for cereals is predicted to remain unchanged. Area for the energy crops i.e. rape is declining in Latvia, although slight slowdown of the decrease is predicted in 2050 according to the 2-degree scenario.

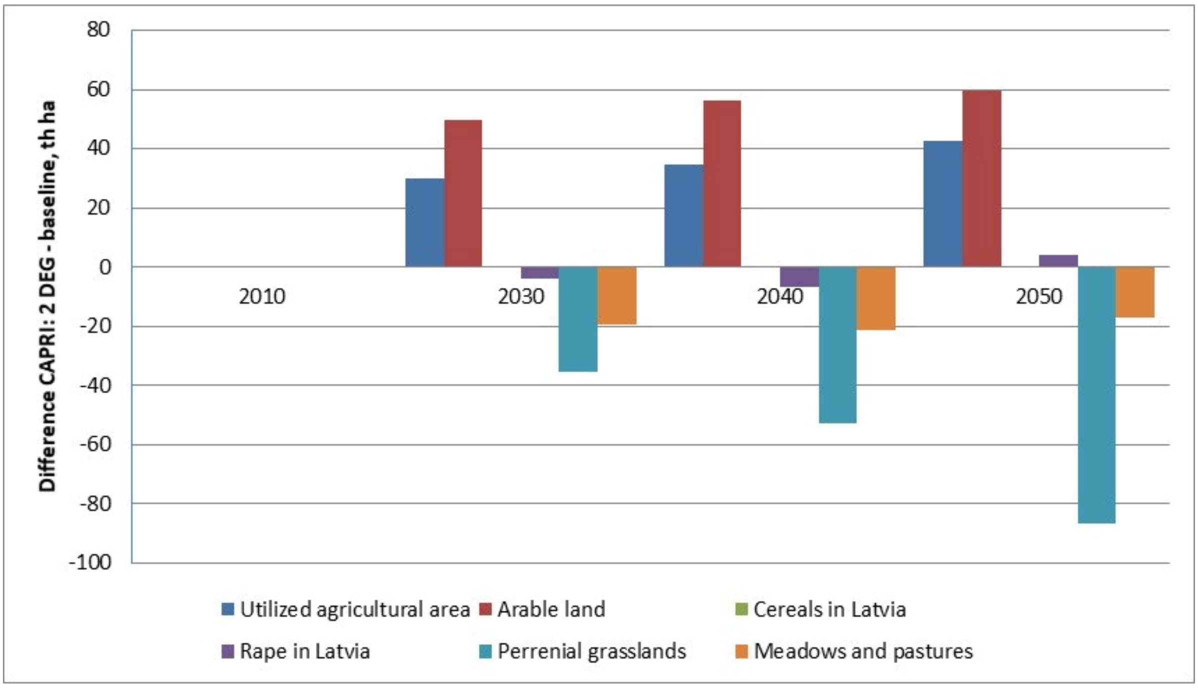

Figure 24. The difference of 2-degree and baseline scenario for utilised agricultural area in Latvia, 2010 – 2050. Data source: CAPRI.

The CAPRI model provides prediction for the economic aspects related to income (Eur/ha) from various uses of agricultural area (Figure 25). In the period from 2010 to 2050, the increasing income from utilised agricultural area is indicated in Latvia being more pronounced in the 2-degree scenario compared to the baseline. The baseline prediction reflects high and stable income from growing of energy crops (rape), while the 2-degree scenario shows decreasing economic effect from this cultivar. Economic value of the land unit (ha) for perennial grasslands, meadows and pastures is higher in the 2-degree scenario, although the total area for this land use type is predicted to shrink (Figure 24). Economic value of the land unit for cereals is considerably higher compared to pulses, however farmers must make a reasonable choice to comply with the greening requirements set by the EU agricultural policy.

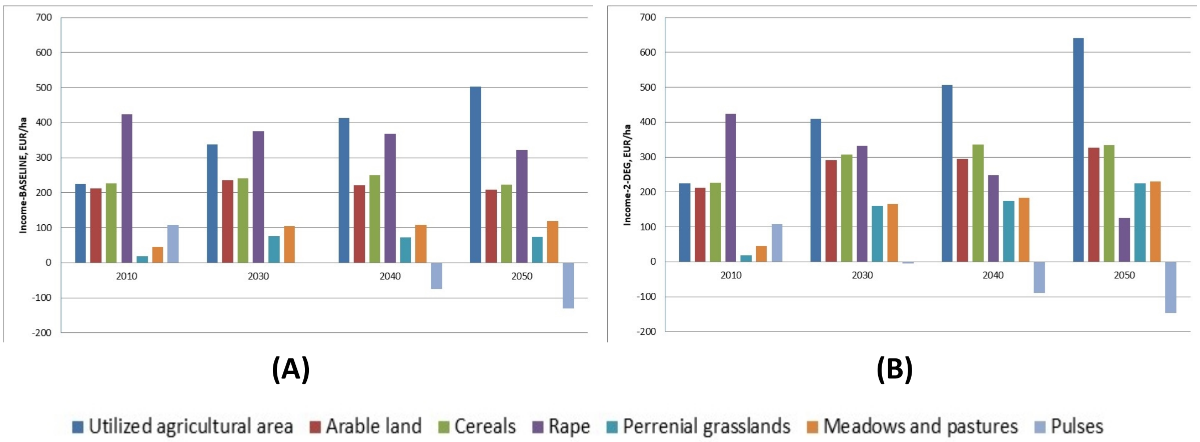

FIGURE 25. PREDICTED INCOME (EUR/HA) FROM VARIOUS USES OF AGRICULTURAL AREA IN LATVIA 2010 – 2050. DATA SOURCE: CAPRI.

4.5.4 Concluding remarks on the application of thematic models

Application of thematic models in the Latvia case provided insights of possible development trends in energy and agriculture sectors. BEF Latvia is planning to reflect the model results in the workshop with stakeholders in the country (planned in Spring 2020). The discussion will be aimed to contribute to the development of SIM4NEXUS policy recommendations.

For the time being the results are partly incorporated in the policy cards developed for the purpose of the Serious Game. However, results of the thematic models alone do not allow to explain NEXUS interlinkages and to perform integration of NEXUS concept for policy analysis. BEF Latvia utilised the model prediction results as a feed-in for the System Dynamics Modelling by preparing data sets up to 2050. In case of multiple data sets i.e. national predictions and CAPRI results, the case developers tried to find the compromise to reflect best that the national circumstances are accounted for.

4.6 Netherlands case study

4.6.1 Short description of the case study

For the Netherlands, the Paris UNFCCC agreements and EU Energy and Climate goals and targets are leading, which means an 80-95% reduction of GHG emissions in 2050 compared to 1990. The GHG-equivalent emissions in the Netherlands declined between 1995 and 2014 but in 2015 there was an increase mainly due to an increase of the coal and natural gas generated energy by the electricity producers, see Figure 1 (Statistics Netherlands 2015). The main GHG emitted was CO_2, which has been fairly stable since 1990. The other GHG emissions, such as CH_4 and N_2O-emissions, declined between 1990 and 2015. Agriculture is responsible for the majority of CH_4 and N_2O-emissions and for 12.5% of total Dutch GHG emissions (measured in CO_2 equivalents). Sources of agricultural emissions are livestock, the use of fertilizer on crop lands, the use of fossil fuels for pumping, heating and tractor use, see agrimatie.nl.

The 2017 coalition agreement in the Netherlands formulated a target for GHG emission reduction between 49-55 percent in 2030 as compared to the emission level in 1990. This is a target which is proportionate to a 95% reduction in 2050. The main contribution to the reduction will come from CCS. The low-carbon economy corresponds to a maximum emission level of 11 Mton CO_2-eq. in 2050. Note that GHG emissions from international shipping (8 Mton CO_2-eq. in 2013) and LULUCF (4 Mton CO_2-eq. in 2013) are excluded from the emission targets, see Tabel 2.1 in (Ros et al. 2016).

To reach a low-carbon economy in 2050, Ros et al. (2016) identified five categories of technological measures: 1) energy saving; 2) production of electricity without CO_2 emissions; 3) transition from oil/gas to electricity (electrification); 4) energy from biomass, and 5) carbon capture and Storage (CCS). Ros et al. (2016) argued that a mix of all these measures is necessary to reach a low-carbon economy in 2050. However, it is not clear yet how successful these measures can be implemented and what policy mix is required to change the economy in the Netherlands into the direction of a low-carbon economy. All these technological measures will have different consequences for GHG gases emissions, the production and use of energy and food, and the use of and consequences for water and land. These technological options will have socioeconomic consequences. Moreover, policies and socioeconomic interventions can contribute to the reduction of GHG emissions. These societal consequences or their cost-effectiveness have not yet been evaluated. For instance, energy saving can be realised with replacing energy-intensive technologies with less energy-intensive technologies or in some cases by non-energy requiring technologies.

The overall objective of the Dutch case study in SIM4NEXUS is to identify low-carbon and resource-efficient pathways for the water-land-food-energy nexus in 2050. In particular, what can be the role of biomass in the transition to a low-carbon economy in 2050 considering the interaction with water, land, energy, food and climate. Biomass will be needed to achieve the 95 percent GHG emission reduction to develop a low-carbon economy in 2050. However, the application of biomass needs to be sustainable and therefore has requirements and limitations. The Dutch case study made use of the projection results of three thematic models, namely CAPRI for agricultural land use and agricultural practices, E3ME for the production of energy, the demand for energy, sectoral Value Added and GDP, and MAGNET for the development of energy prices. Additional information on population, nature areas, water use, nutrient contents of agricultural products, detailed information on different types of renewable energy were collected from other data sources like Statistic Netherlands.

4.6.2 Description of the selected simulation scenarios

4.6.2.1 Base scenario

For the future projections of the case study, the second shared socioeconomic pathway (SSP2) scenario of the IPCC is taken as the baseline scenario. The IPCC is the intergovernmental panel on climate change which is a large group of scientist which have constructed five pathways for the future based on five different demographic and socioeconomic projections. The SSP2 scenario is described as the Middle of the Road scenario with medium challenges to mitigation and adaptation (Riahi et al. 2017). They state that:

> "The world follows a path in which social, economic and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations, Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly

and challenges to reducing vulnerability to societal and environmental changes remain. "

For all thematic models, the consequences of the SSP2 scenarios are evaluated. Key indicators include the share of renewable energy, GHG emissions, energy produced out of (imported) biomass, land use amongst others. For the Dutch case, the indicators for the Netherlands were derived from the results of the thematic models.

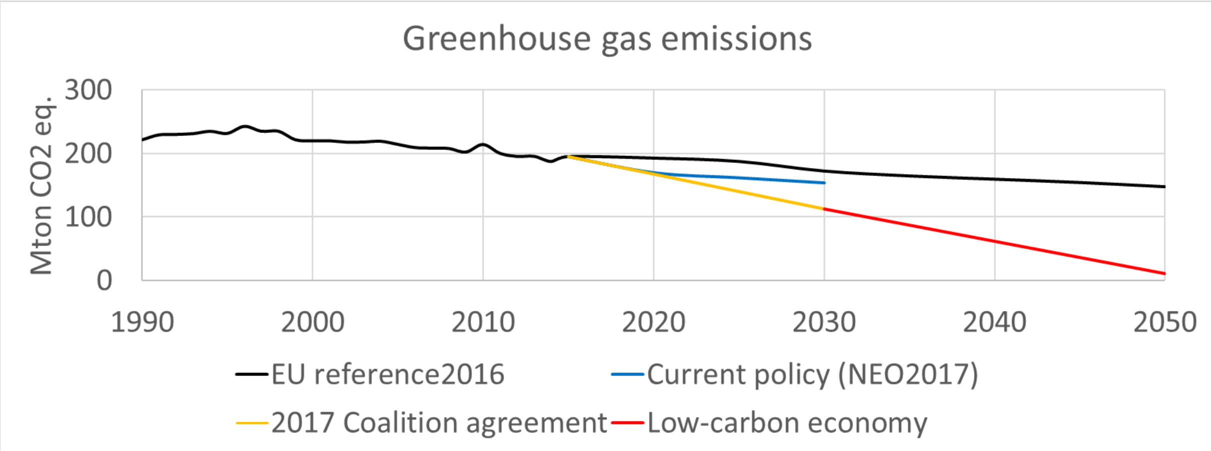

Figure 26. Ambitions for the reduction of greenhouse gas emissions (Mton-CO_2-eq.) according to different governmental documents. Sources: European Commission (2016), 2017 Coalition Agreement (VVD, CDA, D66 & ChristenUnie. 2017) and Schoots et al. (2017)

According to the EU reference study in 2016, the GHG emissions would decline gradually to approximately 150 Mton CO2-eq without any additional policy on GHG emissions reduction, see the black line in Figure 7, European Commission (2016). This is more or less in line with the expectations from the SSP2 scenario. The intended policies until 2030 already would decrease the GHG emissions to the level of 150 Mton CO2-eq (see blue line in Figure 26). In October 2017, the Dutch government released her Coalition Agreement (VVD, CDA, D66 & Christen Unie, 2017; Schoots et al. 2017) after instalment, in which the government presented ambitious reduction targets of 49-55 percent of GHG emissions for 2030, see yellow line in Figure 26. These ambitions coincide with the ambition to achieve a low-carbon economy in 2050, see red line in Figure 26. The goals in the Coalition Agreement will have to be realised with investments in renewable energy, energy saving, CCS and the use of large-scale biomass for energy.

4.6.2.2 Two degrees scenario

Within the Dutch case and its System Dynamics Model, the two degrees scenario is not included per se. The 2 degrees mitigation scenarios were developed independently by the thematic models and therefore the mitigation polices vary across the models. We used CAPRI and E3ME for reflecting on the 2 degrees scenario as compared to the base line. The results of the two degrees scenarios are used to identify the impacts of different policy cards.

4.6.3 Results of the application of the thematic models

4.6.3.1 CAPRI

CAPRI is an agricultural-economic model for the EU at the level of NUTS2. It projects scenarios of land use based on policy instruments and autonomic changes. The main indicators derived from projections with the Capri model are agricultural activities (agricultural land use, different production types and animal numbers) and environmental indicators, see Table 6 and Table 7 .

Agricultural land use

The baseline projections of agricultural land use with CAPRI in the period 2010-2050 are shown given in Table 6. The total area of cultivated land decreased by more than 100 thousand until 2050. The total area of food crops decreased slightly. The area of grassland decreased from 830 thousand ha to 774 thousand ha. The share of energy crops (potential biomass) increases from 0.4% to about 1.3% in the base run.

Table 6. Land use per food crop, fodder crop and energy crop in the baseline, 2010-2050. Source: CAPRI

	2010	2020	2030	2040	2050
	1,000 HA				
FOOD CROPS					
CEREALS	235	216	232	217	209
POTATOES	159	184	167	165	160
SUGAR BEET	74	66	65	65	60
VEGETABLES AND PERMANENT CROPS	158	197	195	209	224
OTHER ARABLE	36	37	37	38	39
TOTAL FOOD CROPS	662	700	696	694	692
GRASS	830	759	775	774	774
MAIZE	251	227	203	184	165
OTHER FODDER CROPS	122	154	127	114	105
TOTAAL	1203	1140	1105	1072	1044
ENERGY CROPS	7	8	12	18	22
FALLOW	8	10	10	10	9
TOTAL CULTIVATED LAND	1880	1858	1823	1794	1767

Livestock

There are 3 categories of livestock distinguished: cattle, pigs and poultry. For pigs and poultry, the herd sizes are expressed in units such as those used for production rights in the Netherlands (Netherlands Enterprise Agency, RVO), see Table 7.

Table 7. Herd sizes of cattle, pigs and poultry in the baseline 2010-2050

	2010	2010	2020	2030	2040	2050
	MLN	INDEX				
CATTLE	2471	100	94.8	95.5	93.5	84.9
PIGS	21845	100	96.3	95.7	95.5	95.5
POULTRY	249064	100	97.8	103.5	109.8	114.8

Table 7 shows that the herd sizes decrease for cattle and pigs and increase for poultry. This will have consequences for the NEXUS as well with respect to manure production (e.g. energy production, GHG emissions and environmental aspects) and will also depend on technological developments. Livestock numbers in the 2 degree scenario in 2050 are higher as compared to the base run, respectively for cattle, pigs and poultry: 6%, 4% and 2%.

CAPRI projects a further increase of the animal-based products in the diet. In the Dutch cases study we introduced a policy card on the diets and we used the 2 degree scenario for preparing this card. In fact, policy cards are proposed which in particular combinations might lead to the 2-degrees scenario.

For developing policy cards for the Netherlands, the utilized agricultural area is central because land is scarce in the Netherlands, for example, also with respect to increasing the share land needed for biomass for energy and/or solar fields (for specific policy cards included in the Dutch case study). Figure 27 gives an overview of the area available for agriculture in the Netherlands (based on Capri). Both in the base run and the 2-dgree scenario agricultural land use is decreasing leading to less options for biomass or solar panels on agricultural land.

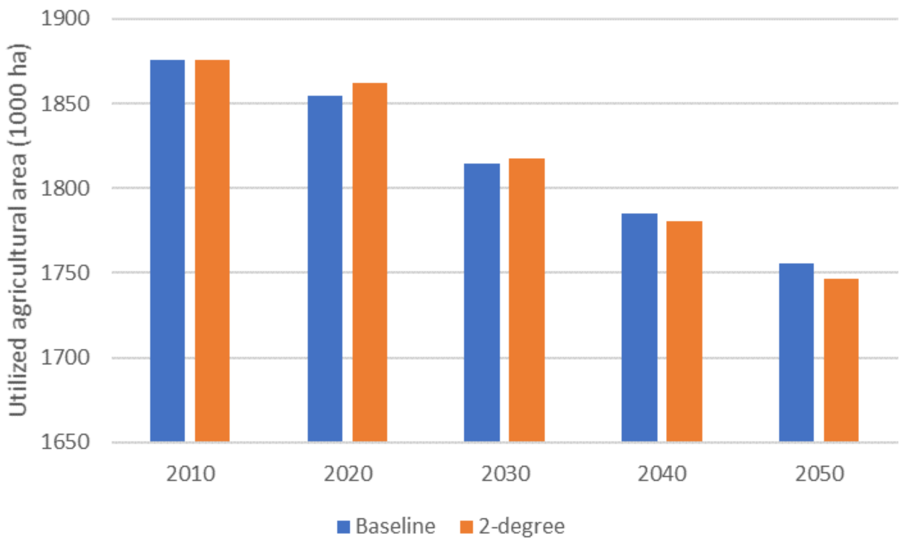

Figure 27. Total utilized agricultural area in the Netherlands for base line and 2 degrees scenario. Source: CAPRI

Figure 28 gives an overview of the area of fodder activities in the Netherlands. This is important for different elements of the NEXUS: e.g. water (high value production versus other crops), feed production, the potential for solar panels. In 2050, almost 63 % of the total cultivated area is used for fodder crops activities. Under the 2 degrees scenario, fodder crop activities are 57 % of total cultivated areas, leading to relatively lower potential for cattle production depending on grassland and other fodder crops.

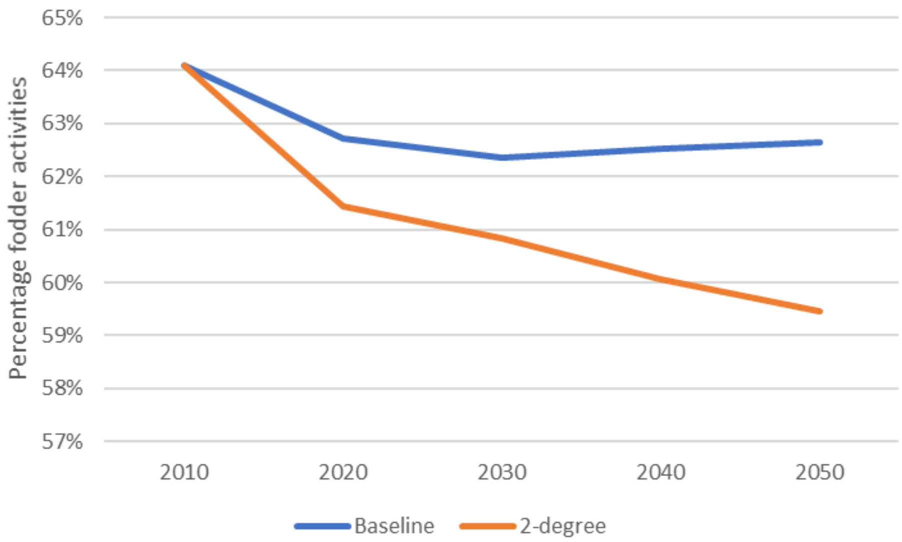

Figure 28. Share of fodder activities as percentage of total utilized agricultural area in the Netherlands. Source: CAPRI.

4.6.3.2 E3ME

The main indicators derived from projections with E3ME model are energy production per main energy carrier, energy use/demand per economic sector, value added per economic sector and greenhouse gas emissions per economic sector.

The E3ME results were available in detail for different economic sectors which were aggregated into the domestic sector (households) and 4 economic production sectors representing the economy: agriculture, manufacturing industry, transport sector, and the services sector. The agricultural sector includes forestry and fisheries. Energy production activities are part of the manufacturing sector. Finally, transport includes transboundary transport like airline travel and overseas shipping, which are often not included in statistics presented at the national level.

Although the E3ME model considers detailed information on energy production technologies, the results of energy production were only provided for 6 main energy carriers. More detailed information was not available for the Dutch case study due to privacy regulations with respect to the E3ME results. For the Dutch case, additional information on renewable energy production (solar power, off-shore wind power, on-shore wind power etc.) were collected from Statistic Netherlands and from policy documents.

Therefore, 6 main categories of energy carriers were distinguished: coal, oil, natural gas, electricity, heat and biomass. The energy carrier electricity includes different production technologies for electricity including nuclear energy, hydro power, solar power and wind power. From the E3ME results for energy production from electricity, it is unclear which share is from renewable sources. Therefore, we used additional information on renewable electricity production from Statistic Netherlands to calculate the renewable energy share from the E3ME results. The energy carrier biomass includes all kinds of bio-energy and bio-fuels such as bio-gas from wastewater, manure etc, and bio-fuels from energy crops, although E3ME did not provide the shares of those technologies. Additional information was collected from Statistic Netherlands and policy documents.

The E3ME results for energy production and energy consumption were presented in tonnes of oil equivalents (toe) but in the Dutch case study these indicators are expressed in PJ using the conversion rate 1 PJ = 23,844 thousand toe. Moreover, for the Dutch case it is assumed that energy production/supply is equal to energy use/demand. The import of energy is not explicitly included, but it is implicitly taken into account in the model.

Value added per sector and gross domestic product (GDP)

In E3ME, the monetary indicators are corrected for inflation. In particular, the indicators such as GDP and value added per sector are expressed in monetary values of 2005. In 2010, the GDP amounted more than EUR 583 bn. The largest sector in terms of Value added is the services sector (EUR 358 bn). The value added of the Manufacturing industry, transport sector and agriculture amounted EUR 119 bn, EUR 14.5 bn, and EUR 9.5 bn respectively. In 2050, GDP increased to EUR 983 bn and there are only minor shifts in the share of the economic sectors, see Figure 29 .

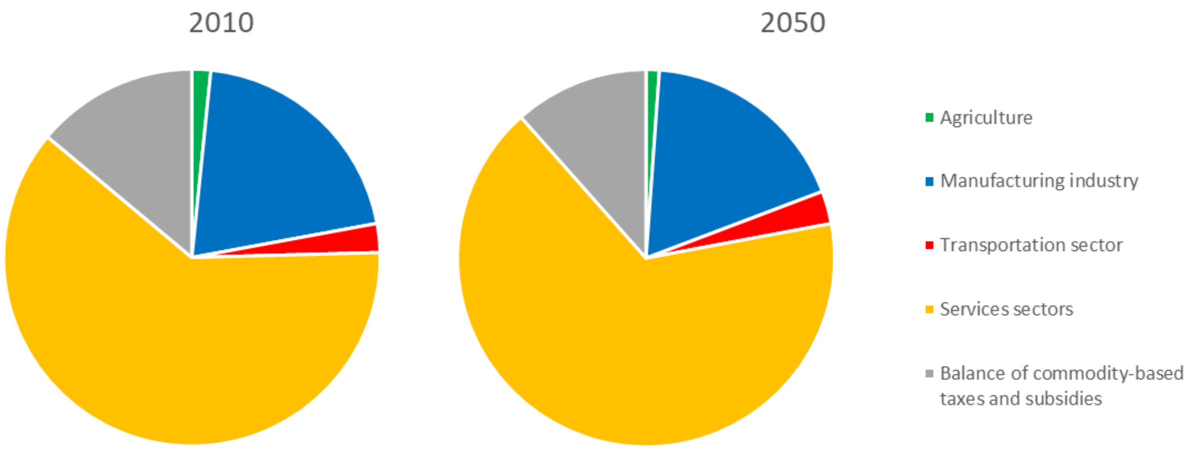

Figure 29. Distribution of value added over sectors and balance of commodity-based taxed and subsidies in 2010 and 2050.

Source: E3ME

According to the baseline projection, GDP increased with more than 56 % in 2050, which is an annual economic growth of 0.9 %, see Figure 30. The largest growths of value added in the period 2010-2050 are observed in the Transport sector 77 % (1.15% per year) followed by the Services sector almost 69 % (1.05% per year). The Manufacturing sector grew with 0.65 % per year and the Agriculture with less than 0.2 % per year.

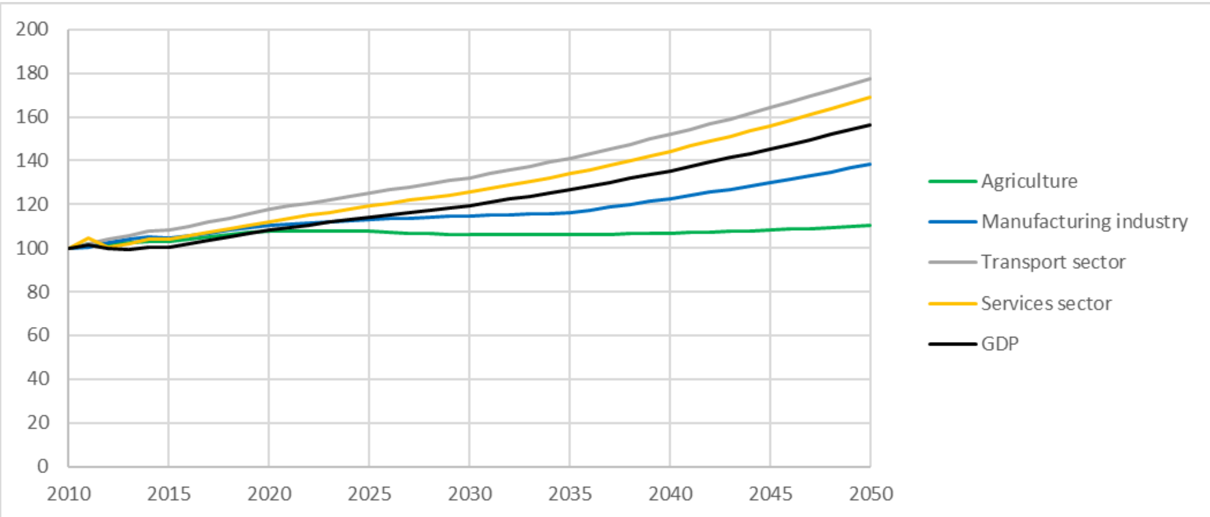

Figure 30. Development of GDP and value added per sector (2010=100) in the baseline (SSP2), 2010-2050.

Source: E3ME

Energy production

Figure 31 shows the 6 energy carriers of total energy use in the Netherlands for the period 2010-2050. As mentioned above, there is assumed that energy supply equals energy demand. Over time, the energy production declines from more than 4000 PJ in 2010 to less than 3300 PJ in 2050, which is a decline of almost 20 % in the period 2010-2050. Given the fact that the GDP increased, the energy intensity of the economy (value added over GDP) in the Netherlands decreased significantly.

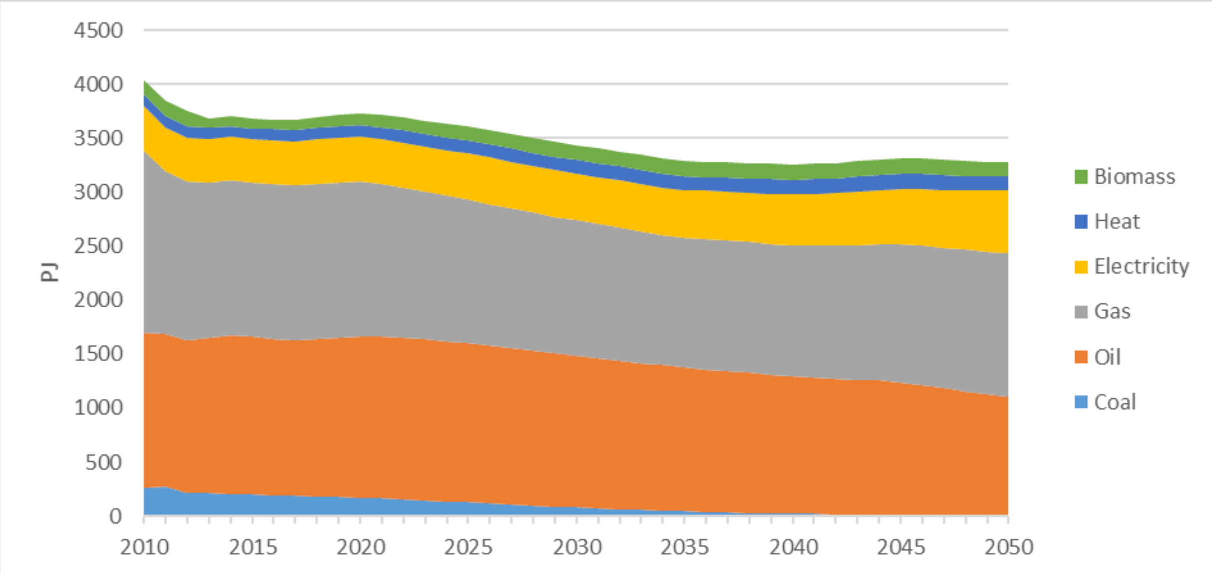

Figure 31. Development of energy production for 6 main energy carriers, 2010-2050.

Source: E3ME

The share of energy carriers changed gradually over time, see Figure 32. The share of coal-fired technologies has almost been abolished in 2050, and the share of electricity (including renewables), heat and biomass increased in 2050 compared to 2010. The share of electricity increased from 10 % in 2010 to more than 17 % in 2050, which is mainly due to implementation of renewable electricity technologies. The share of biomass increased from 3.3 % to 4.1 % in the period 2010-2050. Natural gas and oil are the main energy carriers in 2050, although the shares of both declined slightly from 41.9 to 40.7 % and from 35.6 to 33.3 % respectively.

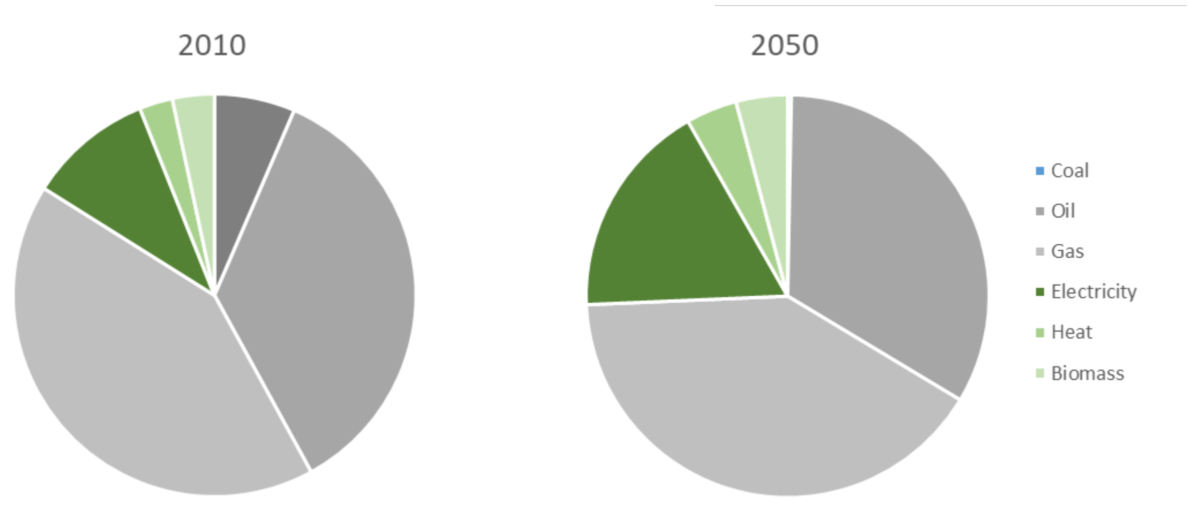

Figure 32. Share of energy carriers in 2010 and 2050 in the Netherlands in the baseline scenario. Source: E3ME

Energy demand

Energy demand is distinguished per sector: domestic sector, agriculture, manufacturing industry including the energy sector, transport sector and services sector including wholesale and retail sector, commercial services sector, and the governmental sector.

Figure 33 shows the gradual decline in energy consumption (or demand) for the 5 economic sectors in the baseline scenario. In 2010 and in 2050, the Manufacturing industry was the largest energy consumer, see Table 8. In the period 2010-2050, total energy consumption in the Netherlands declined with 18.7 %, see Table 8. The energy consumption of the transport sector and the domestic sector decreased by 35 % and 25 % respectively, while the energy consumption decrease in the service sector was only 7 %.

Table 8. Share of energy demand per economic sector in 2010 and in 2050 in the baseline scenario. Source: E3ME

YEAR	UNIT	DOMESTIC SECTOR	AGRICULTURE	MANUFACTURING INDUSTRY	TRANSPORT SECTOR	SERVICES SECTOR	TOTAL
2010	PJ	481.23	141.47	1744.89	627.06	1047.24	4041.89
	%	11.9	3.5	43.2	15.5	25.9	100.0
2050	PJ	360.53	119.66	1425.02	407.88	970.96	3284.04
	%	11.0	3.6	43.4	12.4	29.6	100.0
DECREASE	%	25.1	15.4	18.3	35.0	7.3	18.7

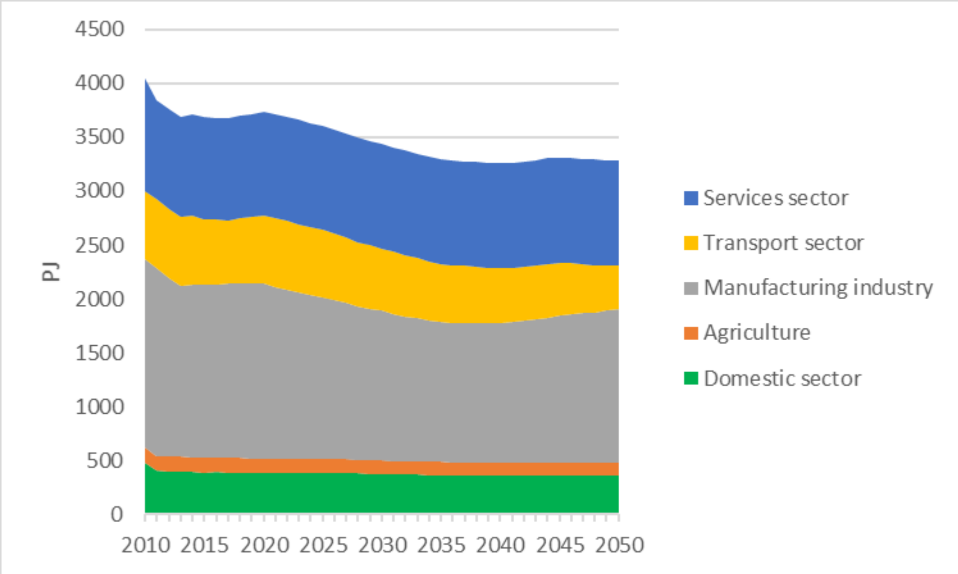

Figure 33. Distribution of energy demand across economic sectors in the baseline scenario, 2010-2050. Source: E3ME

The energy intensity of demand per euro sector has changed as well, see Figure 34. For the Manufacturing industry without the energy sector, the transport sector, and the Service sector, the energy intensity of demand decline gradually. For agriculture, there is only a modest gradual decline. For the Energy sector, there is even a modest increase of energy intensity.

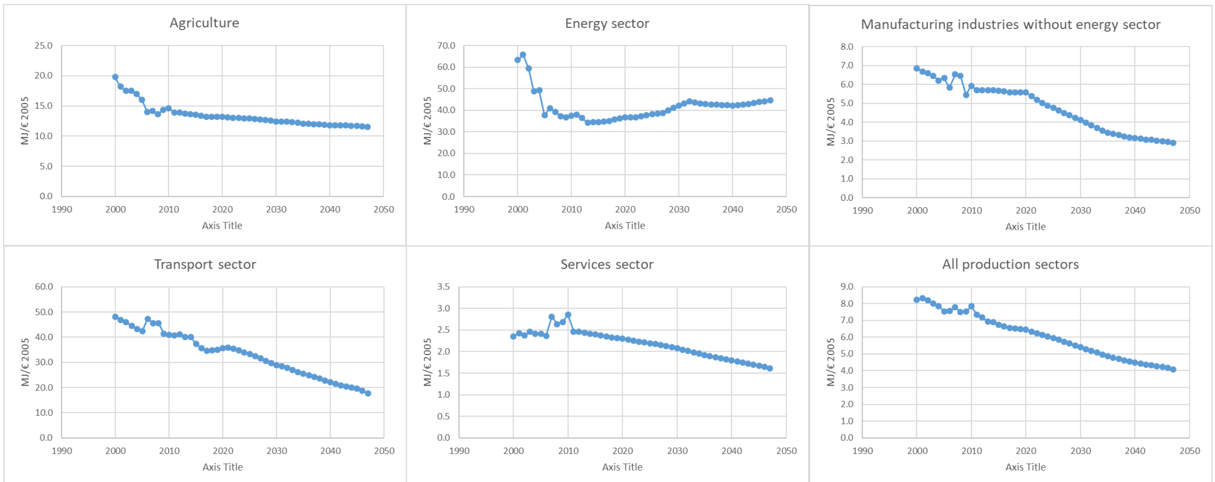

Figure 34. Development of energy intensity (MJ/EUR) with 2005=100 of the 5 economic sectors in the baseline scenario, 2010-2050. Source: E3ME

In addition to the results presented above, we also used information on the energy carriers per economic sector.

Greenhouse gas emissions

Greenhouse gas emissions were provided with two dimensions. First, there is a distinction between CO_2, CH_4 and N_2O emissions, all expressed in CO_2-equivalents, and second, those emissions are also available for all sectors distinguished for the Dutch case. Note that the emissions include the emissions from transboundary transport and also the emissions from land use and land use changes.

Figure 35 shows the GHG emissions in the baseline. The emissions gradually decrease from 227 Mton CO_2-eq. in 2010 to approximately 147 Mton CO_2-eq. in 2050, which is a 35 % reduction of GHG emissions. The largest emitting sector is the Manufacturing industry (including the energy sector) throughout the period 2010-2050. In 2010, the Manufacturing industry was responsible for half of the GHG emissions in the Netherlands. In the period 2010-2050, the GHG emissions of all sectors declined. The Transport sector reduced its GHG emissions by three quarter. Agriculture reduced emissions by almost 10 %.

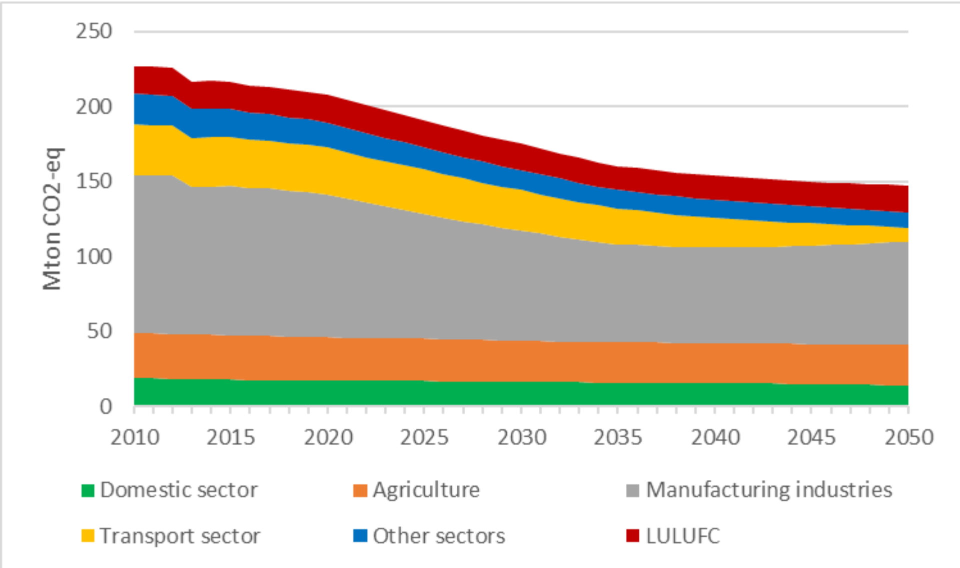

Figure 35: Development of GHG emissions (Mton CO_2-eq) for the 5 economic sectors in the baseline scenario, 2010-2050. Source: E3ME

The composition of the GHG emissions from Agriculture are different from the other production sectors. The largest share of GHG emissions are methane (CH_4) emissions. Moreover, one-fifth of the GHG emissions in Agriculture are Nitrous oxide (N_2O). Both types of GHG emissions are not directly related to energy production of consumption. Figure 36 shows the development of the different GHG emissions in Agriculture in the baseline.

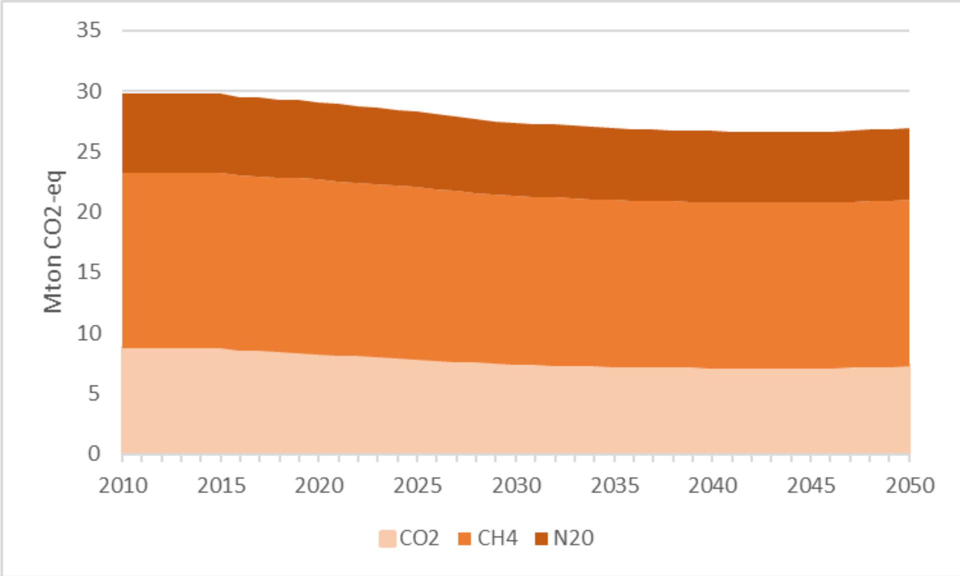

Figure 36. Development of three types of GHG emissions (Mton CO_2-eq) in the agricultural sector, 2010-2050. Source: E3ME

4.6.3.1 MAGNET

Although a number of potential indicators could be derived from the MAGNET model, a selection has been made on corresponding indicators between E3ME and MAGNET for reasons of consistency. From the MAGNET model, two indicators have been selected. These two MAGNET's indicators are the prices for non-renewable and renewable energy for the baseline scenario. For the 2-degrees scenario, similar developments of energy prices are reviewed in order to set the magnitude of policy cards on the option to reduce the ETS ceiling and on the effects of a cost increase of non-energy related emissions.

4.6.4 Concluding remarks on the application of thematic models

The thematic models have mainly enabled the construction of databases used for the SDM consistent with the SIM4NEXUS scenarios. The data from these models offered opportunities to analyse the different domains of the Nexus in much more detail in a more consistent way as compared to a situation in which everything would have been constructed from scratch. The models include the impact of dynamics that go beyond the Netherlands (European and Global). The models offer time series on flows of resources, environmental impacts (GHG emissions, NPK, etc.) but also economic mechanisms.

The thematic models needed to be supplemented with (more detailed) data from other sources like energy and non-agricultural land use (e.g. nature areas). The data were also discussed with stakeholders and experts in specific fields of the NEXUS. In addition, the results of the thematic models were also used to calibrate the policy cards. Policy cards were discussed in several rounds with different stakeholders (policy, business and research). These sessions were meant to go into more depth. These sessions allowed to fill data gaps and to incorporate additional knowledge.

4.7 Sweden case study

4.7.1 Short description of the case study

The Swedish case study focuses on the Nexus of water-energy-climate-food-forest. It tries to establish the optimal use of Swedish resources for the purposes of climate change mitigation and adaptation. The research concentrates on the impacts of introducing mechanisms for decreasing emissions, alternative uses of the additional biomass potential (carbon sequestration in standing forests versus increased bioenergy or agricultural production) and the consequences for the available water supply and quality, and for biodiversity and potential impact on other water goods and services. The goals of the case study are to increase the understanding of forest-water interlinkages in the context of climate change, as well as to bring research and stakeholders together and communicate the results.

Sweden is a country in northern Europe bordered by Norway in the west, the North Sea in the southwest, the Baltic Sea in the east and Finland in the northeast. Sweden is a heavily forested country with uncounted lakes and rivers. Forestry and forest products are of great importance to the national economy. Half of Sweden's electricity is generated from renewable sources such as hydropower and forest biofuels. However, changing climate conditions are expected to heavily affect both water resources, forest ecosystems and their interlinkages. Forests depend on water, but have, at the same time, the potential to regulate water availability and quality. On top of that, both forest and water resources directly control the available potential to generate electricity from forest biofuels or hydropower. These interactions of forest, water, climate change, and bioenergy are of critical importance for the country.

Sweden currently has two major initiatives of interest to these nexus sectors: (1) The Generation Goal, i.e. the overall goal of Swedish environmental policy – defines the direction of the changes in society that need to occur within one generation if the country's environmental quality objectives are to be achieved, and (2) The Environmental Objectives that describe the state of the Swedish environment which environmental action is to result in. These objectives are to be met within one generation, i.e. by 2020 (2050 in the case of the climate objective). According to present forecasts (Swedish Environmental Protection Agency, 2017), these environmental objectives will not be met in time. In fact, the objectives of reducing climate impacts even show a negative trend in the state of the environment, because greenhouse gas emissions are still rising. This clearly shows that the current environmental initiatives are not sufficient to achieve society's agreed environmental objectives for water and forests. For example, the growing demand for bioenergy has led to an intensification of the forest industry through extensions of managed forest land, introduction of fast-growing tree species, increasing use of fertilization and increasing felling rates. The effects of such new management strategies for increased biomass production on forest species, soil resources and water quality at landscape scales are, however, not well understood and not addressed adequately. The question as to whether the goal of becoming a fossil-free nation interferes with some of the national environmental objectives is discussed together with the stakeholders in the Swedish case study.

4.7.2 Description of the selected simulation scenarios

For the purpose of performing the nexus analysis at a higher spatial resolution, Sweden was divided into three sub-regions (Figure 37). Here we tried to find a compromise between administrative boundaries (i.e., county administration boards) and natural boundaries (i.e., river basin administration boards), which resulted in three distinct regions: (1) south-east Sweden, (2) south-west Sweden and (3) northern Sweden (Figure 37). South-east Sweden (region 1) covers roughly 26% of Sweden's land area. Region 2 has a share of 13%, while norther Sweden covers the largest area (61 %).

In the Swedish case study, only one scenario was used. The basic assumption is a changing climate according to the RCCP4.5 greenhouse gas emission scenario, which implies a temperature increase of approximately 2°C until 2050 and of roughly 3°C until 2100 (Eklund et al., 2015). This climate change is of particular importance for the projections of future forest growth, available water and the connected future nutrient loads in surface waters.

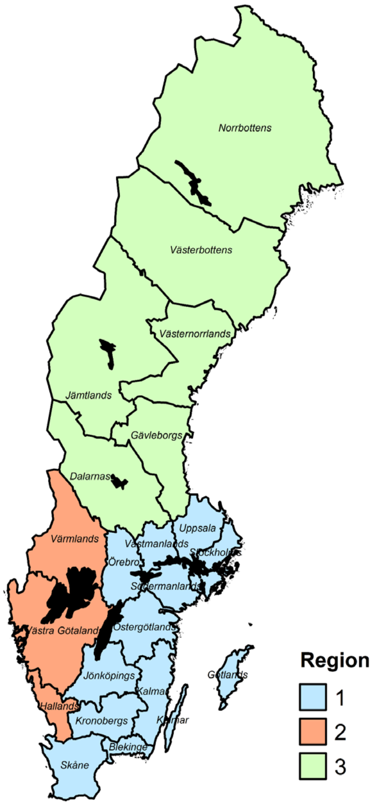

Figure 37 . Sweden, its administrative boundaries (black outlines) and the three sub-regions (coloured in blue, orange and green)

The utilized scenario further follows the so-called 'EU-reference scenario' that was developed by the Swedish Energy Agency (Swedish Energy Agency, 2019) and that combines certain scenarios of the EU commission (e.g. on GHG emission trading, crude oil, coal and natural gas) with simulations by the TIMES-NORDIC model (e.g. for electricity, district heating and solid biofuels) and with economic scenarios provided by the National Institute of Economic Research. It should be emphasized that this scenario includes all those political instruments that had been decided upon until July 2018.

The scenario applied in the Swedish case study further assumes a continuation of the recently observed quick population increase until 2030, resulting in a 19% larger population compared to 2010 (Figure 38). This is followed by a somewhat slowed down population increase until 2050, which is characterized by a 26% larger population compared to 2010 (Figure 38).

In the land sector, the scenario assumed future forest practices based on a scenario developed by the Swedish University of Agricultural Sciences on behalf of the Swedish government (SLU, 2019). It includes a positive climate effect (based on RCP4.5) on the forest growth. It was further assumed that about 90% of the annual increment are felled (SLU, 2019). Otherwise, forest management is assumed to emulate the same management as during the period 2000-2009. For the agricultural sector, the scenario assumed a business-as-usual strategy based on past trends and patterns.

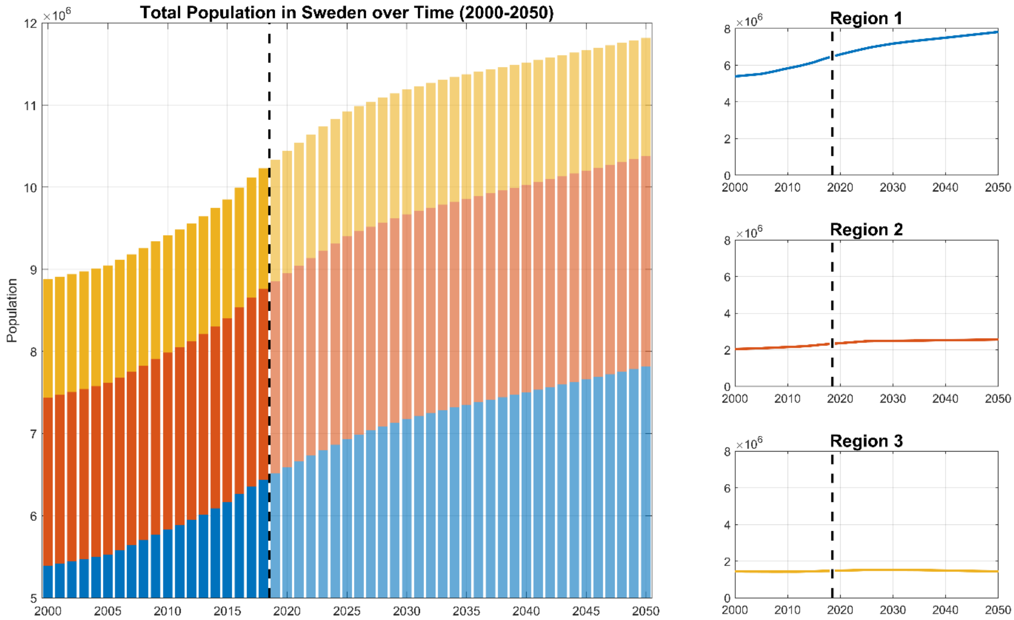

Figure 38. Historic (2000-2018) and projected future (2019-2050) population development in Sweden (left) and in the three studied regions (right): South-east Sweden (Region 1) in blue, south-west Sweden (Region 2) in orange and northern Sweden (Region 3) in yellow.

4.7.3 Results of the application of the thematic models

In the Swedish case study, three main models were selected initially based on review report, the model factsheet and the presentations during the project meeting in Barcelona: CAPRI, MAGNET and GLOBIO. All provided results for the baseline scenario.

4.7.3.1 CAPRI

The Common Agricultural Policy Regionalised Impact modelling system (CAPRI) is a global agroeconomic model designed for the ex-ante impact assessment of agricultural, environmental and trade policies with a focus on the European Union. It is a global spatial partial equilibrium model, solved by sequential iteration between supply and market modules. The unique combination of regional supply-side models with a global market model for agricultural products provides simulated results for the EU at subnational level, whilst, at the same time, simulating global agricultural markets.

CAPRI provides a large number of economic, yield and environmental (e.g. fertilizer and CO2 emissions) indicators of the agricultural sector. In the Swedish case study, we were mainly interested in the environmental indicators related to the use of fertilizer, nutrient balances and total emissions. The model projected a 16% decrease of the total nitrogen surplus until 2040, and thereafter a slight increase until 2050 (Figure 39, left, blue curve). In contrast, the levels of surplus phosphorus are projected to increase during all decades, having 53% higher levels in 2050 compared to 2011 (Figure 39, left, orange curve). At the same time, the greenhouse gas (GHG) emissions are projected to decrease by 18% until 2040, but will – according to the model – increase thereafter (Figure 39, right). Consequently, the level of GHG emissions in 2050 is projected to be at a similar level as in 2030 (Figure 39, right).

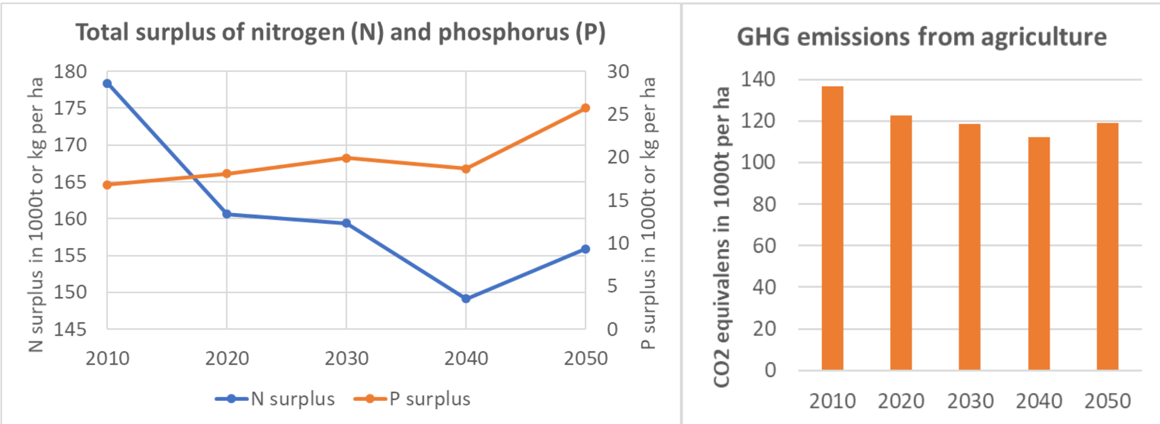

Figure 39. Comparison of future projections of total surplus of nitrogen and phosphorus (left) and total greenhouse gas (GHG) emissions from agriculture (right) as simulated by the CAPRI model

4.7.3.2 MAGNET

MAGNET (Modular Agricultural GeNeral Equilibrium Tool) is a general computable equilibrium model, with an additional focus on agriculture, designed for economic impact assessment. MAGNET builds on the global general equilibrium Global Trade Analysis Project (GTAP) model. MAGNET is a tool for analysis of trade, agricultural, climate and bioenergy policies.

For the Swedish case study, MAGNET provided mainly a number of economic variables (e.g., GDP), consumption behaviour, imports/exports of food, energy and other resources, as well as emissions. The GDP is projected to more than double from 535’397 million US $ in 2011 to 1’219’209 million US $ in 2050 (Figure 40, orange circles). These projections are in line with the future projections made by the Swedish Ministry of Finance (Figure 40, blue line), which are also projected to increase by more than 100% (Almerud et al., 2015).

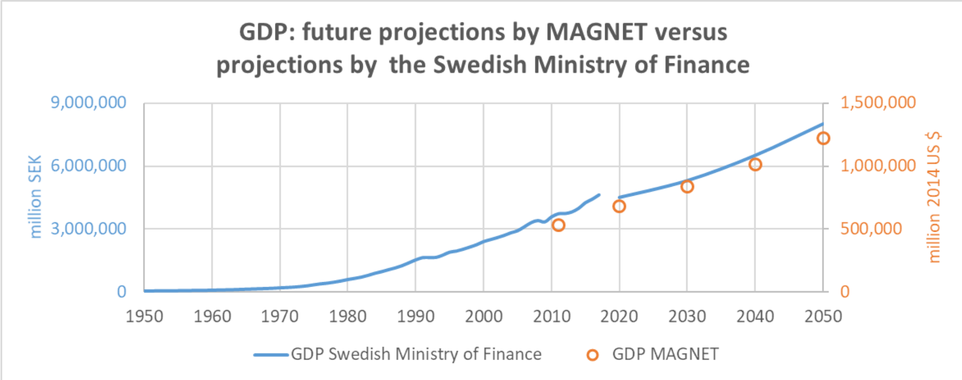

Figure 40. Comparison of future GDP projections made by MAGNET and made by the Swedish Ministry of Finance.

Both imports and exports are projected to increase considerably (Figure 41). By 2050, imports are projected to increase by 55%, while exports are projected to increase by 87%. The main sources of the increasing imports are services, chemical/rubber/other plastic products, petroleum/gas products, transport sector and other industry (Figure 41, left). The main drivers behind increasing exports are services, chemical/rubber/other plastic products, the transport sector, other industry and crude oil (Figure 41, right).

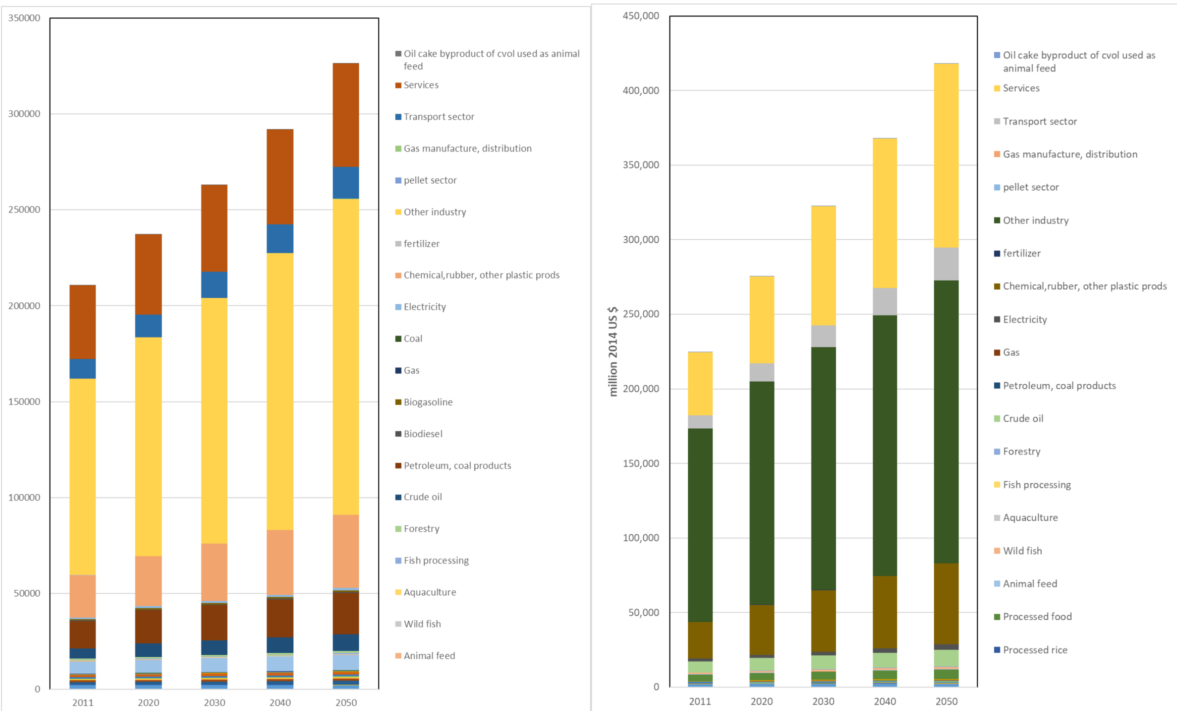

Figure 41. Overview of import (left) and export (right) volume at market prices as projected by MAGNET from 2011 to 2050

The MAGNET model runs projected the total emissions to increase by 70% from 37.9 million tons of CO2 equivalents in 2011 to 64.27 million tons of CO2 equivalents in 2050 (Figure 42). The largest contributors to this increase are transport sector, other industry, petroleum/coal products, services and electricity from coal (Figure 42).

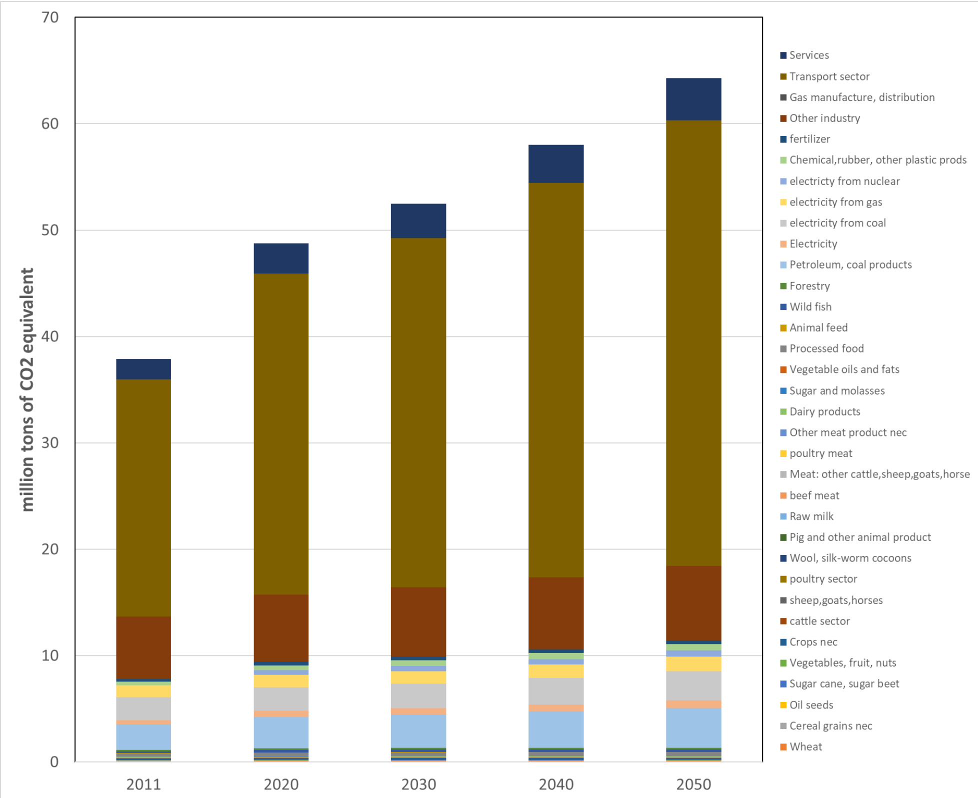

Figure 42. Overview of future emissions as projected by MAGNET for different sectors/products

4.7.3.3 GLOBIO

The GLOBIO (Global Biodiversity) model is used to assess the consequences of global environmental change on biodiversity (terrestrial and aquatic), and ecosystem services (GLOBIO-ES). For the Swedish case study, the GLOBIO model delivered mainly parameters for surface water quality and biodiversity. It included the total nitrogen and total phosphorus concentrations in surface water as well as the following indicators for biodiversity intactness: (1) percentage of lakes with high concentrations of blue-green algae in summer, (2) biodiversity intactness in lakes, (3) biodiversity intactness in rivers, (4) biodiversity intactness in wetlands, (5) average freshwater biodiversity intactness, (6) biodiversity loss in rivers due to flow disturbance, (7) terrestrial biodiversity intactness, and (8) fraction of urban + agricultural land. Hereafter, the results of those variables for the years 2010, 2030 and 2050 are shortly presented: the total nitrogen concentration in surface water is projected to decrease over time from 1.3 mg N/L in 2010, to 1.16 mg N/L in 2030 and down to 1.08 mg N/L in 2050 (Figure 43). Similarly, the percentage of waters with a nitrogen concentration above 2.0 mg/L is projected to decrease in the future (Figure 44).

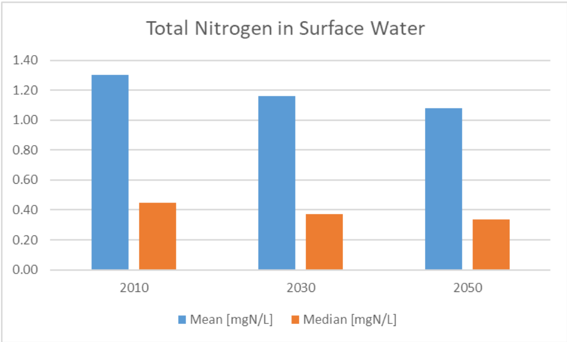

Figure 43. Concentration of total nitrogen in surface water for present and future conditions

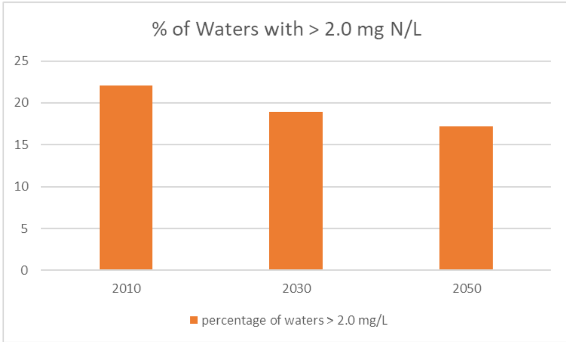

Figure 44. Concentration of total nitrogen in surface water for present and future condition

The total phosphorus concentration in surface water is projected to slightly decrease from 0.057 mg/L in 2010 to 0.055 mg/L in 2030, but will then likely stagnate at this level until 2050 (Figure 45). In terms of the total percentage of waters with concentrations above 0.2 mg/L, an upward trend from 5.08 % in 2010 to 5.65% in 2050 is projected by GLOBIO (Figure 46).

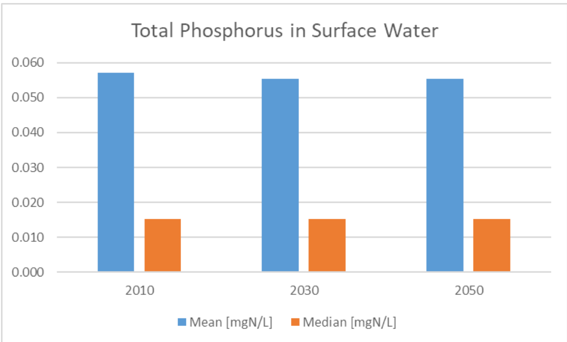

Figure 45. Concentration of total phosphorus in surface water for present and future conditions

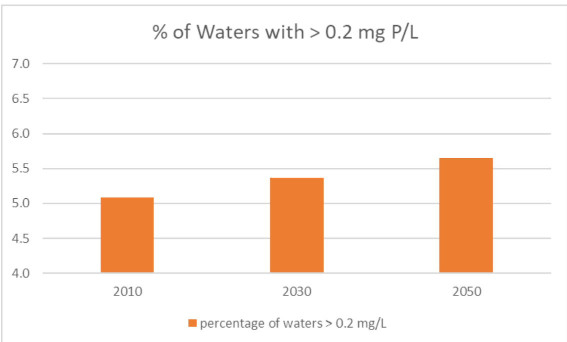

Figure 46. Concentration of total phosphorus in surface water for present and future condition

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

The biodiversity indicators revealed a number of different trends. Many of the indicators (including the fraction of urban and agricultural land, biodiversity loss in rivers due to flow disturbance, biodiversity intactness in wetlands and rivers) were projected to stay constant until 2050 (Figure 47). Two of the indicators are projected to increase slightly: namely the average freshwater biodiversity (from 0.69 in 2010 to 0.71 in 2050) and biodiversity intactness in lakes (from 0.69 in 2010 to 0.73 in 2050). At the same time, terrestrial biodiversity intactness is the only indicator that is projected to decrease (from 0.52 in 2010 to 0.39 in 2050), indicating a loss in terrestrial biodiversity in the future.

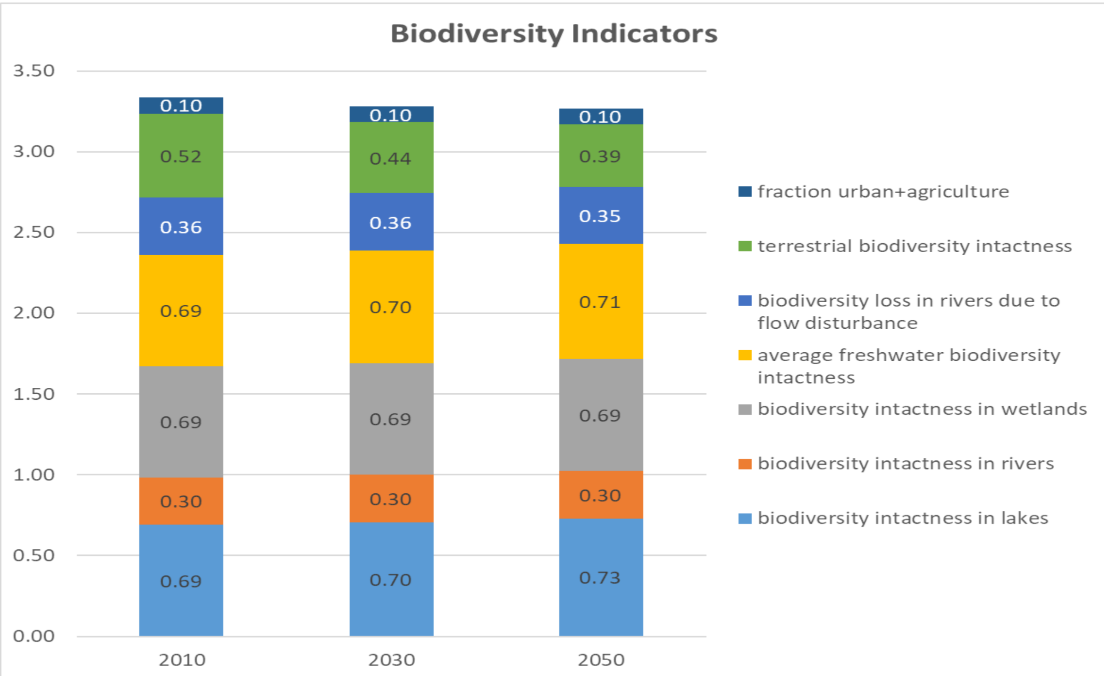

Figure 47. Overview of projected trends in biodiversity indicators

4.7.4 Concluding remarks on the application of thematic models

The data of the three thematic models was presented to the stakeholders during a stakeholder workshop held in March 2019 at Uppsala University. In an interactive exercise, stakeholders were presented with historic trends of a number of variables and were asked to continue drawing the curves into the future based on their expert judgement. These judgements were subsequently compared to the actual projections made by the thematic models and other data sources. Thereafter, the thematic model results and future trends were extensively discussed with the stakeholders with the aim of identifying gaps and selecting suitable future scenarios. These discussions resulted in the insight that the chosen thematic models are not

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

able to simulate a large number of water- and forest-related variables that would be needed for Sweden, given the scope of this particular case study. Therefore, the case study leads had to find additional potential data sources for the analysis of the nexus. The majority of the data used for the system dynamics modelling and the subsequent analysis of the nexus was provided by Swedish authorities. For instance, the majority of population dynamics, emissions, land-use, agriculture and forestry data, water demand, as well as food production/consumption was available through Statistics Sweden, most of the energy data was provided by the Swedish Energy Agency, while the data on available water was provided by the Swedish Meteorological and Hydrological Institute, to mention only a few.

4.8 Azerbaijan case study

4.8.1 Short description of the case study

This case study (CS) explores the implications of Azerbaijan's transition to a low carbon economy to a range of nexus domains, which have their specific challenges and priorities. The case study is a first attempt to develop a set of key indicators for tracking nexus challenges in Azerbaijan.

The initial step of the CS was a literature review to understand the nexus trends, interlinkages and challenges in Azerbaijan. Based on the findings a first conceptual model was developed to graphically represent the interlinkages between the biophysical sectors of the country. In a first stakeholder workshop the conceptual model has been refined and a set of relevant indicators has been defined. Using the gained knowledge of interlinkages and indicators of interest three models were selected to explore the nexus of water – land – food – energy sector. These models are E3ME, OSeMOSYS and MAGNET. In all three models, Azerbaijan is modelled as one region. OSeMOSYS and E3ME were soft-linked by taking the resulting energy demand from E3ME as an input for OSeMOSYS. A set of three scenarios is defined in order to identify and quantify different synergies and trade-offs between the nexus sectors.

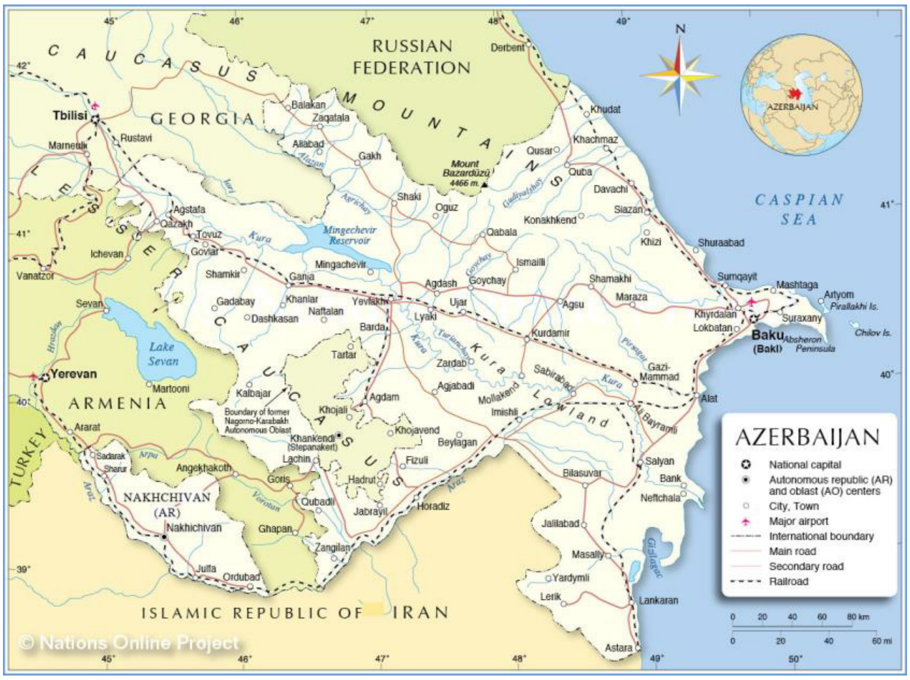

Figure 48. Political mas of the Republic of Azerbaijan. Source: nationonline.org

4.8.2 Description of the selected simulation scenarios

As mentioned in the previous section, three scenarios were developed for the Azerbaijan CS. First, a baseline scenario consistent with the SSP2 projections. The baseline scenario forms the reference for the two so-called pathway scenarios. In these scenarios the impacts of climate change on the country and its different sectors are pictured while varying between a scenario with mitigation measures and a scenario without such measures. The scenarios can be described as below.

- **Baseline**: This scenario is constructed upon techno-economic data taken from the SSP2 (IIASA n.d.). No government policies are considered.
- **Bad scenario** (Climate change without mitigation): Climate change effects are considered, including extreme climate events, while no adaptation is considered.
- **Good scenario** (Climate change with mitigation): This scenario revolves around the transition of a carbon intensive economy to a low carbon future. Azerbaijan also aims at shifting from being an oil-based economy to become a more diversified one, reducing the risks and vulnerabilities of a hydrocarbon-centred economy, while promoting sustainable development.

In the Table 9 below the model set-up for each of the three scenarios are briefly described.

Table 9. Azerbaijan Case Study scenario assumptions across models

	E3ME	MAGNET	OSeMOSYS
Baseline	Population and GDP growth in line with SSP2	- Population and GDP growth consistent with SSP2 - Climate impacts on crop yields as in RCP6.0	- No particular policies considered - Gradual improvement of transmission-system assumed
Bad scenario	Emission levels from the baseline scenario used to estimate damage by climate change. These were then induced into the model	Crop yields as in RCP8.5, otherwise like baseline	Demand updated with E3ME output
Good scenario	Damages induced as in the “Bad scenario”. 2% of GDP dedicated to adoption and mitigation.	- 20% renewables generation by 2050 - Increased crop productivity - 10% reduction in transport cost by 2030 - 2.5% increase per period in household energy efficiency - CO2 tax to achieve 35% reduction in GHG emissions by 2030 compared to 1990	- Demand updated with E3ME output - 20% decarbonisation by 2050 in comparison to 2020

4.8.3 Results of the application of the thematic models

E3ME

Figure 49 to 51 show results from the macroeconomic model E3ME. The left graph in Figure 49 shows the GDP development in the baseline scenario. A strong growth can be observed. The graph on the right hand side shows the difference in GDP of the good and the Bad scenario (Climate change impacts) and the Good scenario (Climate change impacts + support) in comparison to the baseline. One can see that in both scenarios lower GDP than in the baseline needs to be expected. However, one can also observe that the measures against climate change and for adaptation reduce to some extend the impact of climate change on the GDP.

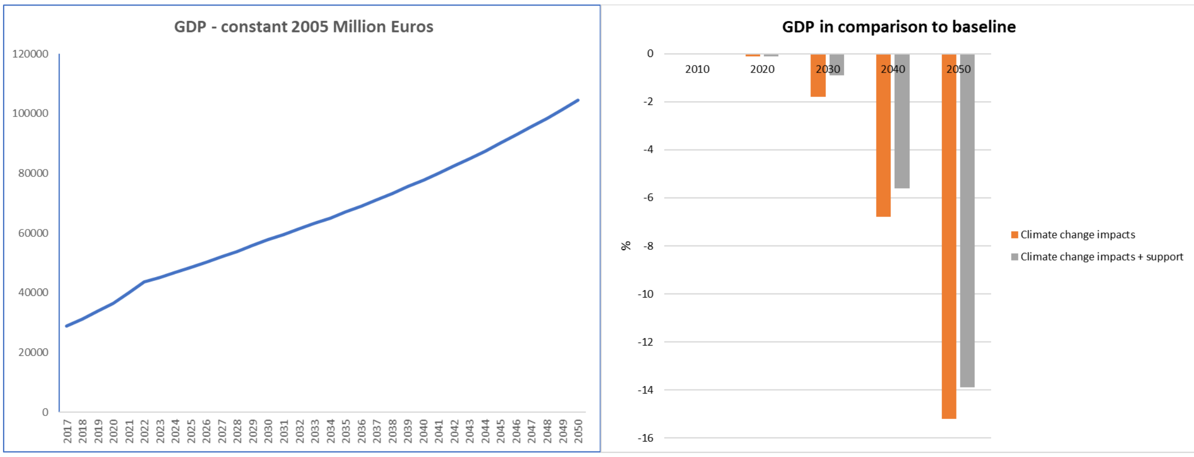

Figure 49. Azerbaijan GDP development

An important source of income for Azerbaijan is the export of oil and gas. Figure 50 indicates the share of fuel exports in the GDP. A strong decline in the first years of the modelling period can be noticed, followed by slow decline from 2021 onwards. In combination with the predicted GDP development on can assume that the decline of fuel exports does not indicate a shrinking of the oil and gas sector but reduction in its importance in the Azeri economy due to the growth in other sectors.

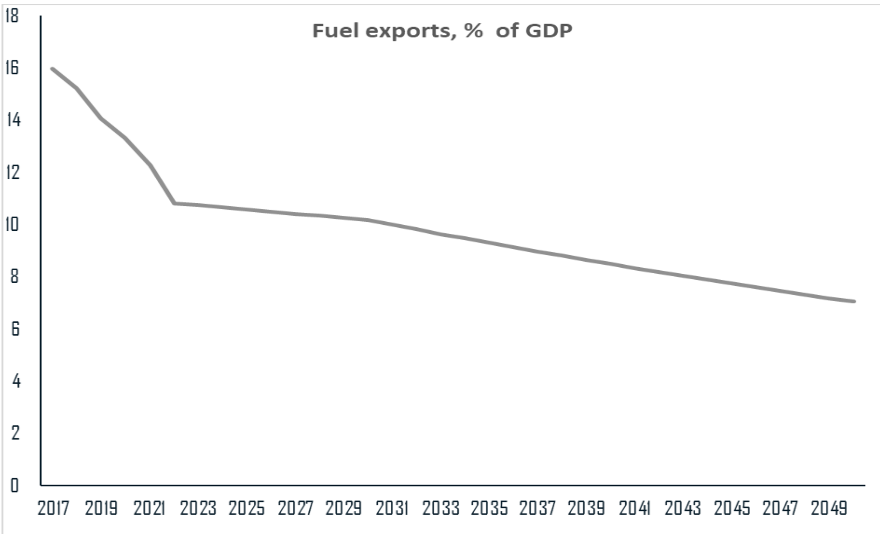

Figure 50. Share of fuel exports in GDP

Figure 51 shows the development of deployment in Azerbaijan between the years 2010 and 2030 and across scenarios. The sector with by far most people working in is the agricultural one. However, from 2010 to 2030 a decrease can be expected according to the baseline scenario. Looking at the divergence of the climate change scenarios on the right indicates that no major changes in the employment structure occur due to climate change. The maximum are 2.2% more employment in the real estate sector in the Good scenario. Noticeable is that no sector is benefiting in the Bad scenario, but several do in the Good scenario. However, also in the good scenario there are more sectors with a reduction in employment than sectors that have an increase in employment.

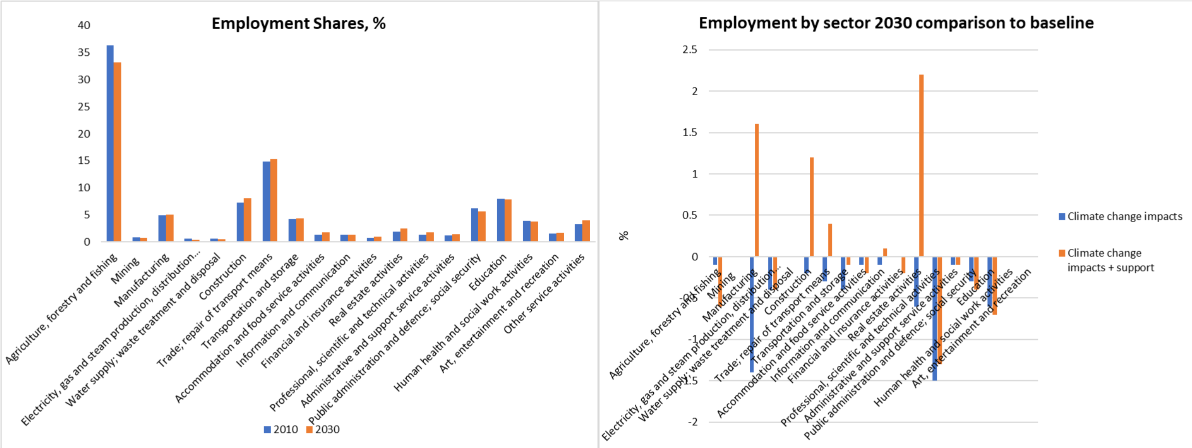

Figure 51. Employment development in Azerbaijan

MAGNET

Figure 52 to 54 show results from the Modular Agricultural GeNeral Equilibrium Tool – MAGNET.

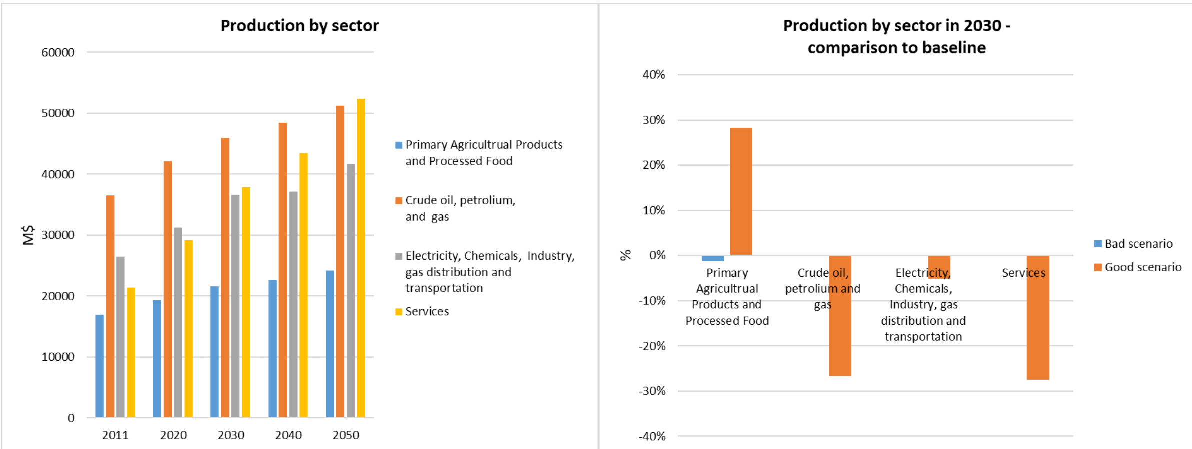

Figure 52. Production by sector in Azerbaijan

Figure 52 shows the production by sector in Azerbaijan. On the left hand side one can observe that all sectors are expected to increase their outputs. However, the composition of the production changes over time. Is the service sector the second smallest sector listed in 2011, is it together with the oil and gas sector the largest sector of the country in 2050. This indicates the transition towards a service economy in Azerbaijan. On the right side of Figure 52 the differences in the climate scenarios to the Baseline are indicated. It is clear that no sector is benefitting of climate change without mitigation. For the Good scenario – climate change with support we see a mixed picture. On the one hand the agricultural sector – which provides a lot of jobs in Azerbaijan see Figure 51 – is benefitting. On the other hand the other sectors are loosing productivity.

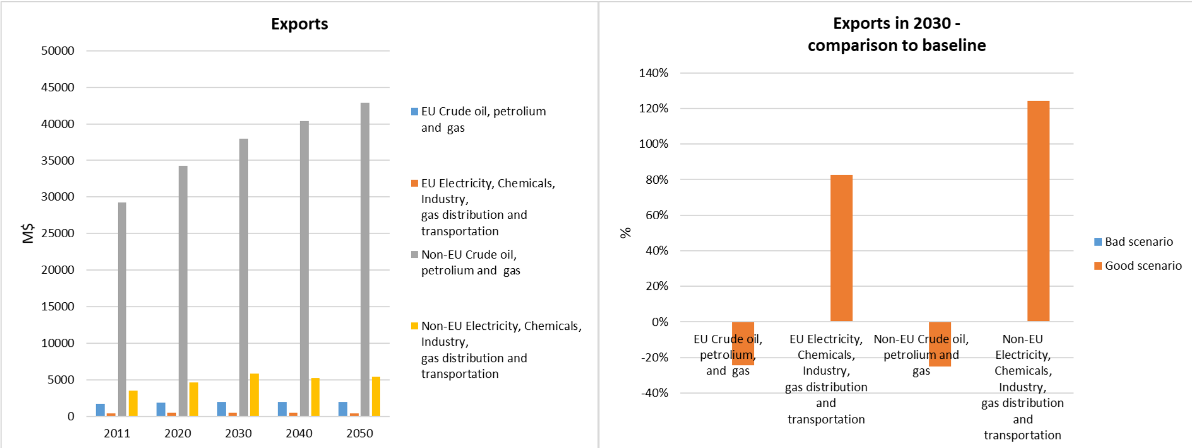

Figure 53. Exports from Azerbaijan

Previously the importance of the exports of oil and gas to the Azeri economy have been indicated – see Figure 50. Figure 53 shows the dominant role of oil and gas among the exports from Azerbaijan. Considering potential impacts of climate change leads to a shift in export destinations. While the exports to EU countries reduce in both scenarios with climate change, the exports to non-EU countries increase. In the case of oil stronger when there are no climate change support measures and in the case of other products the exports increase especially when there are support measures for climate change adaptation and mitigation.

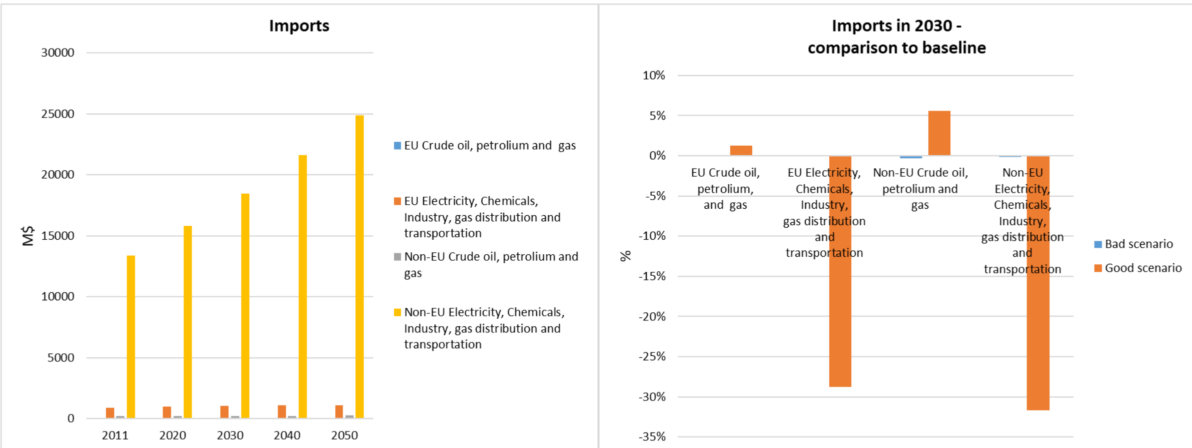

Figure 54. Imports to Azerbaijan

Figure 54 indicates the development of imports to Azerbaijan and the significant increase of imports of industrial goods from non-EU countries, shown on the left side. As for the exports, the consideration of climate change reduces the imports from EU-countries and increases mostly the imports from non-EU countries.

OSeMOSYS

Figure 55 to 56 show results of the Open Source energy MOdelling SYStem – OSeMOSYS for power sector of Azerbaijan.

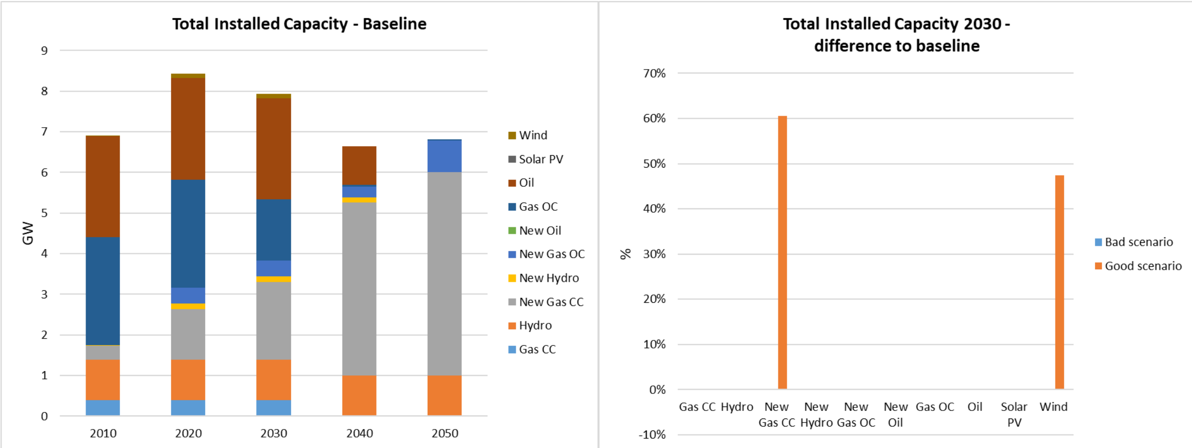

Figure 55. Total Installed Capacity Azerbaijan

In Figure 55 the power generation capacities in Azerbaijan for the years 2010, 2020, 2030, and 2040 are indicated. In 2010 the generation capacity consists predominantly of oil and gas burning technologies and about 1 GW of hydro power. Over the modelling period this mix shifts towards a mix that is dominated by gas burning technologies. On the right the difference of the climate scenario to the baseline are shown. Apparently the Bad scenario is not changing in the capacity nor generation mix (see Figure 56). However, in the good scenario wind power and new combined cycle gas turbines are increasing in capacity and generation. Together they are pushing other gas and oil power plants out of the generation mix – see Figure 56 right side.

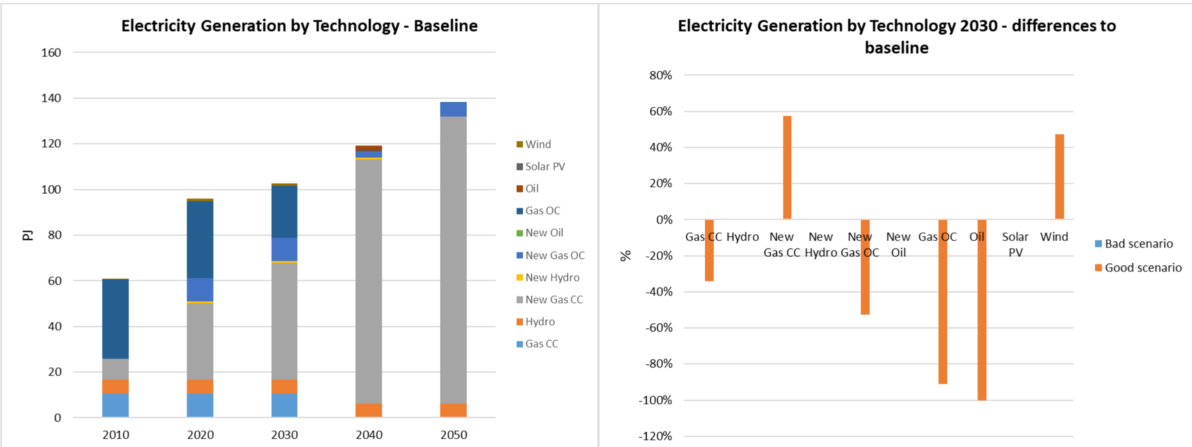

Figure 56. Electricity Generation by Technology Azerbaijan

The development of CO_2 and nitrogen oxide (NOX) in the scenarios is shown in Figure 57. Considering the power mix from Figure 56 and the economic development from Figure 49, it is not surprising that CO_2 and NOX emissions show an increasing trend. The measures to reduce CO_2 emissions in the Good scenario show expectably their effect in Figure 57 on the right side. The CO_2 emissions reduce by about 15%.

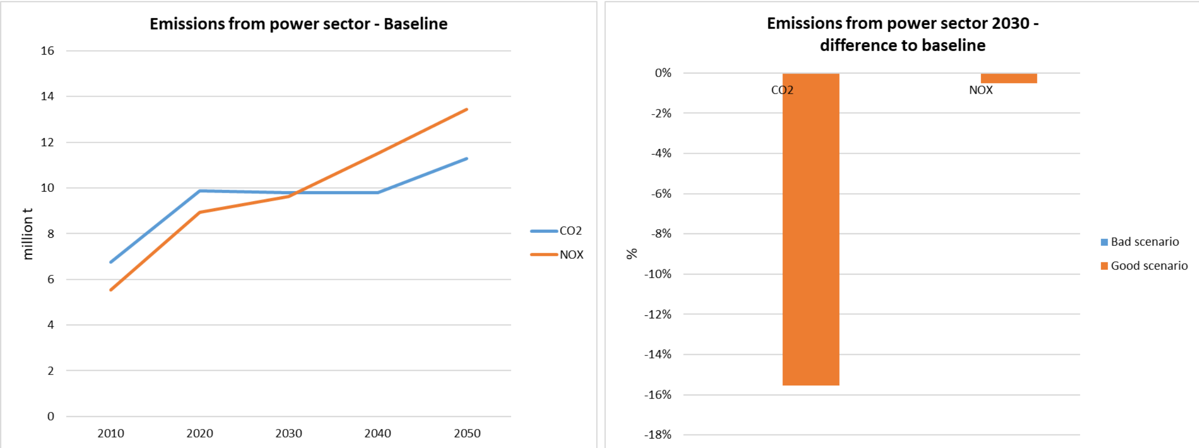

Figure 57. Emissions from power sector Azerbaijan

4.8.4 Concluding remarks on the application of thematic models

The results indicate that climate change impacts have the potential to slow down the growth of the Azeri economy and that adaptation and mitigation measures have the potential to soften this reduction in economic growth. Furthermore, climate change could significantly affect the exchange of goods with EU countries. However, this will also depend on the development of EU policies, which are not considered in this case study.

Overall it needs to be noticed that this is results analysis has several limiting factors. Firstly and fundamentally, the modellers faced issues with finding high quality data for building their models. This is partly caused by the lack of a local stakeholder, but also the general poor availability. Furthermore, this analysis is only preliminary. An in depth analysis of the results is still pending due delays in the modelling schedule.

4.9 Transboundary France-Germany case study

4.9.1 Short description of the case study

The transboundary France-Germany case study (CS) is situated in the Upper Rhine region and covers the federal state of Baden-Württemberg on the German side and the recently formed (2016) Grand Est Region[5] on the French side, with the (Upper) Rhine playing the role of physical and administrative borders in its middle[6]. The area along the Rhine is one of the most densely populated and highly industrialized areas of the European continent. The Upper Rhine region is also part of the so-called *Blue Banana* in Western Europe, encompassing the highly

[5] It integrates the former Alsace, Lorraine and Champagne administrative regions.

[6] The case study does not include the Swiss part of the territory which is usually defined as the Upper Rhine in a water management context.

and very densely populated region from Birmingham down along the Rhine axis through Alsace and Baden-Württemberg, to Torino and Florence. This highlights the importance of the economy along the Rhine, its role in the provision of water for electricity generation and transportation in a European context.

The CS focuses on the links and synergies between energy policies and the transition to a low-carbon economy on one side, and the management of natural resources - in particular water and land - on the other side. The main identified Nexus challenges are the following:

- Despite the significant development of other renewable energy generation technologies in the CS region (wind-power in Grand Est and PV-Solar in Baden-Württemberg) hydroelectricity still plays a key role. Moreover, a significant share of electricity generation in Grand Est and Baden-Württemberg regions is based on nuclear and thermal power, displaying substantial water requirements for cooling. This raises the question of energy security in a climate change context, characterized by a high degree of uncertainty about future water availability and the expected increase in the frequency of extreme weather events (droughts and floods).
- Transition to a low-carbon economy in the case-study area translated – among others – into the development of bioenergy (especially biofuel production and energy generation based on methanation) through the implementation of support mechanisms. This development has significant implications in terms of land use change and pressure on water resources both in qualitative and quantitative terms, not forgetting competition with food production.
- The protection of water, agricultural, forest ecosystems and biodiversity is also central to this CS. In particular, water ecosystems are of key importance in the CS area for flood and drought management but also for climate change mitigation.

These main identified challenges, as well as its transboundary character, have significantly influenced the choice of simulated scenarios and data requests made to thematic models, as described in the following section. Indeed, because of its transboundary character, this CS also investigates the links between policy development and implementation on both sides of the Rhine, and whether there would be opportunities for enhancing cooperation and policy coherence between France and Germany for achieving jointly set policy objectives in an effective manner.

4.9.2 Description of the selected simulation scenarios

4.9.2.1 Baseline and 2°C scenarios

Baseline and 2°C scenarios were selected for this CS to determine the implications of the energy transition on the different Nexus components. The comparison of the results from these two scenarios aimed at highlighting in particular the impacts of a further development of renewable energies and bioenergy in the 2°C scenario compared to the Baseline scenario.

The thematic models CAPRI, E3ME, IMAGE-GLOBIO and SWIM have been used to build the databases for the Water, Land, Energy and Food domains of the Nexus. The data base for the Climate sector has been built mainly based on a literature review; however, it includes some results from the CAPRI model (i.e., methane output from livestock). For both the Baseline and the 2°C scenarios, the results produced by the thematic models were used in two ways:

- Direct integration of the results produced by these models into the data bases (for some of them after a slight restructuring or down/up-scaling) when they were available at a scale corresponding (i.e., regional) or close to the scale of the CS. This was the case for the supply variables of the Food sector, hydrological variables in the Water sector, cultivated areas in the Land sector, methane emissions from livestock in the Climate sector;
- When the results produced by the thematic models were not available at a scale close to the scale of the CS, and when local data could be collected, we used these results to build trends for the extrapolation of local data. This was the case for energy demand and production in the Energy sector, Water demand variables, non-agricultural areas of the Land sector and demand, imports and exports variables for the Food sector.

No additional assumptions were considered for the definition of these two scenarios compared to the definition established by the thematic modelers. However, it was necessary to make specific assumptions when extrapolating local data and restructuring model results. These assumptions and modifications are described below for each concerned component of the Nexus:

Land:

For the Land sector, we focused on three main types of land-use: natural areas (forest, grassland and wetlands), artificialized areas (urban, industrial and transport infrastructures) as well as on agricultural areas. Moreover, particular attention was paid to agricultural land-use and its allocation between food/feed production and biomass production for energy.

The baseline and 2°C trends determined based on IMAGE results for Europe were used to extrapolate historical local land-use data (Corine Land Cover) for non-agricultural land-use.
Agricultural land-use and its evolution over time was determined based on CAPRI results for the Baseline and the 2°C scenario. We applied additional assumptions – based on local data collection and literature review – to the latter results to determine the allocation (in k hectares) of cultivated area for each type of crop for food/feed production and biomass production for energy respectively. For the Baseline scenario, we combined the following information:

- The share of total utilized agricultural area (or area when available) dedicated to the production of biomass for energy;
- The relative share of bioethanol, biodiesel and biogas production in total energy biomass production;
- The crop-specific share in the production of biodiesel or bioethanol.

The value of these parameters is considered constant for the whole 2010-2050 period. The assumptions made for these parameters as well as the corresponding sources are detailed in Appendix 1.1.5.1.

For the 2°C scenario, we use the trend defined based on IMAGE results for Europe to determine the evolution of the share of total utilized agricultural area dedicated to biomass for energy production compared to the Baseline scenario. Assumptions made for the relative share of bioethanol, biodiesel and biogas production in total energy biomass production and crop-specific shares are identical to those made for the Baseline scenario.

Water:

For the Water sector, we aimed at investigating the balanced use of water resources. Moreover, particular attention was paid to the evolution of water resources and water use in the "Rhine system" given its central role for energy generation, irrigation as well as for aquatic biodiversity and ecosystems.

Results from the SWIM model were used as a basis to determine the hydrological dynamics of surface water and groundwater resources. The latter results were upscaled (except for the Rhine system) to match the case-study area. SWIM results were also slightly restructured to render CS-specific issues:

- The hydrological dynamics of the "Rhine system" was considered separately from the rest of the surface water system;
- The groundwater resource was considered as a single stock variable for the whole CS area to render the shared nature of the groundwater table between part of the Alsace and part of the Baden-Württemberg regions.

The assumptions described above are made for both the "baseline" and "2 degrees" scenarios and are extensively described in Appendix 1.1.5.2.

Besides, particular attention was paid to water abstraction from the energy, industry and agricultural sectors. The trends determined based on CAPRI and E3ME results were used to extrapolate local historical data for water abstraction for both the "baseline" and "2 degrees" scenarios:

- Industrial output in value (euros 2005m) as determined by E3ME at the national level (France and Germany being considered separately) was used to extrapolate water abstraction from the industrial sector;
- Energy generation based on thermal power (in GWh/year) as determined by E3ME at the national level was used to extrapolate water abstraction from the energy sector;
- Crop-specific cultivated area and irrigated area (as a share of total cultivated area for each type of crop) as well as herd sizes (in k heads) as determined by CAPRI were used to extrapolate water abstraction from the agricultural sector.

Food:

The allocation of agricultural land use between food/feed production and biomass production for energy for each type of crop, as determined for the Land sector, was translated into food/feed and energy biomass production in the food sector based on CAPRI results for crop yields.
Moreover, CAPRI results allowing to determine the distribution of agricultural production between (direct) human consumption, (direct) animal consumption (feed), processing to secondaries as well as data on imports and exports were not available at the regional scale. Here national patterns (i.e., distribution rule between human/animal consumption and processing as well as imports and exports as a share of local supply) were applied at the regional scale.

4.9.2.2 Additional energy scenarios

In addition to the Baseline and the 2°C scenarios, additional CS-specific Energy scenarios have been defined and implemented with the E3ME models.
A first scenario (referred to as "Energy scenario 1" in Table 7) has been defined which simulates the implementation of recent energy policy developments (MTES, 2017; MTES, 2018; BMWi, 2019) involving:

- A reduction in the share of nuclear power in the French energy mix by 2035 and a nuclear phase-out for Germany by 2022.
- Ban on the use of coal as a primary energy source (by 2022 in France and 2039 in Germany).

The simulation of this scenario aimed at exploring the compatibility of the two following objectives for energy policy: 1) decarbonizing the energy mix and 2) reducing dependence on nuclear power (as well as exposure to nuclear risk). We also aimed at determining the implications of this scenario for the evolution of the energy mix as well as its economic (especially for the price of electricity) and environmental (especially in terms of GHG emissions) impacts.

A second scenario (referred to as "Energy scenario 2" in Table 10) has been defined which simulates a nuclear phase-out both in Germany and France by 2050. Here we aimed at investigating the economic, environmental and energy mix implications of implementing such an energy policy in a uniform manner across the Rhine (such a nuclear phase-out policy is already implemented in Germany). The need for such a nuclear phase-out on the French side was underlined by stakeholders of the CS (NGOs); the French part of the CS territory currently hosts four of the 19 French nuclear sites.

Table 10 . Underlying assumptions of coal and nuclear phase-out scenarios

	France	Germany
Energy scenario 1: Coal and nuclear phase out	- Complete coal phase out by 2022 - Decrease nuclear power output to 50% by 2035	- Complete coal phase out by 2038 - Complete nuclear phase out by 2022
Energy scenario 2: Full nuclear phase-out	Complete nuclear phase out by 2050	Complete nuclear phase out by 2050

Finally, the implementation of various energy policy instruments in isolation in addition to the Baseline scenario was simulated. The objective of these additional simulations was to determine the implications, in particular the economic implications, of the implementation of these instruments to inform the definition of CS-specific policy cards for the serious game. Four categories of instruments were considered:

- Improvement of energy efficiency;
- Support for the development of electric vehicles;
- Support for the development of renewable energies;
- Increase in energy prices.

A description of each instrument as well as of the way there were implemented in E3ME is provided in Appendix 1.1.5.3.

4.9.2.3 Dietary shifts

The need for implementing behavioral changes and the effectiveness of the latter for climate change mitigation was highlighted during the second stakeholders workshop organized for this CS.

This scenario was developed in order to investigate the impacts of a dietary shift consisting in decreasing the consumption of animal products in Europe. We investigated the impacts of such a behavioral change in terms of GHG emissions from agriculture, land-use change and for agricultural production (supply, demand, prices and input use) for France and Germany. This scenario was implemented using the CAPRI model: a threshold to be reached in 2050 (i.e., consumption target in kcal/capita x day) was defined for the consumption of each animal product; this consumption target was translated into a consumption reduction implemented linearly between 2020 and 2050. The consumption targets for each type of animal product are described below:

- Calorie intake from animal products: 400 kcal/capita x day
- Calorie intake from meat: 140 kcal/capita x day
- Calorie intake from red meat (includes pork): 45 kcal/capita x day

4.9.3 Results of the application of the thematic models

4.9.3.1 Baseline and 2°C scenarios

4.9.3.1.1 Evolution of the energy mix and energy demand (E3ME)

We focus here on the results of the E3ME model for the evolution of electricity production and the energy mix in France and Germany. These results allow to discuss the potential impacts of such an evolution on other Nexus sectors.
The evolution of the energy mix in both scenarios, for both France and Germany, is marked by a net decrease in power generation from non-renewable energies (i.e. fossil fuels and nuclear power) between 2010 and 2050 as well as by a large scale deployment of renewable energies. These two trends are more pronounced in the 2°C Scenario than in the Baseline, both in terms of electricity generation and in terms of the share of each major energy type in the energy mix (i.e., renewable vs. non-renewable energy).

Such an evolution of the energy mix highlights a potential positive impact on the evolution of GHG emissions and the Climate domain of the Nexus. However, the significant development of electricity production based on solar energy and hydropower (common to both countries and more pronounced in the case of the 2°C scenario) highlights potential negative impacts on the Water and Land domains of the Nexus, with an increased pressure on these resources (+600% and 1500% increase in installed capacity for solar power between 2010 and 2050 for Germany and France respectively). The increase in the amount of electricity produced and in the share of hydropower in the French and German energy mix is of concern in a climate change context characterized by uncertainties regarding the availability of water resources.
We present and discuss below the specific results for the German and French mix.

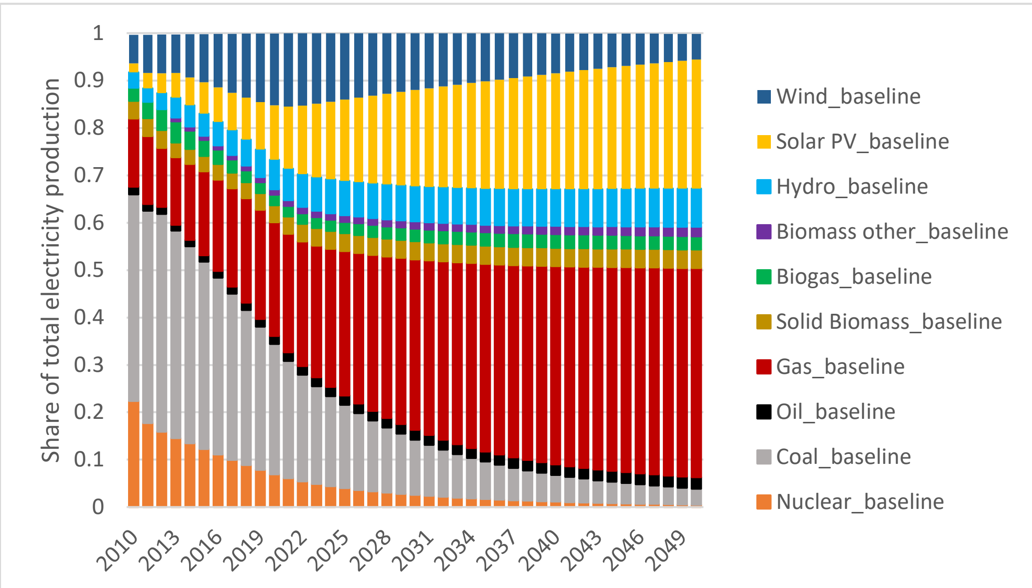

Figure 58. Share in total electricity generation by technology in Germany - Baseline scenario

Germany:

Both the Baseline and 2°C scenarios lead to a net decrease in electricity generation from non-renewable energy (i.e., fossil fuels and nuclear) between 2010 and 2050. For both scenarios there is a sharp decrease in electricity generation based on nuclear power and coal (in absolute and relative terms). However, there is also an increase in electricity generation based on natural gas and oil (in absolute and relative terms) (see for instance Figure 58). This second trend is less pronounced in the 2°C scenario compared to the baseline. As a result, there is a net decrease in electricity produced from fossil fuels between 2010 and 2050 for the 2°C scenario (-11%), while electricity produced based on fossil fuels increases for the baseline (+6%). In addition, the 2°C scenario leads to a greater deployment of renewable energies for electricity production (in absolute and relative terms) – especially for solar and hydropower. Finally, while for both scenarios an increase in electricity production is observed between 2010 and 2050, this increase is less marked in the case of the 2°C scenario (see Figure 59). The evolution of the German energy mix is therefore likely to have positive impacts for the Nexus Climate domain, especially in the 2°C scenario.

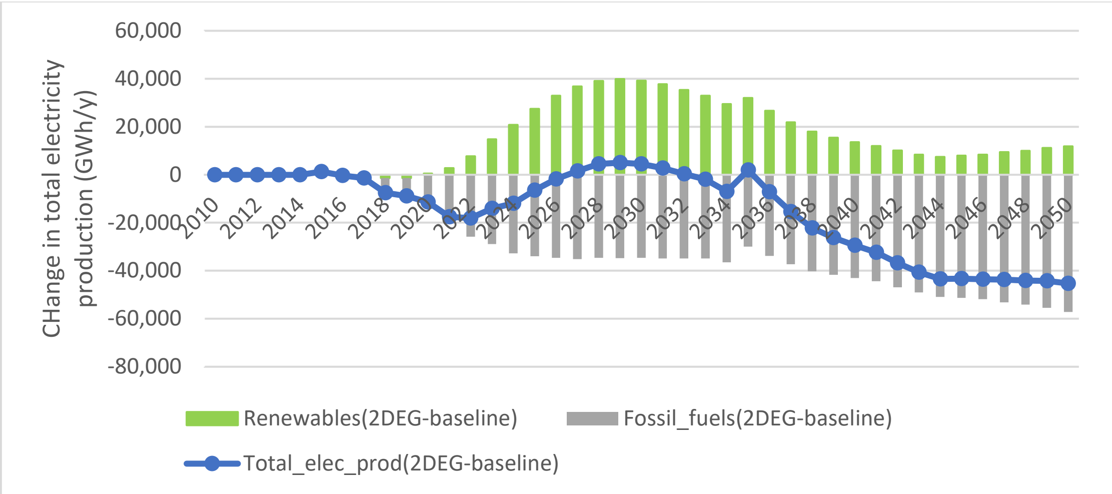

Figure 59 . Difference in total electricity production between 2°C and Baseline scenarios in Germany

France:

The Baseline and 2°C scenarios both lead to a net decrease in electricity production from fossil fuels, a slight increase in electricity production based on nuclear power (after a decline phase) and a strong development of renewables between 2010 and 2050. As France's energy mix is already highly decarbonized, with a large share of electricity generation being provided by nuclear, the reduction in fossil fuel use is only slightly more pronounced in the case of the 2°C scenario (see Figure 60 and Figure 61). The main difference between the two scenarios concerns the share of nuclear and renewables in the energy mix, with nuclear being reduced and renewables being increased in the 2°C scenario compared to the Baseline: in this case, the deployment of renewables is based on hydropower, solar and solid biomass (see Figure 60). It should be noted that the total electricity production is higher in the 2°C scenario compared to the Baseline. In addition, while the share of nuclear in the energy mix is lower in the 2°C scenario, nuclear-based electricity generation is nevertheless more important. This result, as well as the one related to the development of hydropower, highlights an increase in the pressure on water resources which, as previously mentioned, is of concern in a climate change context. The significant deployment of solar energy (and biomass to a lesser extent) points to an increase in pressure on the Land domain of the Nexus, particularly in the 2°C scenario.

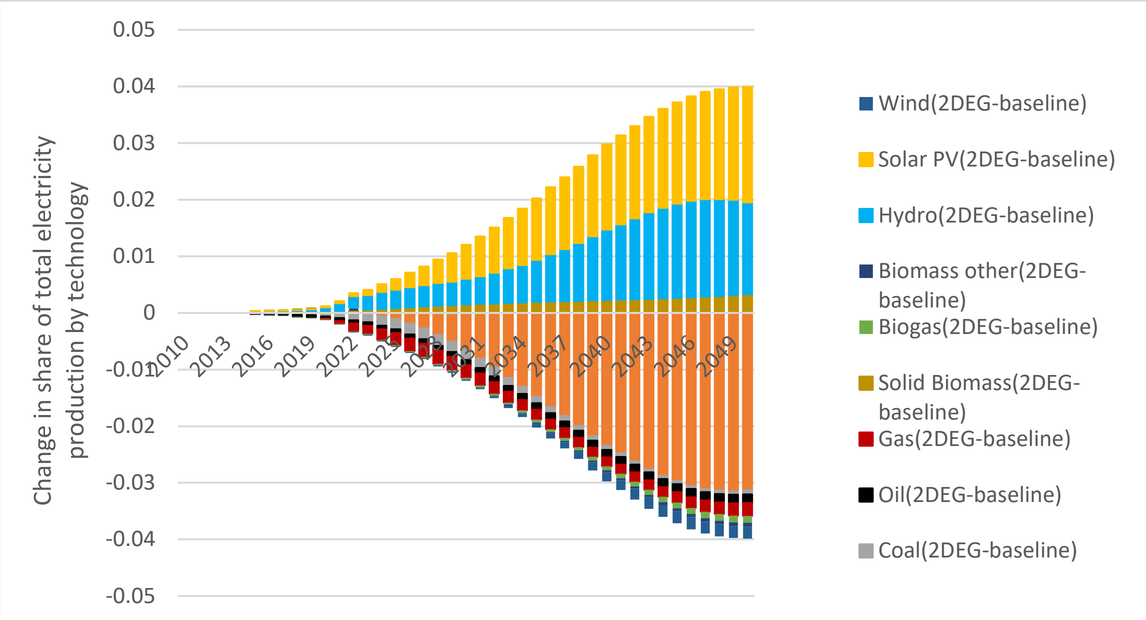

Figure 60. Difference in the share of total electricity production by technology between 2°C and Baseline scenarios in France

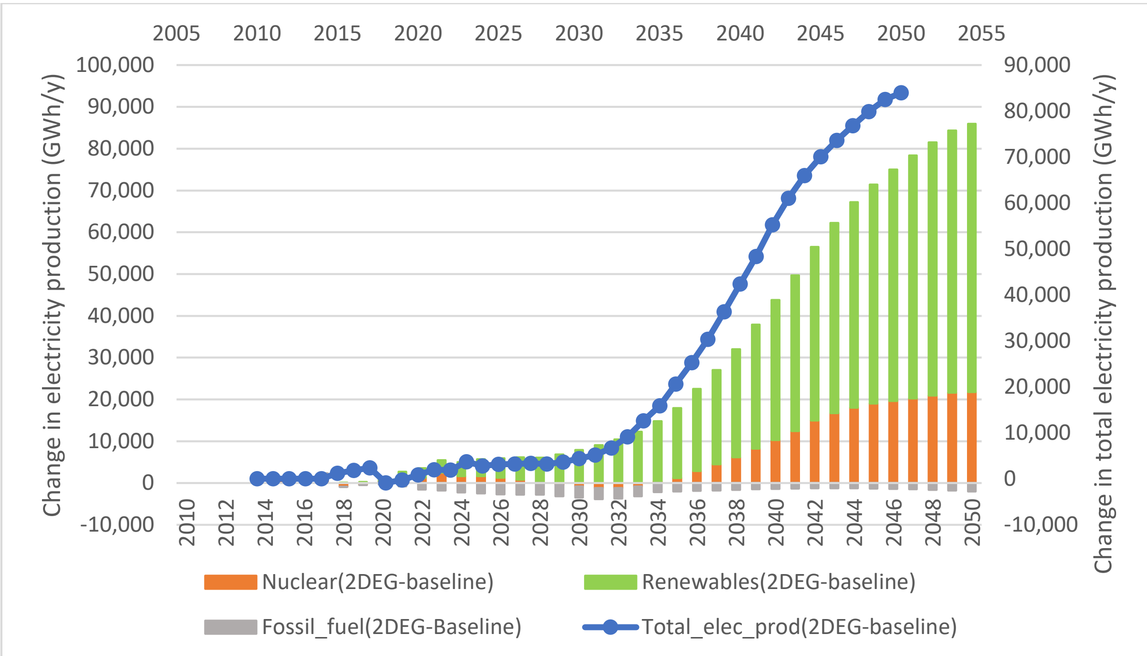

Figure 61 . Difference in electricity production between 2°C and Baseline scenarios in France

Discussion:

As mentioned previously, these national trends were applied to the Grand-Est and Baden-Württemberg regions to extrapolate local data for energy supply and demand since no data/trends was available at the regional scale. These results and their applicability to the context of the case study should therefore be discussed.
As hydropower is already well developed in the case study area (especially along the Rhine), it is likely that the remaining development potential is lower than estimated by E3ME. However, the trend defined by the model suggests that the level of dependence on water resources for energy production will be at least maintained in both scenarios and in particular in the 2°C scenario. The results produced by the model on the evolution of nuclear power in France also point in this direction and call for the same vigilance concerning the use of and pressure on water resources (particularly in terms of quality) in a context of climate change (particularly global warming).
In addition, the deployment of solar power is a specific issue in the case study: on the German side of the Rhine, policy instruments facilitating access to land for the installation of solar parks has been implemented (i.e., “Freiflächenöffnungsverordnung”). The implementation of such a system has been highlighted as a concern by local NGOs regarding sustainable land use. The results of E3ME in addition to these local considerations underline the potential impacts of such deployment on the Land domain of the Nexus.
Finally, the comparison of the level of electricity production between France and Germany for the 2°C and Baseline scenarios leads us to reflect on the interest of cross-border cooperation in electricity production and of a "global" decarburization of the energy mix rather than a decarburization by country. Indeed, in the case of the 2°C scenario, the E3ME results show that France can rely on nuclear power to increase its electricity production (compared to the Baseline) unlike Germany, which has a much more carbon-intensive mix.

4.9.3.1.2 Agricultural production and pressure on water resources (CAPRI)

The main objective of applying the CAPRI model to our case study was to determine the evolution of pressures on water resources – water quality and quantity – based on several indicators (irrigation in m^3/ha, total irrigation, fertilizer use and nitrogen surplus). We also aimed at determining the evolution of cultivated areas for crops of specific interest for the case study area, as highlighted by the stakeholders: we were particularly interested in the evolution of grain maize and silage areas.

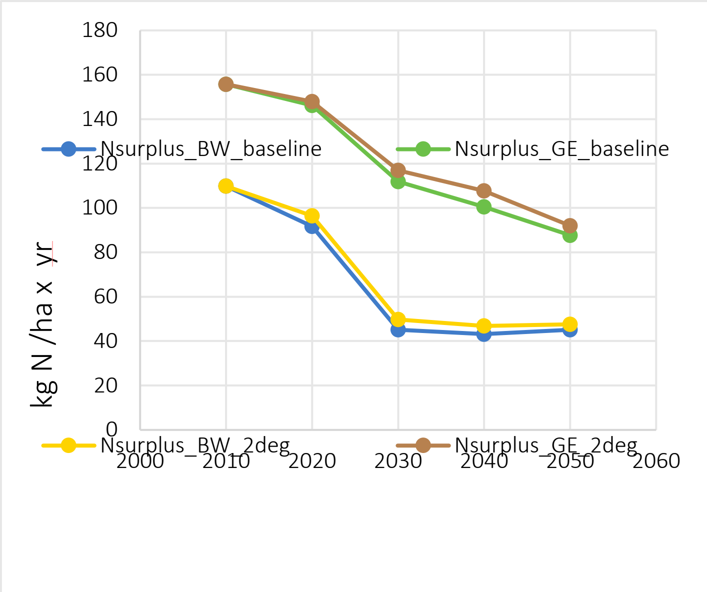

Figure 62 . Nitrogen surplus in Baden-Württemberg and Grand Est

CAPRI results suggest an increase in quantitative pressure on water resources (with little variation between the Baseline and the 2°C scenario). There is an increase in irrigated areas in Baden-Württemberg (stability in the Grand Est) as well as a net increase in water use for irrigation in the two case study regions, despite an overall decrease in gross irrigation requirements in m^3/ha (indicators calculated for the whole of the utilized agricultural area at the case study scale).

For maize cultivation, an increase in cultivated areas (for grain maize in Grand Est and silage maize in Baden-Württemberg) was observed combined with an increase in gross irrigation requirements (in m^3/ha). Such results also suggest an increase in quantitative pressure on water resources, particularly for the Baseline scenario. Moreover, the development of cultivated areas dedicated to these crops is likely to lead to an increase in pressure on water quality, as highlighted by stakeholders. However, a decrease in the nitrogen surplus is observed at the scale of the case study, for both scenarios (indicator calculated for the whole useful agricultural area at the scale of the case study, see Figure 62).

4.9.3.1.3 Land-use change (CAPRI and IMAGE)

The trends defined by IMAGE allow determining the implications of biofuel development in terms of land use under the 2°C scenario. Under this scenario, there is a strong development of the area dedicated to energy crops, which leads a decrease in natural areas (forest, wetlands and grasslands; see for instance Figure 63 hereinafter). The area occupied by these different types of natural areas is stable under the Baseline scenario (a slight decrease can however be observed for grassland areas). This change in land use between the Baseline scenario and the 2°C scenario highlights the existence of a trade-off between the objective of a transition to a low-carbon economy and that of the conservation of natural areas, which is particularly important for this case study. Furthermore, a change in land use resulting in the cultivation of forest or grassland areas is likely to have negative impacts on the Climate domain of the Nexus.

In addition, the CAPRI results show a decrease in agricultural areas in Baden-Württemberg and the Grand Est region under both scenarios; however, this decrease is smaller in the 2°C

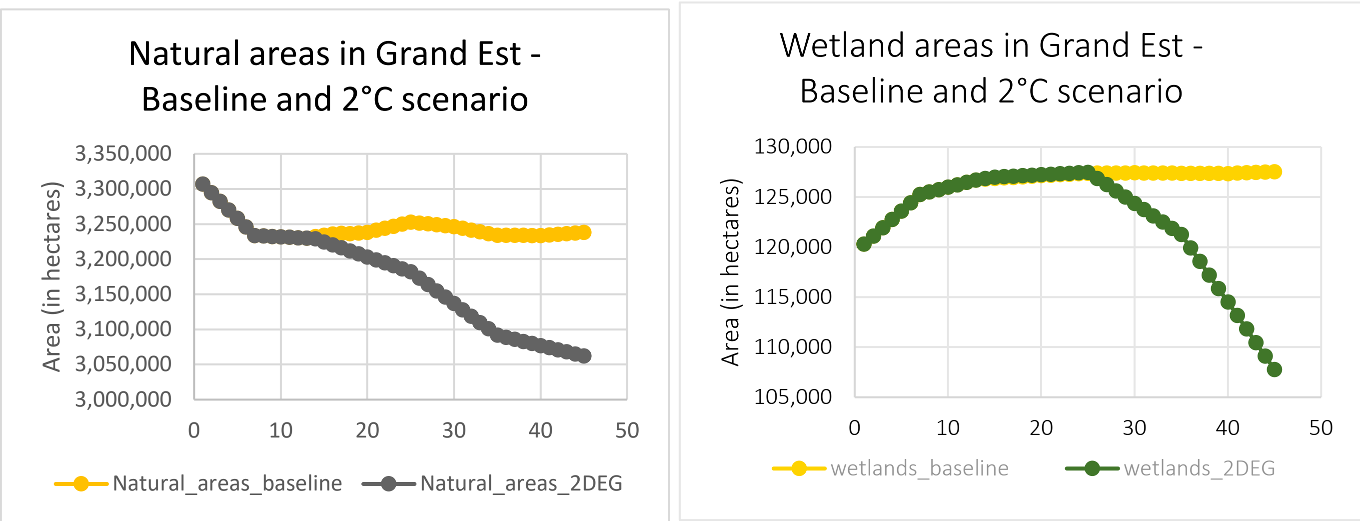

Figure 63. Natural areas and wetlands in Grand Est - Baseline and 2°C scenarios

scenario.

4.9.3.2 Additional energy scenarios

According to the results of the E3ME model simulations for the “Energy 1” and “Energy 2” scenarios, there are clear trade-offs between objectives for the evolution of the energy mix.

It does not seem possible to pursue both an objective of decarbonization of the energy mix and a nuclear phase-out: reducing the share of nuclear power implies increasing the share of natural gas both in France and Germany (see Figure 64 and Figure 65).

Moreover, a "nuclear phase-out" scenario for France (without associating it with other policies) is likely to have neutral or even negative environmental impacts (regarding the fight against climate change, pollutants, water use) and neutral economic impacts compared to current policies; the impact of such a scenario appears neutral overall for Germany.

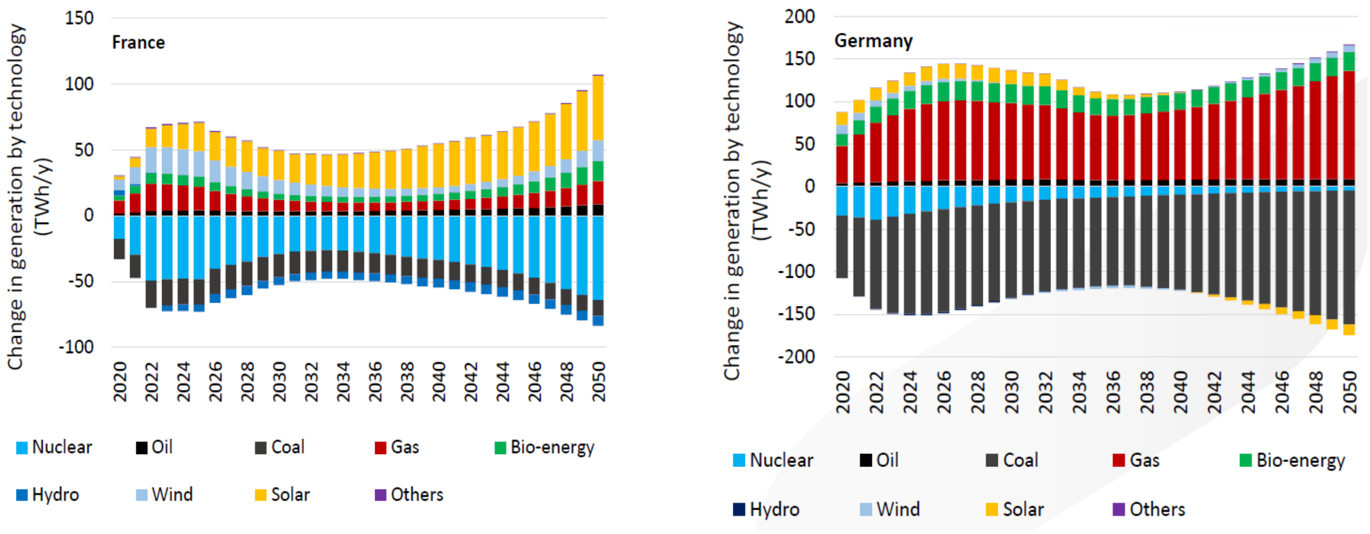

Figure 64. Change in generation by technology between "Energy 1" and Baseline scenario in France and Germany

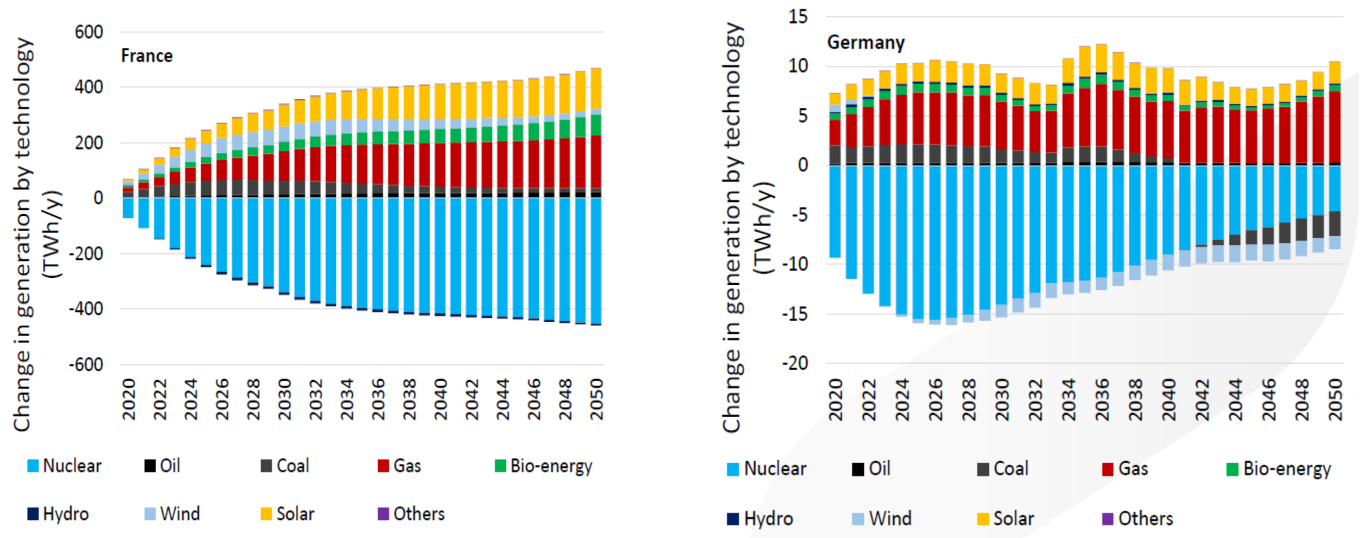

Figure 65. Change in generation by technology between "Energy 1" and Baseline scenario in France and Germany

4.9.4 Concluding remarks on the application of thematic models

The application of thematic models has mainly enabled the development of databases used for the construction of the SDM. The observation of the results from these models also allowed us to reflect on the emergence of conflicts or synergies between the different domains of the Nexus.

In addition, the results of the thematic models were also used to calibrate the policy cards. The consideration of global economic dynamics by these models (i.e., E3ME and CAPRI) allowed the determination of a wide variety of impacts for the different scenarios/public policy instruments: impacts in terms of "physical" flows of resources, environmental impacts

(GHG emissions, etc.) but also economic impacts (impacts on prices, GDP, structure of the economy, income).
However, the application of these thematic models to our case study showed some limitations, in particular due to its scale. As some results were produced at the national (or even continental) scale, the latter do not necessarily render the specificities of the territory. Proceeding to a critical examination of final results/trends as well as to their adjustment in cooperation with stakeholders is therefore an indispensable step for us.

4.10 Transboundary Germany-Czechia-Slovakia case study

4.10.1 Short description of the case study

The DE-CZ-SK case study covers the German federal states approximating the area of the former German Democratic Republic and the national territories of the Czech Republic and Slovakia, the area of former Czechoslovakia. Hence the domain shares a common history of socialist rule which shaped the landscape, i.a. there are now very large field blocks generated through collectivisation that are still present and visible as uniform agricultural monocultures despite the original, splintered property rights being re-established.

These uniform agricultural areas become very dry when harvested and perpetuate their own climate by transforming solar radiation into sensible heat and the movements of the hot air generated. This also leads to increased probabilities for extreme precipitation events from thunderstorms triggered by the convection patterns.

Other issues of the case study area are the energy sector which is still characterised by lignite mining and combustion and is challenged by the unstable electricity input from solar and wind generator plants concentrated in Germany. Bioenergy plants exist as well, but the major renewable crop grown in the area is silage maize which is in concurrence to food crops otherwise grown on the same fields.

The case study area is divided up into 15 sub-regions based on NUTS-2 units, see Figure 66. While the complete domain is modelled by SWIM – the principal thematic model for this case study – in various spatial discretisations, there are coupled individual SDMs and Serious Game regions representing exactly one sub-region each. CAPRI data were available for NUTS-2 units which helped enabling spatially differentiated crop shares in SWIM. Energy sector data from E3ME was however only produced at the national level despite some disaggregation efforts based on regional statistical data gathered by the case study representatives.

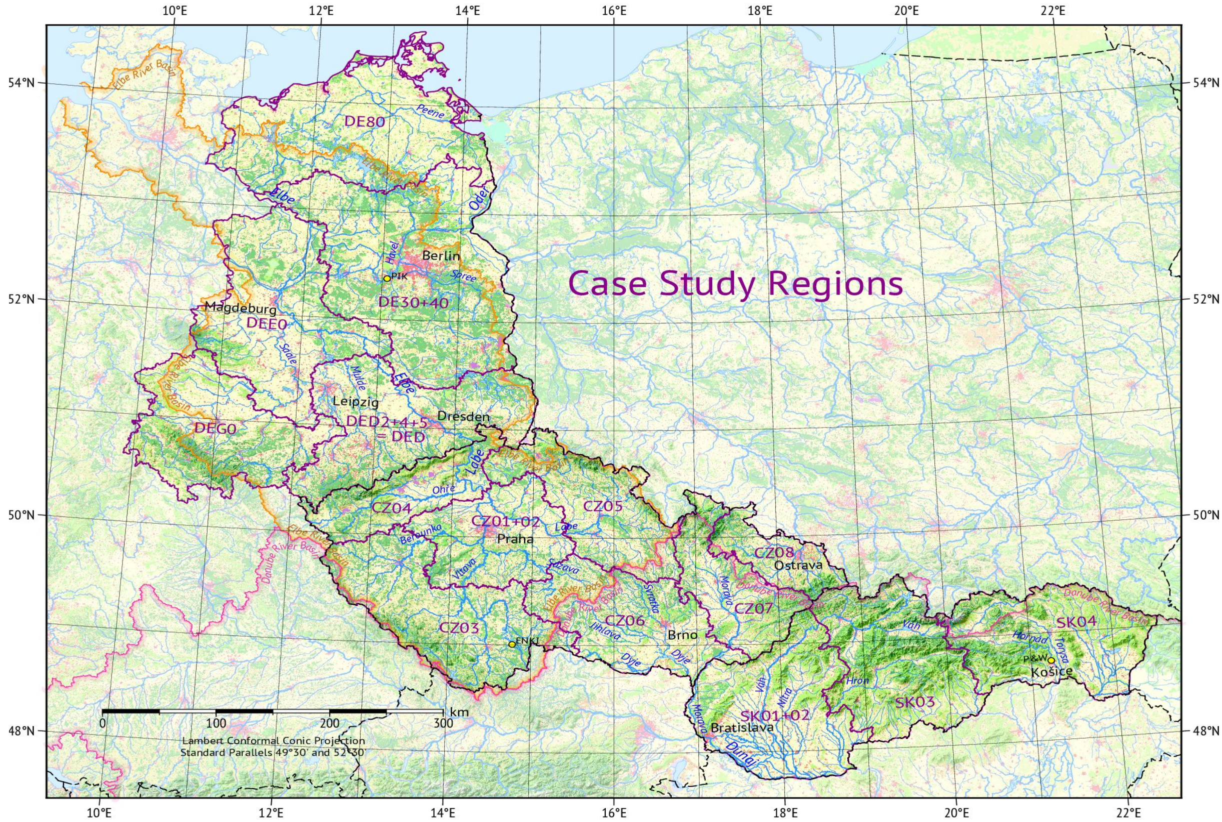

Figure 66. Map of the DE-CZ-SK transboundary case study with its model sub-regions

1.1.1 Description of the selected simulation scenarios

For the simulations the baseline and the 2-degrees scenario were selected. It had been intended to moderate these by combinations with SSP2 (middle-of-the-road, baseline) and SSP3 (fragmentation), but there is no reasonable way to consider socio-economic scenarios in the SWIM model. The baseline model runs were driven by RCP6.0 climate realisations, the 2-degrees scenario was produced with the RCP2.6 climate scenario accordingly. CAPRI data, the main input besides climate, were restricted to few scenarios anyway of which we chose the baseline and 2-degrees as matching input data to the respective SWIM runs.

The nexus challenges could be addressed only very selectively by the thematic modelling. To explain the problem in detail, the SWIM model shall be recapitulated first. At the core of the model, there are so-called hydrotopes: small, homogeneous landscape units with well-defined soil profile and land cover (basically, other factors can be skipped here). Then there are daily weather inputs (precipitation, radiation, air humidity, and temperatures). Accordingly, the hydrological responses of the hydrotope are simulated on a daily basis: How much rain water evaporates, how much infiltrates, becomes runoff, or is taken up by the plants. The daily vegetation (or crop) growth is simulated, considering root development and water and nutrient status in the different soil layers. Runoff is divided up into quick ("overland") and intermediate ("subsurface") components, and there is also groundwater recharge. At the end of each daily timestep, the lateral flows from the hydrotopes are collected at subbasin level, each subbasin consisting of one or (regularly) many hydrotopes. Then the water is routed through the subbasins representing the streams of the natural river network. Groundwater runoff is added along the way from subbasin groundwater storages. Erosion and sediment freights are calculated along, as are annual crop yields. As a consequence, the very core of the SWIM model resembles the hydrology in a natural landscape. SWIM cannot model local weather and climate, it is only driven by weather data provided as input. SWIM is also rather inflexible in modelling alternative agricultural practices, it can neither picture the energy sector nor does it take any socio-economic input.

There have been implemented at least two extensions for the needs of SIM4NEXUS: special subbasins representing the 96 most important reservoirs of the modelling domain including assumptions of their operation, the calculation of hydropower generation, and the realisation of relative crop shares in the SDM regions as given by CAPRI through the distribution of 14 different crops in 42 randomly shifted six-year rotations among the agricultural hydrotopes within each of these regions. Setting up SWIM this way, finally characterised by 2248 subbasins and 49641 hydrotopes representing 15 land use classes and 188 soil profiles, also considering hydrologically connected parts of the Elbe River basin outside the politically defined case study domain, required more resources than expected and delayed the final provision of the output data. Producing another scenario depending on further inputs would have required further model tweaking and was therefore no option.

The overarching nexus challenge the data respond to is of course climate change. Generally, water availability, agricultural yields and hydropower production were expected to decrease over time because of elevated evapotranspiration. Further consequences of diminishing water resources in the landscape may be derived. Other case study specific challenges such as increasing risks for power grid instabilities or the mutual exclusivity of food and energy crops which are addressed in the Serious Game by some policy cards can of course not be mirrored by the eco-hydrological scenarios alone.

1.1.2 Results of the application of the thematic models

As already stated the most important driver for the thematic modelling of this case study is the climate. Figure 67 and Figure 68 summarise the climate change signals of temperature and precipitation for the baseline (RCP 6.0) scenario averaged over the case study domain.

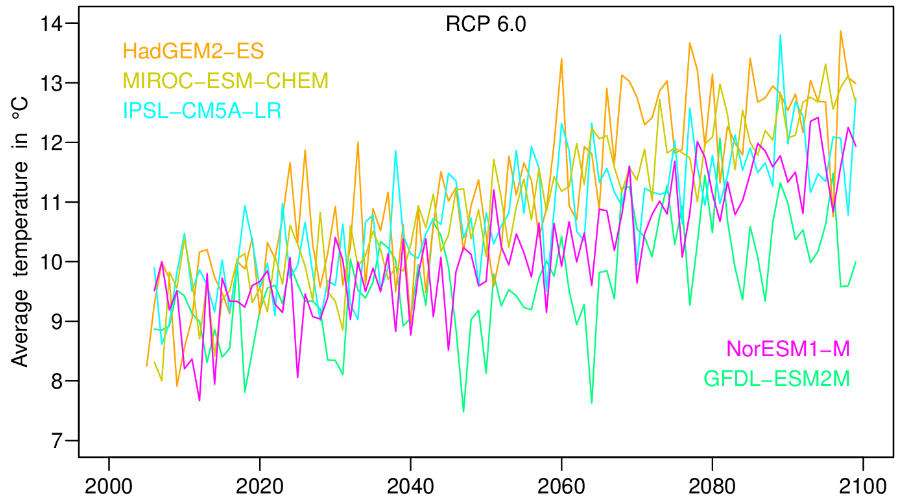

Figure 67. Annual average temperatures over the 21st century, baseline scenario

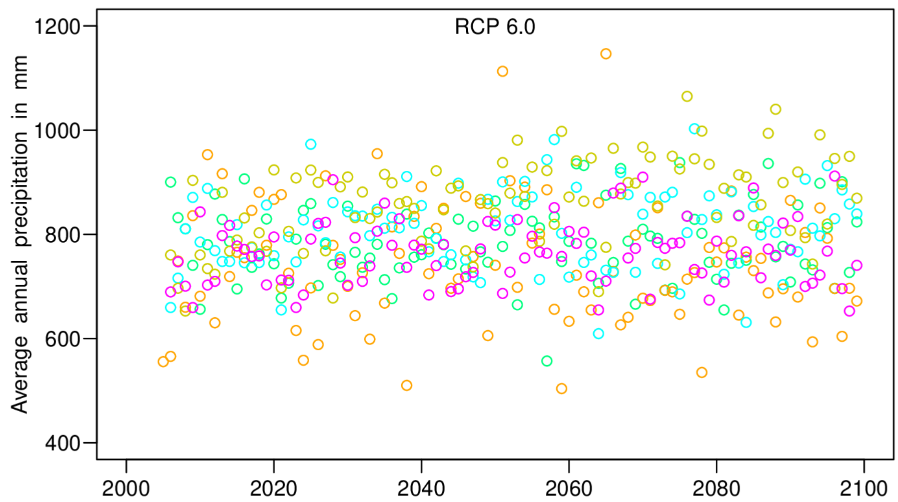

Figure 68. Annual average precipitation over the 21st century, baseline scenario

There is a rather linear temperature trend with an increase of approximately 0.35 K per decade. Hence the baseline warming during the SIM4NEXUS core modelling period will exceed 1.5 K. Only the GFDL-ESM2M model suggests a slightly weaker temperature signal. Precipitation is a more uncertain variable in climate modelling. The MIROC-ESM-CHEM model tends to produce wetter results than the other realisations, and HadGEM2-ES exposes the highest interannual variability. Taken the different models together the precipitation simulations weakly indicate an accelerated hydrological cycle for the baseline scenario.

The RCP 2.6 realisations show similar trends only at the beginning of the century and stabilize about the fourth decade of the century (Figure 69 and Figure 70). Therefore they are not considered in the presentation of SWIM results below; the respective 2-degrees scenario results were however generated as well.

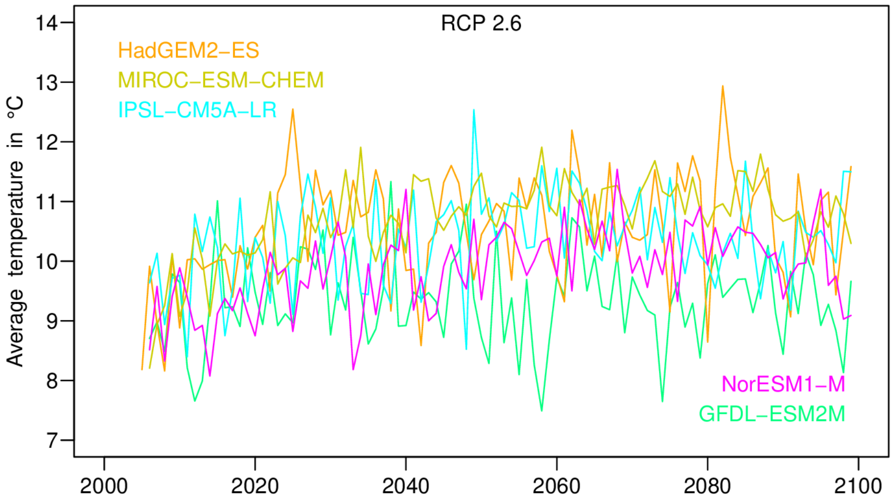

Figure 69. Annual average temperatures over the 21st century, 2-degrees scenario

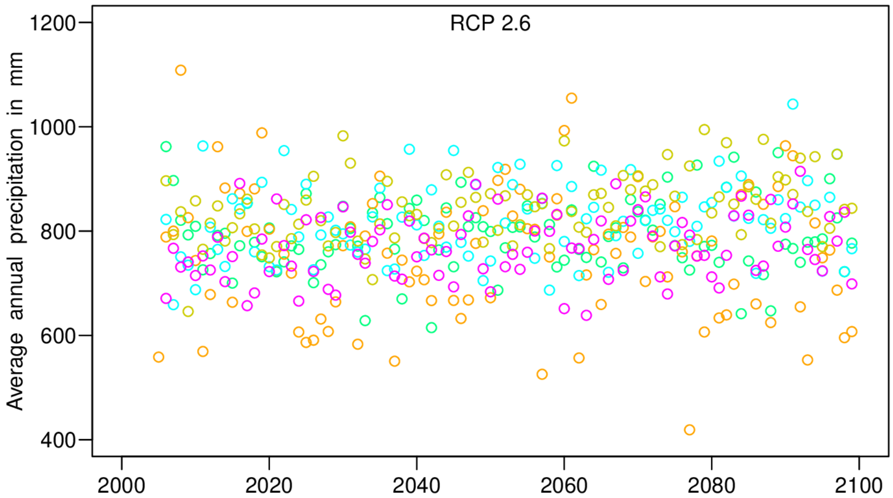

Figure 70. Annual average precipitation over the 21st century, 2-degrees scenario

As SWIM is an eco-hydrological model, most output variables are hydrology-related. For each SDM model region, there is one complete set of variables, usually aggregated to monthly time steps. Furthermore, the five climate model realisations are mirrored by respective parallel SWIM runs. The list of individual output variables starts with effective precipitation which is corrected by interception losses of the vegetation cover (that dynamically changes with the seasons). However, the general dynamics of effective precipitation hardly differ from the original precipitation input.

The second important group of variables refers to evapotranspiration, and here things become interesting: Figure 72 shows the temporal evolution of potential evapotranspiration (ETp) in Western Slovakia (just to show an example, the pattern is similar for all model regions); ETp rates tendentially increase under climate change which seems logical because air can take up the more water per volumetric unit the warmer it is. At the beginning of the century, the average ETp (level of the black line in Figure 72) amounts to 2.1 mm/d, in the years about 2050, the average ETp exceeds 2.4 mm/d, a relative increase of more than 10%. The water column actually evaporating from soil and vegetation surfaces is always smaller than ETp, because there are often water deficits (dry soils), and plants close their leaf stomata to reduce transpiration. This was modelled as actual evapotranspiration (ETa), and the respective output for Western Slovakia is shown in Figure 69.

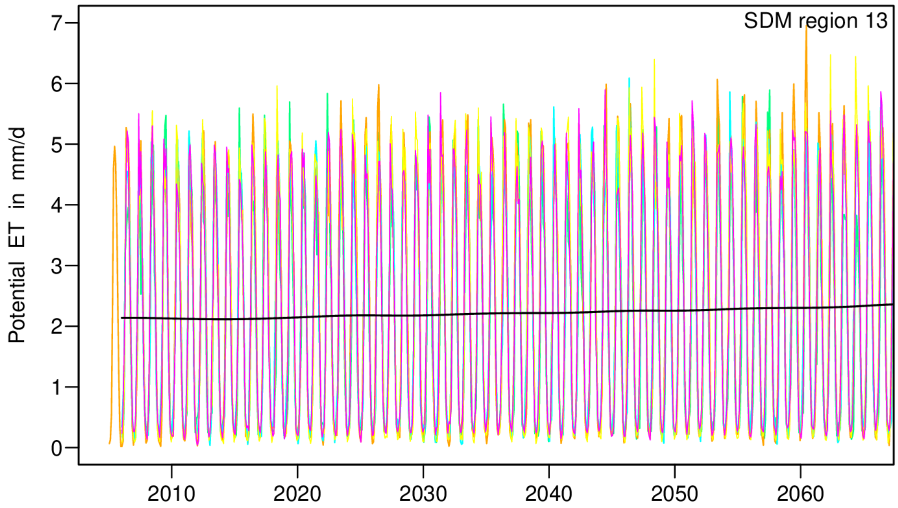

Figure 71. Potential Evapotranspiration in Western Slovakia. The black line is a time-smoothed aggregate of the annual cycles

ETa turns out to be at a level of two thirds of Etp at the beginning of the century and decreases to about the half of ETp in the 2050s, the final decade of SIM4NEXUS modelling. In numbers, it decreases from average values of about 1.4 mm/day to approximately 1.25 mm/day. A probable reason is an under-development of vegetation, especially annual crops, caused by more frequent droughts in the growing season. In reality, a drought the case study region suffered in 2018 killed many crops in premature stages, producing dry surfaces with very low actual evapotranspiration.

Actual evapotranspiration was modelled individually per crop. Figure 73 shows an example for the differences in evapotranspiratiion seasonalities between winter wheat and silage maize in Saxony, Germany. Please note that the actual locations (hydrotopes) where each crop is grown vary between the single years based on the crop rotations considered in the model. The earlier development and harvest of wheat compared to maize can be spotted in the evapotranspiration graphs; also reflected is maize as bigger plant generally producing higher ETa; and there are secondary peaks for wheat in autumn, this mirrors the growth of the newly sown winter wheat before winter.

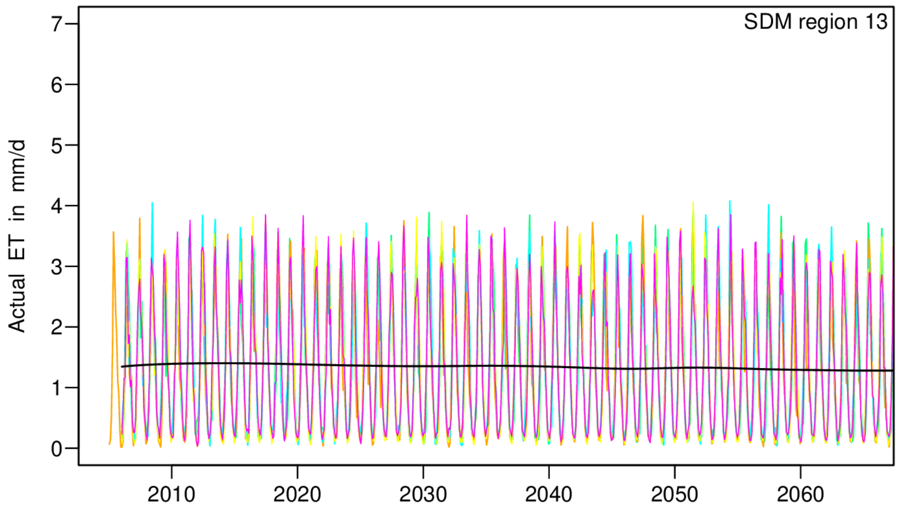

Figure 72. Actual Evapotranspiration in Western Slovakia. The black line is a time-smoothed aggregate of the annual cycles. The y-axis has the same scale as in Fig 55

Among the other SWIM outputs describing surface hydrology are direct runoff, erosion, and the water balance; each of these together with the respective subset for agricultural areas. The subterranean fluxes and storages are recorded through subsurface runoff, soil water index, aquifer recharge (seepage towards the groundwater), and relative groundwater height, usually also with agriculture-only complements. Contrary to what had been expected, aquifer recharge (and consequently also groundwater runoff) show increasing trends in all sub-model areas. The general level is mostly determined by elevation and not by the geographic location: The higher the area, the more aquifer recharge. Two extreme examples are shown in Figure 75 and Figure 74. This elevation dependency reflects the likewise pattern for precipitation (which is absorbed by the aggregate outputs for model regions containing both mountains and lowlands). And the genereally upward trends signal that considerable drought impacts on the vegetation cover are omnipresent.

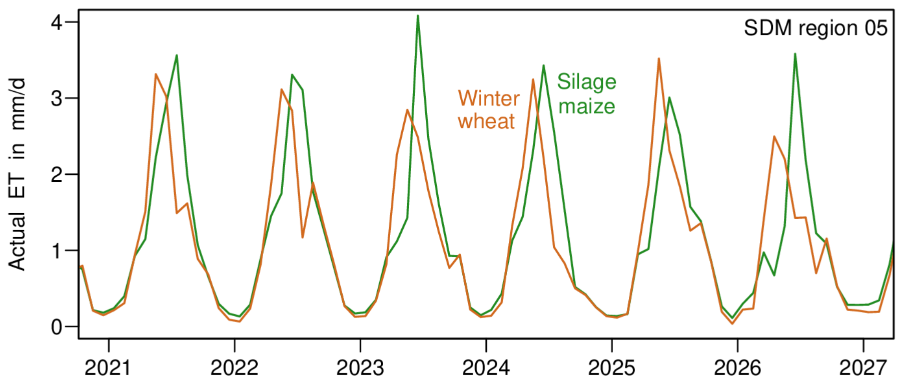

Figure 73. Average evapotranspiration from the winter wheat and silage maize stands in Saxony, Germany. Arbitrary selection of six modelling years

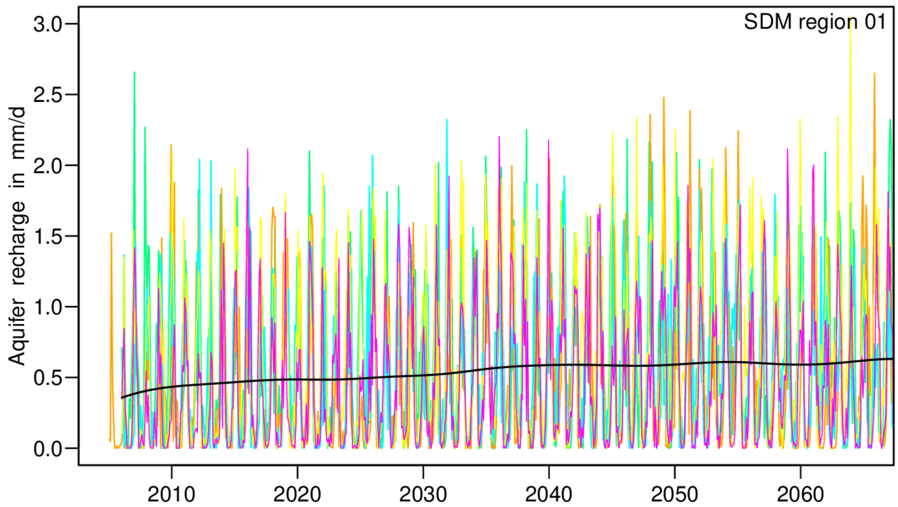

Figure 74. Average aquifer recharge in Central Slovakia, a region characterised by mountainous areas. The black line is a time-smoothed aggregate of the annual cycles.

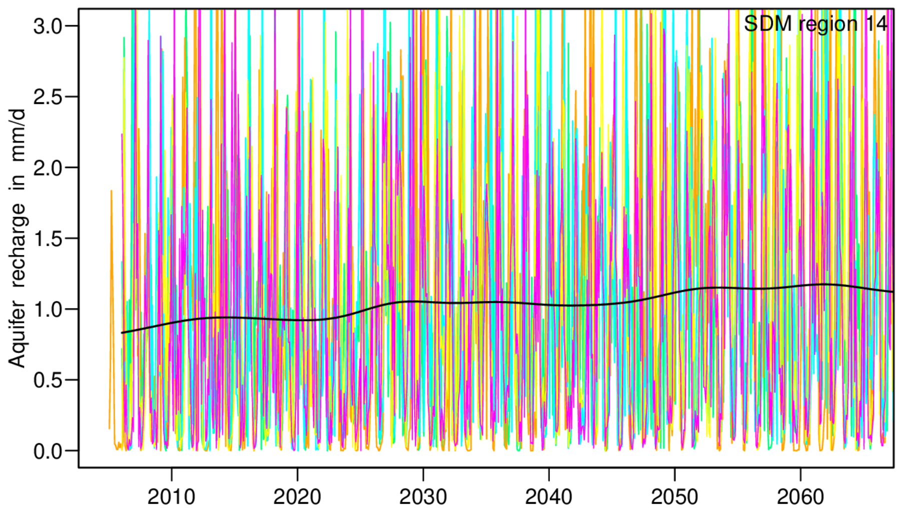

Figure 75. Average aquifer recharge in Central Slovakia, a region characterised by mountainous areas. The black line is a time-smoothed aggregate of the annual cycles.

At the end of the hydrological cascade there is river runoff. Outputs are made for the total amount, the groundwater component, and the contribution from agricultural areas. There are also outputs for hydropower generation and for the surface water exchanges between the 15 SDM domains and the surrounding landscapes; Figure 76 displays an excerpt of these data.

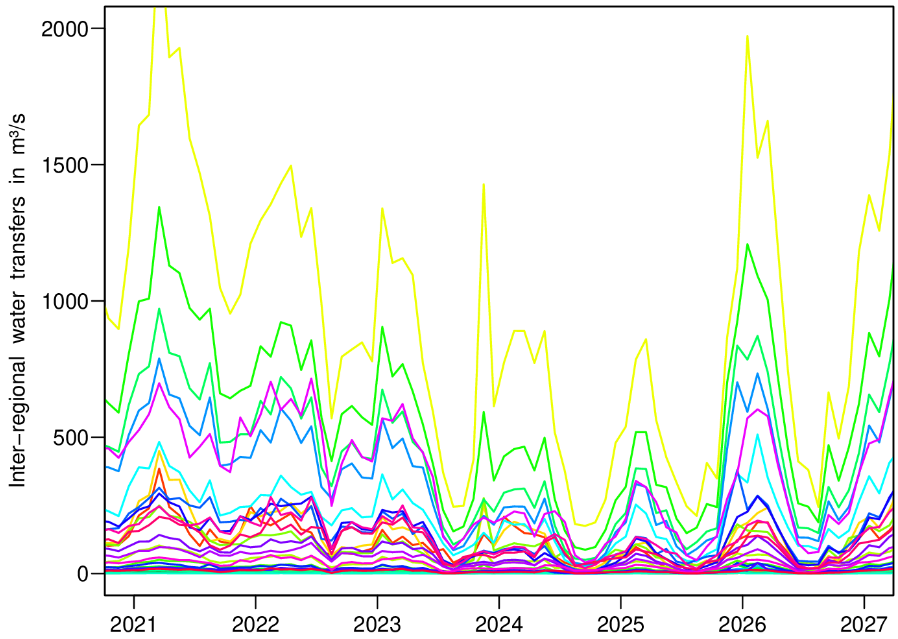

Figure 76. Water transfers between the model sub-regions. The yellowish line with the highest values represents the downstream losses of SDM region 03 which are virtually identical to the Elbe River runoff. Arbitrary selection of six model years.

The most important non-hydrological output are the agricultural yields for the 14 different crops considered. There are considerable variations between single years as Figure 75 illustrates for winter wheat. There are no clear long-term trends: The increasing drought and heat challenges are counterbalanced by increasing precipitation in winter and more favourable temperature conditions in higher elevated places.

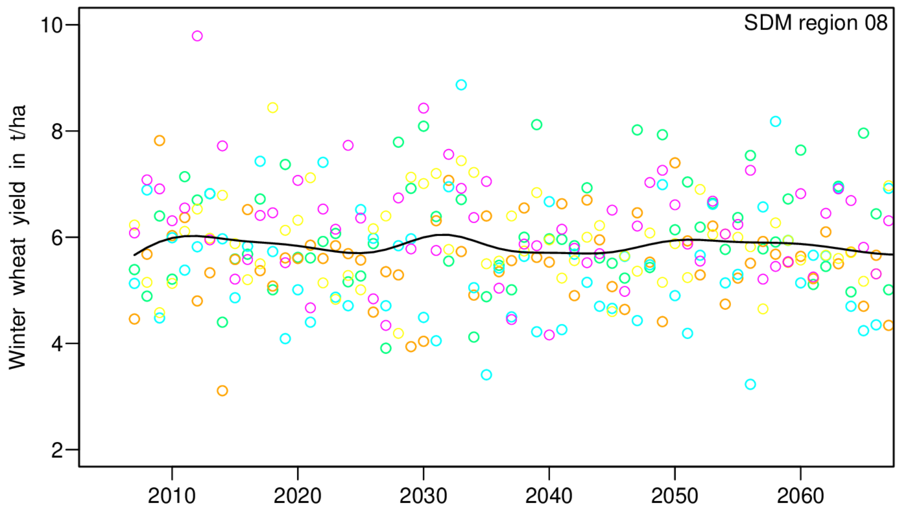

Figure 77. Annual winter wheat yields in the model region around Prague, Czech Republic

1.1.3 Concluding remarks on the application of thematic models

For the DE-CZ-SK transboundary case study, SWIM was the central thematic model. The climate scenarios RCP6.0 and RCP2.6 were the principal drivers, together with crop share data provided by CAPRI for both the baseline and the 2-degrees scenario, respectively. There were also some data on the national energy sectors provided by E3ME. As already stated in 4.10.2, the eco-hydrologic scenarios provided by SWIM are insensitive to a broad range of cross-sector Nexus effects; filling these gaps with simplified quantitative dependencies is up to the SDM modelling. As hydrology, erosion, agricultural yields, and perhaps also hydropower production are at the core of the health indicators for this case study, the thematic model outputs of SWIM may however provide a suitable basis for the further steps towards developing the Serious Game for the 15 DE-CZ-SK regions.

4.11 European case study

4.11.1 Short description of the case study

The Continental European case study examines the impact of a transition to a low carbon economy in Europe on the five elements of the Nexus: Climate, Energy, Land, Water and Food. The case study focuses on the entire European continent which has been further divided into 6 regions, four regions within the European Union and 2 regions outside. See Figure 78 , for regional definition. The time frame for the analysis is from 2010 until 2050, with future projections reported in 10 year periods. The case study examines economic incentives, such as carbon prices and renewable energy subsidies, as well as regulatory policies on, for example, land use or transport emissions, as possible pathways for the transition to a low carbon economy in Europe as a mitigation strategy to combat climate change. The analysis of European Union nexus policies in deliverable 2.1 from work package 2 was an important input in designing the scenarios for the thematic models in the European Case study and helped to inform the focus of the analysis.

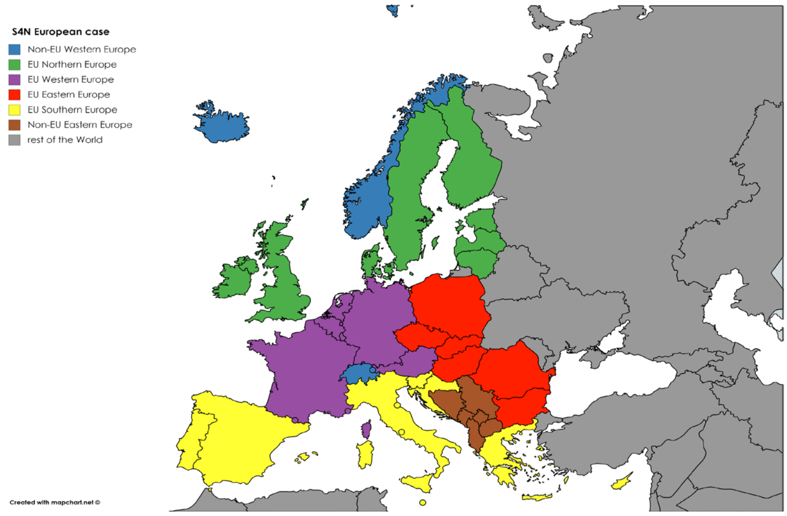

Figure 78. Spatial scale and regional definition of the European Case Study, not pictured, Greenland which is included in Non-EU Western Europe

To explore possibilities in the transition to a low carbon we economy we employ five different models each with its own particular focus such that when used together create a picture of the larger scale Nexus interactions and themes while still retaining important detail on specific nexus elements. We use three different economic models, E3ME a macro-econometric model of global coverage with focus on energy in Europe; CAPRI a partial equilibrium model with global coverage and a focus on agriculture in Europe and MAGNET a global general equilibrium model with a focus on agriculture and trade. In addition to the economic models we include MAgPIE a global land use allocation model and IMAGE-GLOBIO a global integrated assessment model with a focus on land use, agriculture, bio-diversity and ecosystem services.

4.11.2 Description of the selected simulation scenarios

4.11.2.1 Baseline

In the European case study we first analyse a baseline scenario, which is run by all thematic models participating in the case study. This baseline is informed by the 2nd Shared Socio-economic Pathway (SSP2) which is the "business as usual" future projection scenario for the period 2010-2050 O'Neill et al. (2017). The results from the other policy scenarios described in this deliverable on the Water, Land, Energy, Food and Climate (WLEFC) nexus are then compared to the baseline results to explore the Nexus impacts of various transition pathways to a low carbon economy. This study has a particular focus on Europe but connects the future projections of the nexus related developments in Europe with larger SSP2 trends and developments related to the nexus around the globe. For more detail on the exact implementation of the baseline scenario in all participating models see Milestone 17.

4.11.2.2 2 degree scenario

Mindful of international commitments to reduce greenhouse gas emissions this case study has a particular focus on the large scale mitigation possibilities of, for example, carbon taxes, renewable energy subsidies or increasing designated nature areas as a carbon sink. To explore this, all participating thematic models ran a “2 degree” scenario where various mitigation policies were enacted to alter the global greenhouse gas emission pathway from the baseline to an emission pathway consistent with restricting global warming by 2 degrees by the end of the century. The baseline emission pathway follows the representative concentration pathway (RCP) 6.0, while the 2 degree scenario follows the RCP2.6 (van Vuuren et al. 2011a,b). Each participating thematic model was given the freedom to choose the mitigation policies that best suit the logic of their model. An overview of the mitigation policies implemented in each model is given in Table 8. A detailed overview is given in Milestone 17.

Results from an additional European 2 degree scenario are presented by the MAGNET model. This scenario explores the possibility that Europe completes the transition to the RCP2.6 emission pathway but the rest of the world remains in the baseline business as usual scenario. The MAGNET model implements the mitigation policies in the Global 2 degree scenario primarily via a carbon tax and restrictions on agricultural land expansion. In the European 2 degree scenario this same tax is applied only to Europe.

Table 11. An overview of the climate mitigation policies for the thematic models.

Models	Model type	Economic Coverage	Nexus focus	Main Climate Policies
MAGNET	General Equilibrium	Full Economy	Energy and Agriculture	Carbon Tax on all emissions; Land Based mitigation from IMAGE
IMAGE	Integrated Assessment	Linked to MAGNET	Land, Agriculture, Energy	Carbon tax on energy and industry, protection of all forests with carbon storage of >10 tC/ha, mitigation in agriculture based MAC from Lucas et al. (2007)
CAPRI	Partial Equilibrium	Agriculture	Agriculture	Price on non-CO2 emissions in Agriculture
E3ME	Econometric	Full Economy	Energy and Climate	Carbon tax, investments in energy efficiency and renewable energy, regulations on energy efficiency, vehicle emission etc…
MAgPIE	Partial Equilibrium	Agriculture	Agriculture	Increase in Bio-energy demand consistent with Popp et al. (2018); Land based mitigation reforestation based on NDCs;mitigation in agriculture based MAC from Lucas et al. (2007)

4.11.2.3 2 degree scenario with increased technology

The “2 degree with increased technology” scenario is based on the initial 2-degree scenario but with higher learning rates for renewables in power generation, household heating and transport technologies. This scenario is run exclusively by the E3ME model, taking advantage of this models detail in the energy sector.

In power generation the learning rates for bioenergy generation, wind, solar, tidal and geothermal technologies are increased by 30 percent compared to the standard 2-degree scenario. Solar technology sees a 20 percent increase in learning rates. No changes have been made to hydro-power. For transport technologies a 10 percent increase in learning rates has been added for hybrids and electric vehicles. For household heating, a 10 percent improvement in learning rates has been added to heat pump technologies and solar thermal. The changes in learning rates have been implemented from 2020 onwards.

4.11.2.4 Diet transition towards eating less animal products scenario

The “Diet transition towards eating less animal products” scenario implements a dietary transition in Europe of a 35 percent reduction in meat consumption as compared to the baseline. This transition takes place gradually over the period 2020-2050 with the same percentage reduction in meat consumption per period. Total expenditure on food is fixed so the reduction in meat consumption is replaced by increased consumption of crop based food products. This diet transition is for Europe only but is similar in nature to the global diet scenario described in Frank et al. (2019).

4.11.3 Results of the application of the thematic models

4.11.3.1 2 degree scenario

The price of agricultural commodities shown in Figure 79, increase as a result of the mitigation policies in the 2 degree scenario. The pressures on agricultural production comes from reduced land availability, as all models restrict agricultural land expansion, and also (with the exception of the IMAGE model) from a tax on agricultural emissions which represents the burden on agricultural producers to reduce emissions. These various pressures increase the price of producing agricultural products, particularly livestock herds, as these have a higher greenhouse gas emission per value of output than crops. Each of the thematic models then makes assumptions on the consumer response to the change in prices. MAgPIE for example has much stricter consumer preferences each food type, this results in a higher average price for agricultural commodities than the results from CAPRI and MAGNET which expect the consumer to change behaviour more easily when confronted by higher prices.

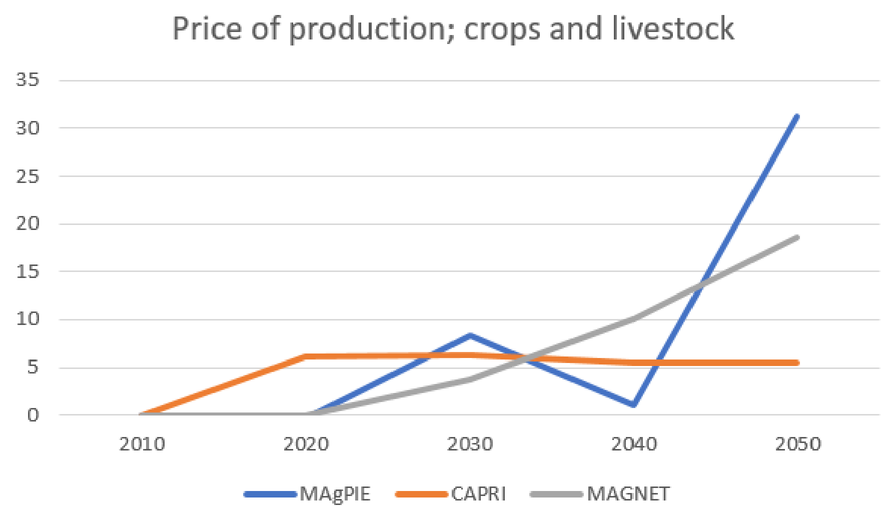

Figure 79. Average price of production of crops and livestock in Europe in the 2 degree scenario as a percent difference with the baseline.

Figure 80 shows the changes in agricultural land use in Europe in the 2 degree scenario as compared with the baseline. There are many interacting factors which determine the agricultural response to the mitigation measures imposed in the 2 degree scenario and these factors differ across the thematic models. In IMAGE and MAgPIE for example, dedicated energy crops for bio-energy can be grown on degraded lands which are unsuitable for other type of agriculture. This is not the case in MAGNET where dedicated energy crops must compete with other type of agriculture for land. The MAGNET model on the other hand makes more generous assumptions on the availability of crop residues for use in bio-energy. These crop residues provide additional income for crop farmers. The CAPRI model does not include bio-energy.

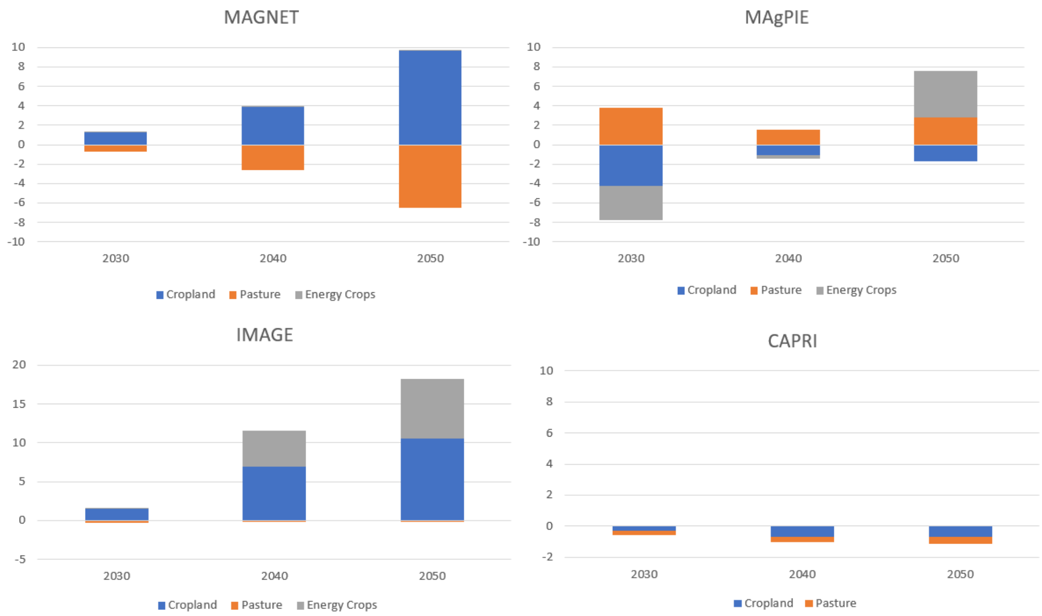

Figure 80. Changes in agricultural land use in Europe for the 2 degree scenario compared with the baseline. Unites are million square hectares.

Assumptions on the competition for land between crops and livestock such as, the consumer reaction to price increases and the competitive advantage of European agriculture with compared to the rest of the world with respect to greenhouse gas emissions, also determine changing patterns in agricultural production and land use in Europe. In MAGNET higher prices for livestock products means that consumers substitute away from animal products when the prices rise. This reduced demand for livestock results in less production and the shrinking livestock sector then allows for the expansion of crop land. In MAgPIE, the demand for animal products is rather stable in the 2° scenario. Yet, pasture area is in turn increased because the ruminant sector in Europe has a rather low emission intensity and therefore gains in international competitiveness under emission pricing. In 2050, bioenergy demand increases and requires additional land. Due to higher land scarcity, croplands are intensified. In IMAGE, crop and livestock production is exempted from the carbon tax. In combination with high current efficiency and further global increases in food demand this leads to an increase in cropland and continued use of existing pasture lands. In CAPRI land allocation is fixed according to the common agriculture policy (CAP) and the small reductions in land use are exogenously specified. European livestock production in CAPRI increases slightly as it has a comparative advantage with non-European livestock with respect to greenhouse gas mitigation.

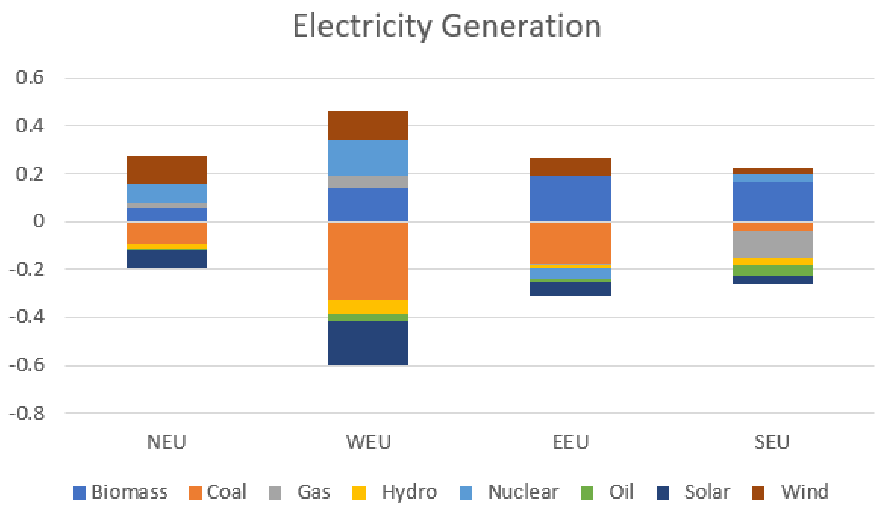

Figure 81. Absolute change in electricity generation in 2050 for the four case study regions in the European Union regions in units of exajoules. The 2 degree scenario compared with the baseline. From the E3ME model. NEU, WEU, EEU, SEU are Northern, Western, Eastern and Southern European Union respectively.

Figure 81 shows the transition in the electricity generation mix for the four regions that make up the European Union in the 2 degree scenario compared with the baseline. All regions show a relative reduction in electricity generation from coal and an increase in electricity generation from wind and biomass as compared to the baseline in 2050. The Southern European Union region has a large reduction in electricity from gas, while the Northern and Western European Union regions have a slight increase. Electricity from gas has relatively fewer greenhouse gas emissions when compared to coal and the two regions with an increase in electricity from gas reduce their electricity from coal compared to the baseline. The energy investments in the E3ME model in the 2 degree scenario also impact the growth of the electricity generation mix from various renewable energy sources, solar and hydro-power increase less in the 2 degree scenario compared to the baseline, while electricity from wind and bio-mass increase more. Further with the exception of the Northern European Union all regions reduce their total electricity demand as a result of investments in energy efficiency. In examining Figure 67 it is also important to note that all regions reduce electricity from coal and increase electricity generation from renewables in the baseline in 2050 as compared to 2010.

Figure 82 and Figure 83 explore the impact on European agriculture of an alternative 2 degree scenario where Europe presses forward in the transition to a low carbon economy while the rest of the world continues with the baseline business as usual scenario.

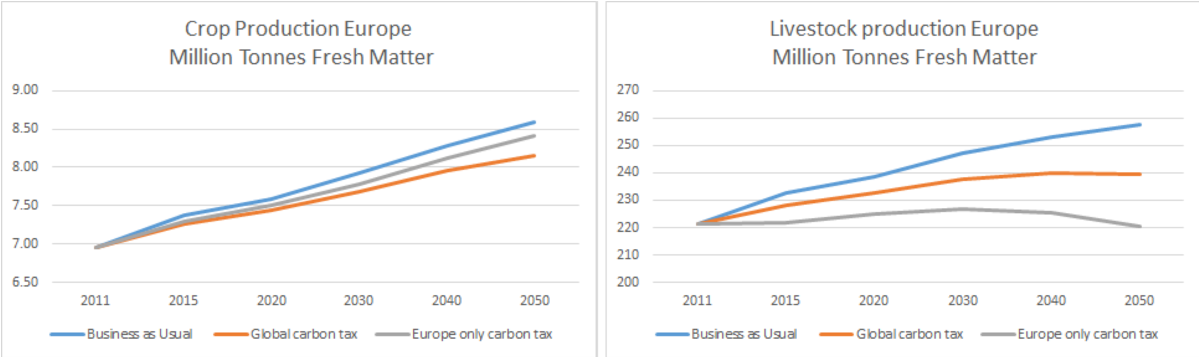

Figure 82. Agricultural production from the MAGNET model comparing the baseline SSP2 "business as usual" to a global 2 degree scenario and a European 2 degree scenario where only Europe mitigation ghg emissions while the rest of the world does not.

Figure 82 shows the impact on European agricultural production of the European 2 degree scenario when compared with the global 2 degree scenario and the business as usual SSP2 baseline. Livestock production reduces even further in the European 2-degree scenario when compared with the global 2-degree scenario. This is expected as the European trading partners are not subjected to a carbon tax as they are in the global 2-degree scenario leading to more imports and fewer exports of livestock products.

With respect to crop production however, the European only 2-degree scenario shows a larger production of crops in Europe than in the global 2-degree scenario although crop production is still smaller than in the business as usual scenario. This is because despite a carbon tax being imposed on European agriculture only, the crop sector benefits more from agricultural resources (land, labour etc...) that is not being utilized by the livestock sector.

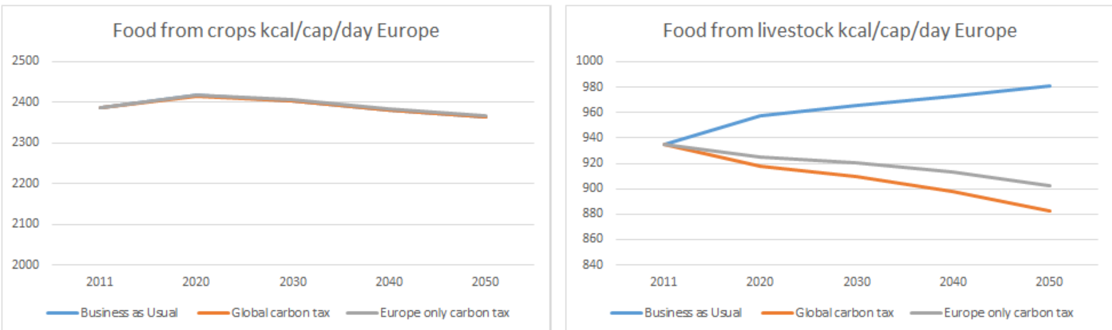

Figure 83. Food consumption from the MAGNET model comparing the baseline SSP2 "business as usual" to a global 2 degree scenario and a European 2 degree scenario where only Europe mitigation ghg emissions while the rest of the world does not.

Figure 83 shows the impacts on food consumption in Europe separately for crop and livestock products. Calories from crop consumption in Europe are essentially unchanged in all three scenarios. Calorie consumption from livestock products decreases by approximately 10 percent in the global 2 degree scenario and 8 percent in the European 2 degree scenario compared to the baseline. Even though Figure 83 shows that livestock production decreases more in the European 2 degree scenario, compared with the global scenario, consumption of livestock products increases because of higher imports into Europe. There is a significant carbon leakage effect from the European mitigation efforts with respect to agriculture. The reduction in emissions from European agriculture is offset by increasing agriculture emissions from increasing production in the rest of the world equal to approximately 50 percent of the reduced emissions in Europe.

4.11.3.2 2 Degree with increased technology

Figure 84 shows the change in electricity generation for the 2-degree with increased technology scenario compared to the standard 2 degree scenario, for the combined four EU regions. Current total EU power generation is about 3,000 TWh, and it is not expected to increase by much over the projection period. Therefore, the shift that can be observed in learning rate changes is quite big relative to baseline. Wind power benefits substantially from the technology shift. Solar power benefits in the short term but then wind power continues to increase its share after solar appears to have reached its maximum. In particular, on-shore wind is the one that increases substantially, off-shore doesn’t really expand that much even with the improved learning rates. While solar photovoltaic (PV) only benefits in the short-term, concentrated solar power (CSP) also increases substantially in the version with higher learning rates, but it is starting from a small base so it’s not really that visible. Most of these changes are the expense of nuclear.

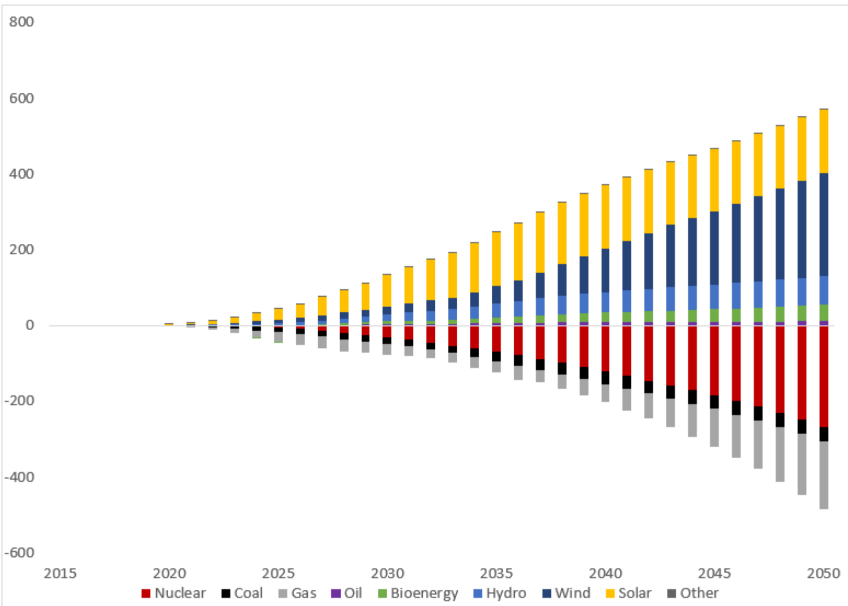

Figure 84. Change in electricity generation for the combined 4 regions of the European Union in the 2-degree scenario compared to 2-degree with increased learning rates. Units are TWh/y.

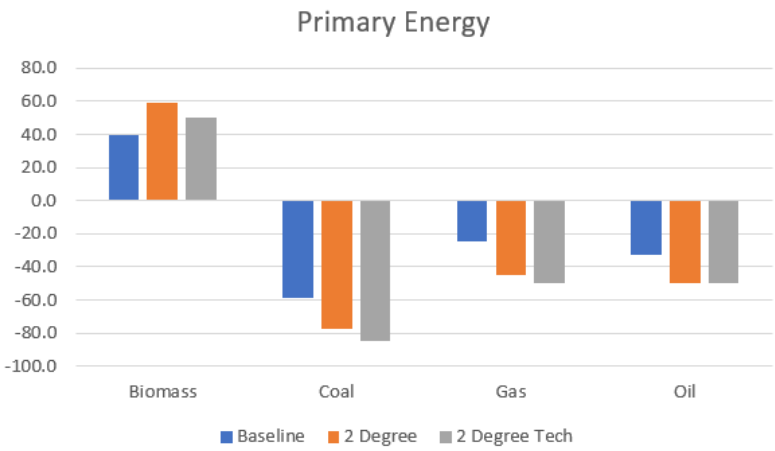

Figure 85. Primary Energy use of Biomass, Coal, Gas and Oil in Europe in 2050 as a percent change from 2010. Results are shown for the from the E3ME model for the baseline, 2 Degree and 2 Degree Technology scenarios.

Figure 85 shows the percent change in primary energy use in Europe in 2050 compared to 2010. The baseline already shows a trend away from fossil fuels and towards biomass (and other renewables). The 2 degree scenario accelerates this trend. The 2 degree technology scenario with its additional assumptions of household energy savings and increased learning rates of renewable technologies reduces the consumption of coal, gas and biomass. Even though from Figure 84 we see that bio-electricity increases in the 2 degree technology scenario compared with the standard 2 degree scenario, overall use of biomass decreases because of increases in efficiency as well as reduction of demand in other areas.

4.11.3.3 Diet transition towards eating less animal products

Figure 86 shows the percent change in the price of production of crops and livestock when there is a shift in European diets from livestock products to crop based products. This diet shift is analysed for both the baseline and the 2-degree scenario. The diet shift in the baseline reduces the price of both crop and livestock outputs. The reduction in price for livestock products is due the reduction in demand, while the reduction of price of crop products, despite the increased demand for crops for food, is due to the availability of land from the shrinking livestock sector and shrinking demand of the livestock sector for feed. Similarly, a diet shifts in the 2-degree scenario reduces the prices of crops and livestock compared to the 2-degree scenario without the diet shift. These reduced prices help consumers and also the crop sector which see increased demand and can expand into new land. However, livestock farmers see both a reduction in demand for their products and also an increase in costs because of the mitigation measure in the 2-degree scenario.

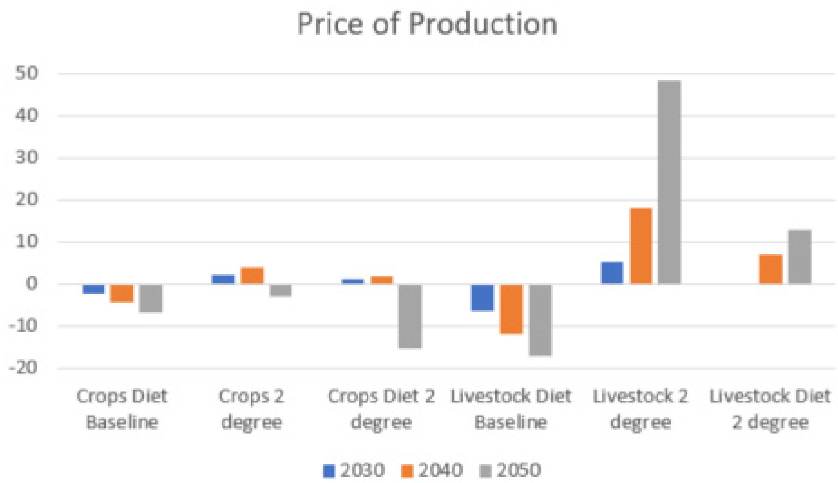

Figure 86. The price of production of crops and livestock in Europe for the three scenarios: Diet shift away from consumption animal products in the baseline, standard 2-degree scenario, and diet shift away from consumption of animal products in the 2-degree scenario. Prices are presented as percent changes from the standard baseline scenario.

4.11.4 Concluding remarks on the application of thematic models

The European case study relies heavily on the data and expertise provided by the 5 thematic models IMAGE-GLOBIO, CAPRI, MAGNET, E3ME and MAgPIE. Taken together these models cover all five elements of the nexus and their interactions. The sampling of results provided in this deliverable illustrate the nexus challenges of moving towards a low carbon economy as well pointing to possible synergies and solutions provided by resource efficiency and healthy consumer diets. The data provided by the 5 thematic models combined with the analysis of European Union Nexus policy from Deliverable 2.1 provide the data, structure and vision for the system dynamics model and serious game for the European case study.

4.12 Global case study

4.12.1 Short description of the case study

The global case study investigates nexus issues at the global scale. The focus is on interactions between the water, land, food, energy and climate sectors. A set of six scenarios is defined in order to identify and quantify different synergies and trade-offs between the nexus sectors. As many thematic models as possible are applied to cover uncertainty and differences related to model design and setup. Where possible, the models are applied at the aggregated level of eight world regions (see Figure 87).

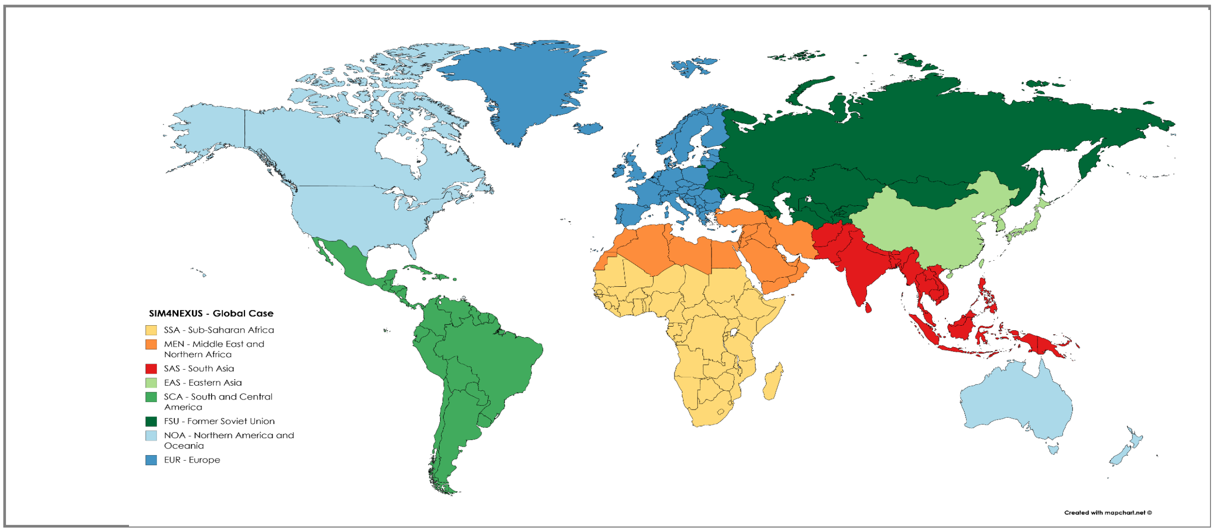

Figure 87. regional aggregation used in the global case study.

4.12.2 Description of the selected simulation scenarios

For the global case six scenarios were developed (Table 12). First, a reference scenario based on the SSP2 scenario (Riahi et al., 2016) (for more detail see deliverable 5.2). The reference scenario forms the basis for 5 so-called target scenarios. In each target scenario, one or two nexus sectors are selected in which a range of policy actions is adopted that substantially improves this specific sector. In addition, a scenario is developed that aims to optimize policy action across nexus sectors:

1. The energy and climate scenario: this scenario aims to limit global warming to 2 degrees above pre-industrial temperatures. Dependent on model characteristics, a range of mitigation actions is taken in the energy, industry and land sectors such as increased use of renewable energy sources, phasing out of fossil fuel sources, improved energy efficiency, more use of bio-energy, carbon-capture-and-storage, afforestation, and more. In most models this is to a large extent driven by an increasing carbon price that increases the costs of emitting greenhouse gasses.
2. The land and biodiversity scenario: this scenario aims to halt the loss of terrestrial biodiversity. In order to achieve this a major expansion of protected areas is implemented to limit the conversion of natural areas. In addition, major improvements in fertilizer efficiency are implemented in order to reduce nitrogen deposition.
3. The water scenario: this scenario aims to substantially improve the water sector regarding water availability and water quality. To achieve this, it is assumed that environmental flow requirements are respected by limiting the extraction of water to a pre-defined amount. Next to that, assumptions are made that reduce water demand by preventing additional expansion of irrigated cropland, by improving the efficiency of existing irrigation systems and by improving the efficiency of water use in other sectors such as households, industry and energy production. In addition, policy action

is implemented to improve water quality: this involves improved fertilizer use efficiency and improved waste water treatment.

4. The food scenario: this scenario aims to implement healthy and sufficient diets for all. To achieve this it is assumed that people will eat less animal-based products that are replaced by plant-based products in line with the suggested diet of a recent Lancet article on healthy diets (Willet et al., 2019). A large share of this will be based on legumes in order to provide sufficient proteins. In addition, major improvements in the efficiency of the agricultural sector are assumed to produce more and cheaper food to be able to feed the part of the population that is currently undernourished.
5. The total scenario: this scenario aims to find the best combination of all policies to improve all nexus sectors considered. To achieve this, all policy actions as described in the scenarios above are combined. In some cases, policy actions overlap. For example, improved fertilizer efficiency is assumed in both the land and biodiversity scenario and the water scenario. In the total scenario it is assumed that these policies are combined to achieve a double fertilizer efficiency improvement.

Table 12. scenario assumptions for the global case.

Scenario-specific assumptions	**Reference**	**Energy and climate**	**Land and biodiversity**	**Water**	**Food**	**Total**
Climate policy action						
carbon price/emissions pathway		in line with 2 degrees				in line with 2 degrees
Land policy action						
forest protection		forest protection in line with 2deg target				forest protection in line with 2deg target
biodiversity protection			land protection for terrestrial biodiversity			land protection for terrestrial biodiversity

Nutrient policy action						
fertilizer efficiency			increased fertilizer efficiency	increased fertilizer efficiency		double increase in fertilizer efficiency
Wastewater				improved waste water treatment		improved waste water treatment
Water policy action						
environmental flow requirement				Limit water extraction ensuring sufficient water for aquatic biodiversity		Limit water extraction ensuring sufficient water for aquatic biodiversity
irrigation expansion				limit irrigation expansion		limit irrigation expansion
irrigation efficiency				improve irrigation efficiency		improve irrigation efficiency
water use efficiency				improved efficiency households, industry, energy		improved efficiency households, industry, energy
Diet policy action						
diet change					reduced meat consumption/healthy diet	reduced meat consumption/healthy diet

Agricultural policy action						
yields					high yield improvement	high yield improvement
livestock efficiency					high livestock efficiency improvement	high livestock efficiency improvement
Climate impacts						
clmate impacts	RCP 6.0	RCP 2.6	RCP 6.0	RCP 6.0	RCP 6.0	RCP 2.6

Not all thematic models were able to run all scenarios:
MAgPIE and the IMAGE-MAGNET-GLOBIO models combined developed all six scenarios. OSeMOSYS developed all scenarios except the land scenario. E3ME was limited to the reference and energy and climate scenario as the model does not have an explicit land/water sector. CAPRI was limited to the reference, food and energy and climate scenarios. Please note that due to differences in model setup not all scenario assumptions are implemented in all models.

Table 13. simulation scenarios developed per model.

Scenarios **Models**	**Reference**	**Energy and climate**	**Land and biodiversity**	**Water**	**Food**	**Total**
IMAGE-MAGNET-GLOBIO	x	x	x	X	X	X
OSeMOSYS	x	x		X	X	X
MAgPIE	x	x	x	X	X	X
E3ME	x	x				
CAPRI	x	x			X	

4.12.3 Results of the application of the thematic models

This section provides an impression of the large number of output data that is available for the global case. Not each output variable is available for each model. Figure 88 shows primary energy use for two of the six scenarios for three of the models. All results show how primary energy use changes when moving towards the two-degree target: All models include more renewable energy sources, and a decrease in total primary energy needed.

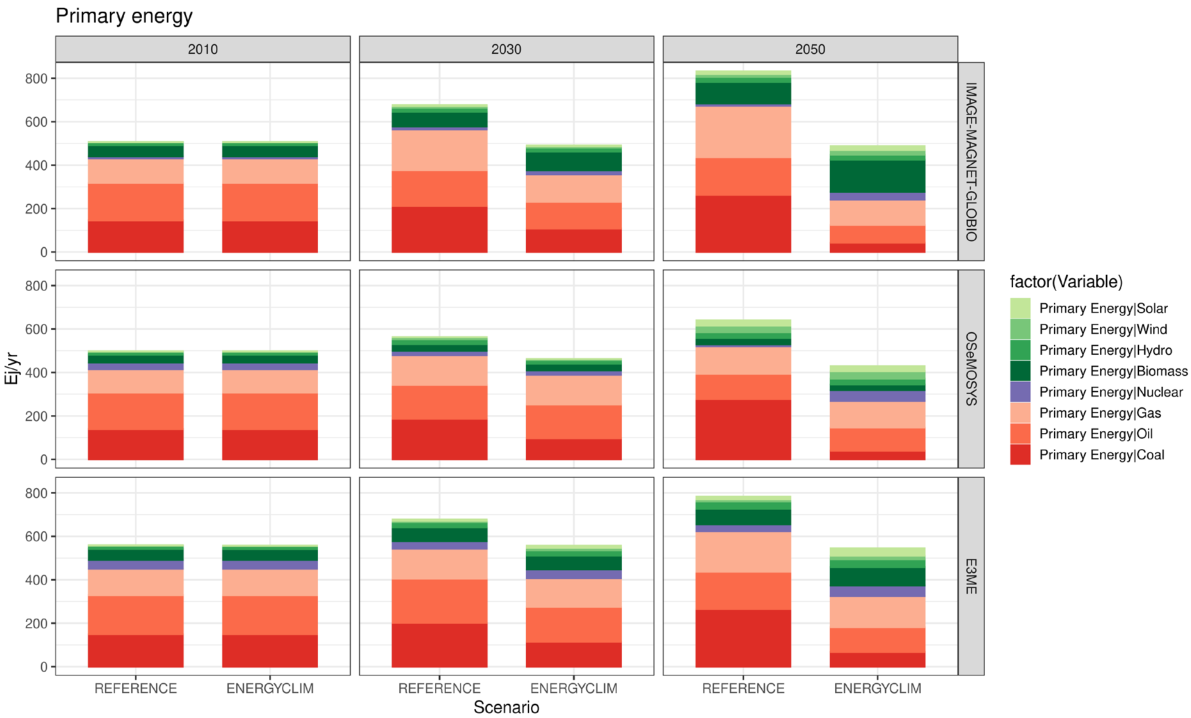

Figure 88. primary energy use.

Figure 89 shows food demand for crops and livestock in the different scenarios for four of the models. MAgPIE, IMAGE-MAGNET-GLOBIO, OSeMOSYS and CAPRI all show a strong decrease in consumption of livestock products induced by the shift towards healthy diets. The CAPRI results show that food demand in the energy and climate scenario compared to the reference scenario differs little, indicating that climate policy has limited impact on consumption patterns.

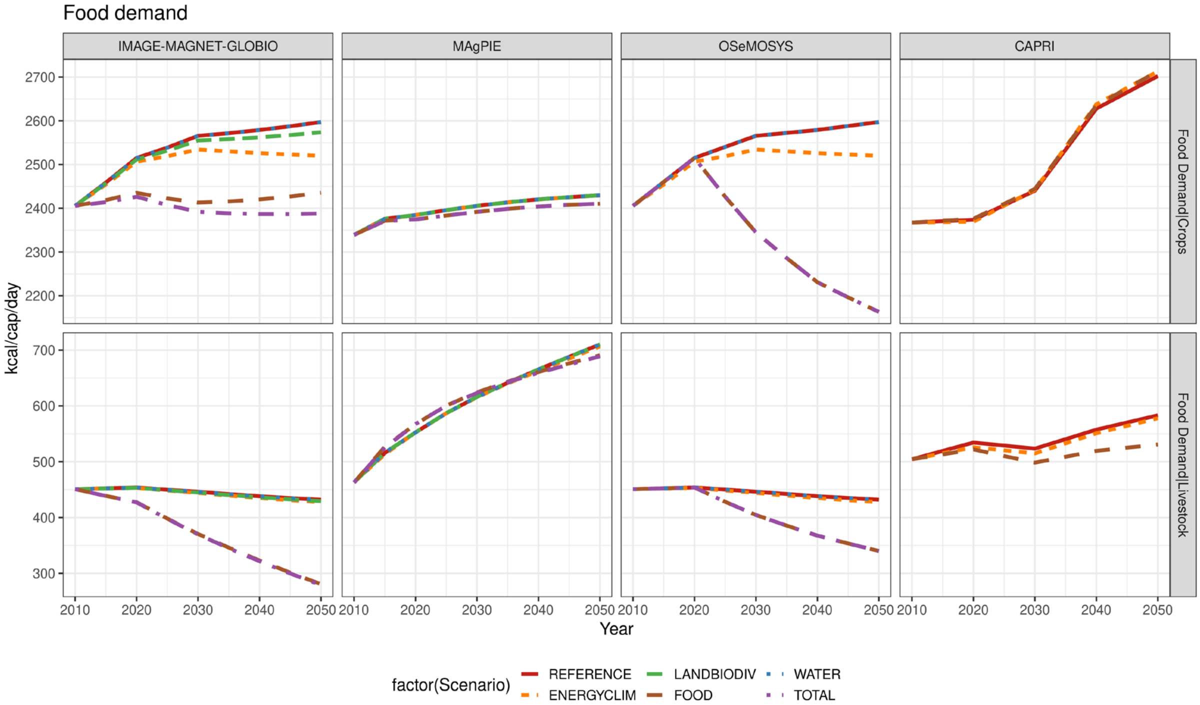

Figure 89. food demand for crops and livestock.

Figure 90 shows land use trends in the different scenarios for four of the models. In MAgPIE, IMAGE-MAGNET-GLOBIO and OSeMOSYS substantial reductions in pasture area take place related to the reduction in livestock consumption. CAPRI only models cropland at the global scale, which is reduced slightly in the FOOD scenario due to reduced crop production for livestock feed. The total scenario also shows a substantial reduction in agricultural land due to reduced livestock consumption and increased agricultural productivity. On the other hand, in the energy and climate scenario and in the total scenario also land use for bio-energy increases substantially due to increased production related to climate policy.

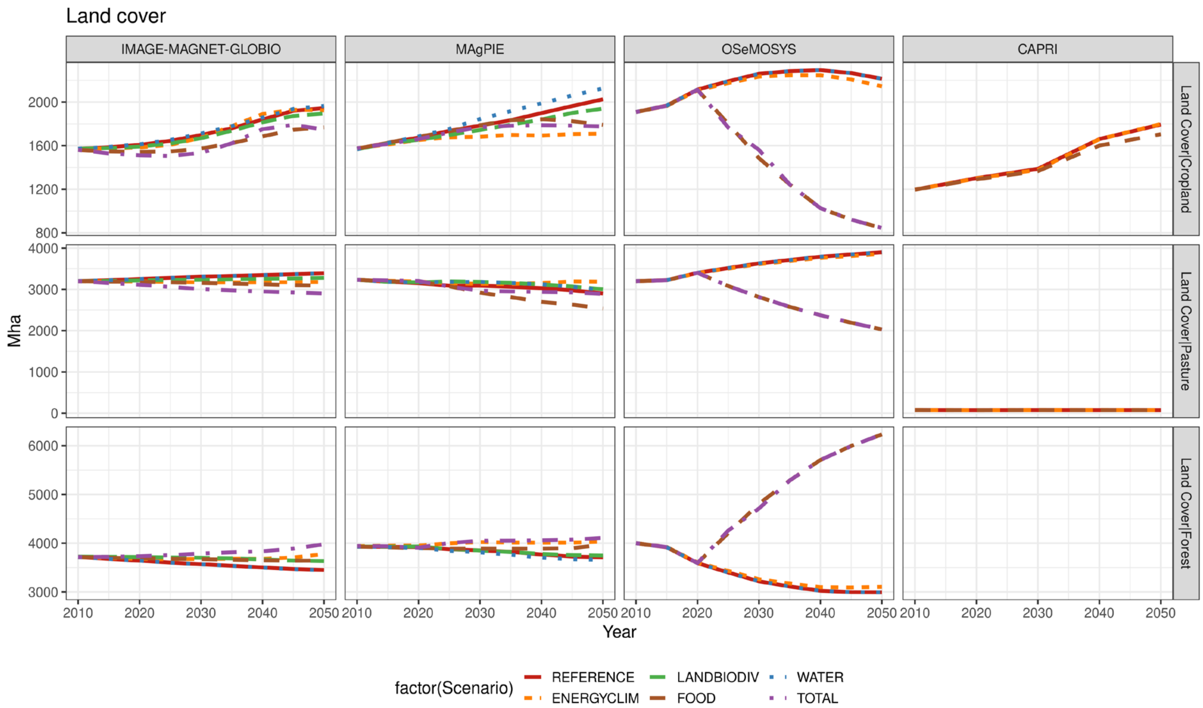

Figure 90. land cover trends for cropland, pasture and forest.

Figure 91 and Figure 92 show CO_2 emissions from energy and AFOLU sector respectively. For the energy sector, a very substantial reduction takes place towards 2050 in order to achieve the two-degree climate target. The AFOLU sector, which for CO_2 emissions is dominated by land-use change, shows interesting dynamics related to land use development. For example, in MAgPIE the food and total scenario shows strong reductions in emissions even resulting in net uptake of carbon from the atmosphere. On the other hand, the water scenario shows a substantial increase in emissions due to limited irrigation which leads to lower agricultural efficiency in turn resulting in more land-use change.

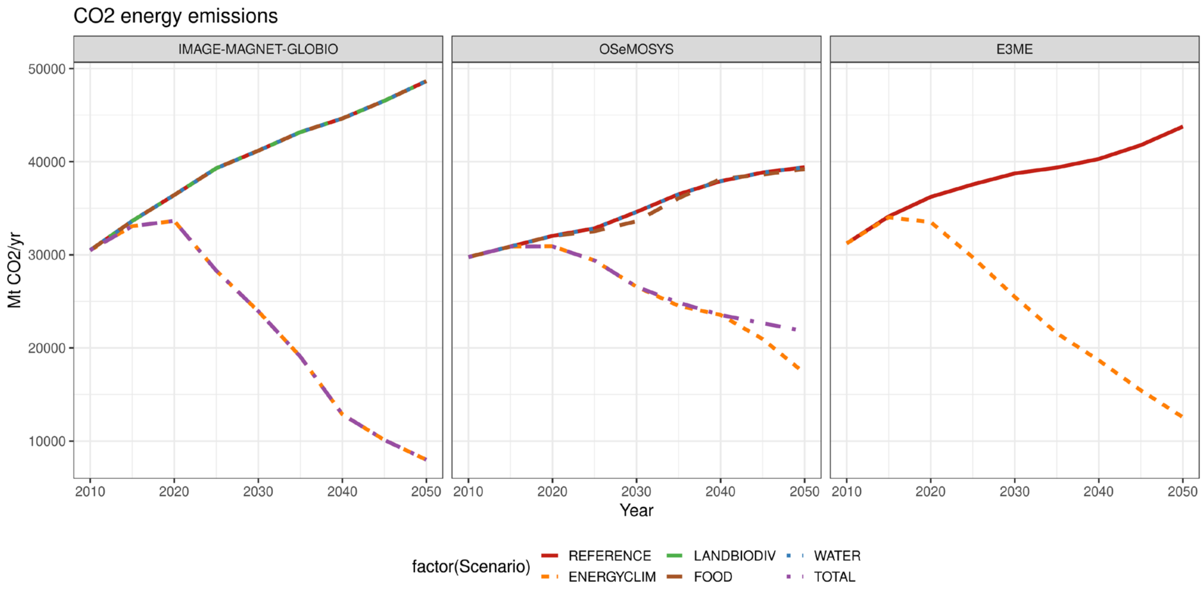

Figure 91. CO2 emissions from the energy sector.

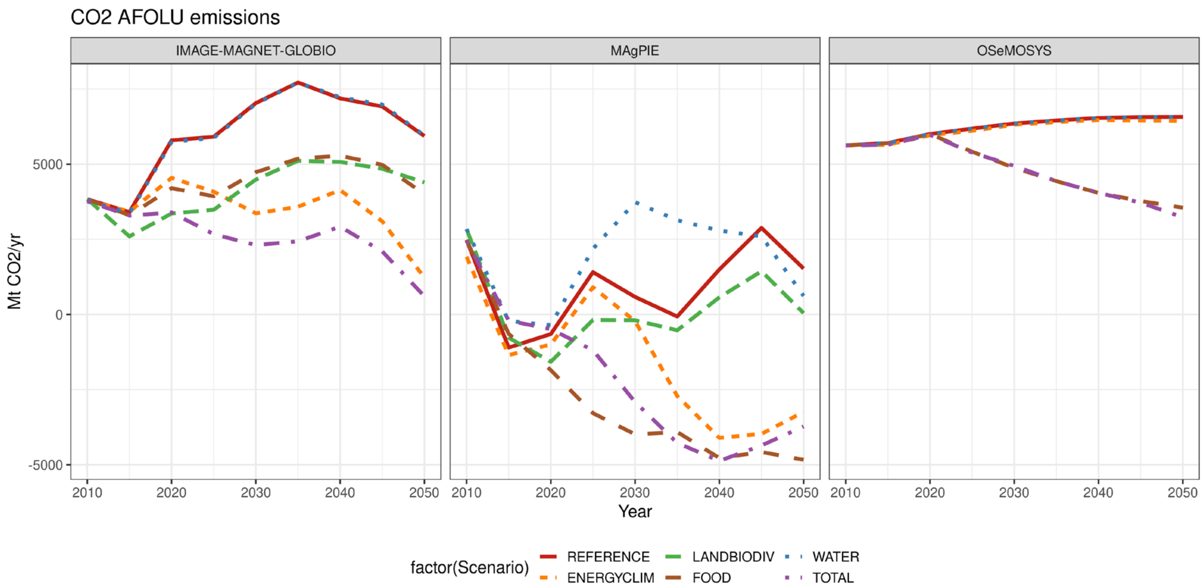

Figure 92. land-use and forestry CO2 emissions.

Figure 93 shows water withdrawals for irrigation from MAgPIE, IMAGE-MAGNET-GLOBIO and OSeMOSYS. The absolute level is quite different due to different assumptions on the availability of groundwater. It is clear to see that the water and total scenario result in major reductions in water withdrawal due to limited irrigation, higher efficiency and restrictions on the amount of water that can be withdrawn to ensure the quality of aquatic biodiversity.

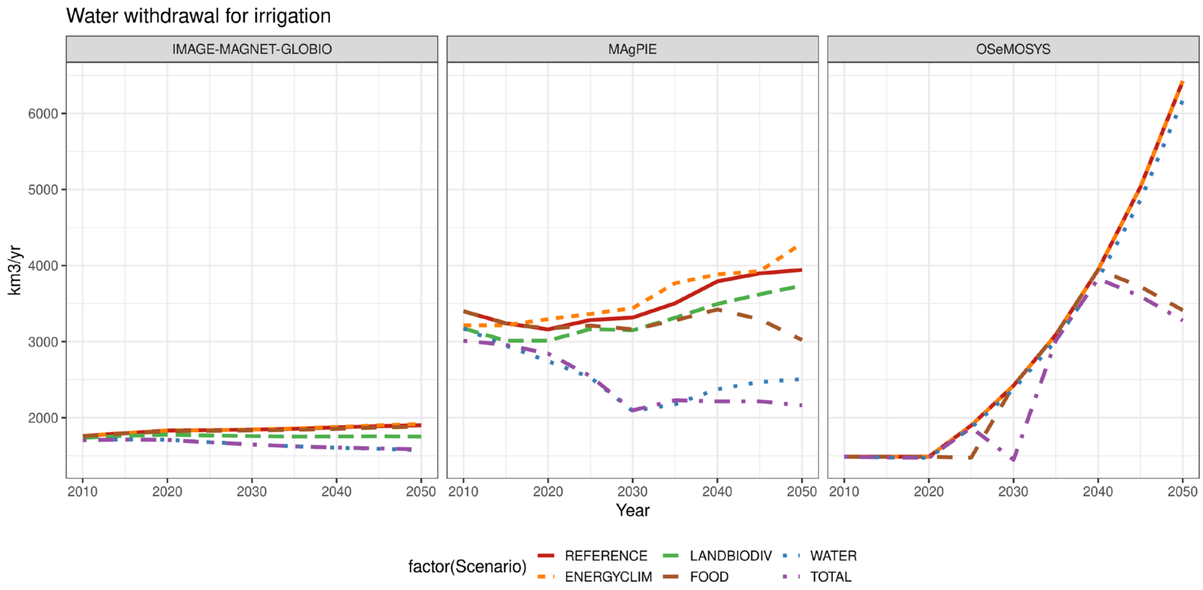

Figure 93. water withdrawal for irrigation.

Figure 94 shows the nitrogen concentration at the river mouths aggregated to the level of eight world regions in the reference and the water scenario from the IMAGE-MAGNET-GLOBIO model. It is clear that some regions have substantially higher absolute levels of nitrogen concentration indicating lower water quality, notably Middle East and Northern Africa, and Eastern Asia. The measures taken in the water scenario such as increased fertilizer efficiency and improved water waste management result in a substantial reduction in nitrogen concentrations indicating an improvement in water quality.

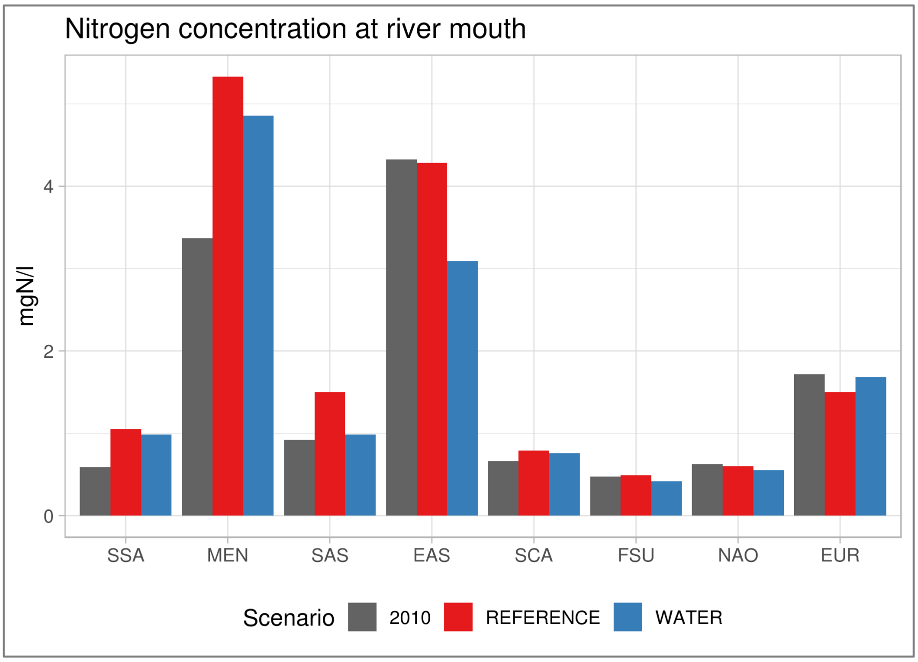

Figure 94. water quality indicator of the nitrogen concentration at the mouth of rivers in the eight world regions of the global case from the IMAGE-MAGNET-GLOBIO model..

4.12.4 Concluding remarks on the application of thematic models

The work performed in the global case study is entirely based on the thematic models. The scenarios developed in the global case and presented in this deliverable provide an explanation of the approach taken and preliminary results. Deliverable 5.5 will go more in depth in the analysis of these scenarios to identify and quantify synergies and trade-offs of the various nexus sectors and related sustainable development goals.

5 Concluding remarks

The objective of the Deliverable is to report on the results of application of the thematic models to each SIM4NEXUS case study. The thematic models use different spatial and temporal scales; some of them can be applied globally while others can only be applied at national, regional or river basin scale. Also, each thematic model covers one or more sectors, but no one is able to cover all the domains of the nexus. By applying a combination of thematic models to each case study, the relevant nexus interlinkages can be analysed. Moreover, the report allows for comparability of results in each case study.

The results from those models offered opportunities to analyse the different domains of the Nexus in much more detail in a more integrated way as compared to a situation in which the analysis is only based on observed data. The analysis of the results from these models also allowed us to reflect on the emergence of conflicts or synergies between the different domains of the Nexus.

Finally, the output from the thematic model provide a suitable basis for the further steps towards developing the SDM and the Serious Game.

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Appendix A: Model Description

Baseline and 2°C scenarios – Additional assumptions for the Land sector

	Grand Est (GE)	Baden-Württemberg (BW)
Share of total utilized agricultural area (UAA) dedicated to energy crops	Crops for biofuel: 3.41% in 2012 (Agrex consulting, 2013)	- Energy crops: 8.2% (in 2011)[7] - Silage maize for biogas: 5.9% (or 83.000 ha in 2011)[8] - Rape: 50%[9]
Relative share of bioethanol, in total energy biomass production	2.7% of UAA in 2012 (Agrex consulting, 2013)	12% of UAA dedicated to crops for biofuel (Agrex consulting, 2013)
Relative share of biodiesel in total energy biomass production	0.71% of UAA in 2012 (Agrex consulting, 2013)	87% of UAA dedicated to crops for biofuel (Agrex consulting, 2013)
Relative share of biodiesel in total energy biomass production		
Crop-specific share in the production of biodiesel	- Rape: 75%[10] - Sunflower: 3.7%[11]	Mainly rape[12]
Crop-specific share in the production of bioethanol	- Sugar beet (37%) - Wheat (42%) - Maize (18%) (Agrex consulting, 2013)	- Sugar beet (35.4%) - Wheat (29.5%) - Rye (21%) - Maize (5%) (Agrex consulting, 2013)

Baseline and 2°C scenarios – Additional assumptions for the Water sector

Upscaling of SWIM results:

The SWIM model covering only a part of the CS area, results for groundwater recharge and discharge variables as well as actual evapotranspiration and runoff (except for the Rhine system) were upscaled simply using the ratio of the CS area covered by SWIM to the actual CS area[13] (results Grand Est and Baden-Württemberg regions were upscaled separately).

Restructuring of SWIM results:

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[7] https://www.foederal-erneuerbar.de/landesinfo/bundesland/BW/kategorie/top+10

[8] https://www.foederal-erneuerbar.de/landesinfo/bundesland/BW/kategorie/top+10

[9] http://www.pflanzenforschung.de/biosicherheit/basisinfo/272.speiseoel-futtermittel-biodiesel.html

[10] https://www.ecologique-solidaire.gouv.fr/biocarburants

[11] https://www.ecologique-solidaire.gouv.fr/biocarburants

[12] http://www.pflanzenforschung.de/biosicherheit/basisinfo/272.speiseoel-futtermittel-biodiesel.html

[13] Ex : Aquifer recharge(Grand Est) = Aquifer recharge(SWIM_Rhine_FR)*(area(Grand Est)/area(SWIM_Rhine_FR))

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)[14].

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 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.

Additional energy scenarios

Table 14 : Energy policy cards selected for the Upper Rhine CS

Policy intervention	Implementation in E3ME
Improve energy efficiency of 5%/10%/20% of dwelling places through a subsidy	Exogenous reduction in energy consumption. Increase in expenditure on energy efficiency goods.
Increase the share of private electric vehicles through a subsidy	Decrease in the cost of a car
Support the deployment of wind-energy	Subsidy, feed in tariff or direct regulation
Support the deployment of PV	Subsidy, feed in tariff or direct regulation
Support the deployment t of electricity generation from biogas	Subsidy, feed in tariff or direct regulation
Command 10%/20%/50% of biofuels in total energy use in the transport sector	Biofuel mandates
Ban on fossil fuels for electricity generation	Regulation, phase out fossil fuel
Decrease the share of nuclear in the energy mix by 10%/25%/50%	Regulation, Setting electricity capacity to a certain maximum in a certain year.
Ban on nuclear power	Regulation, Setting electricity capacity to a certain maximum in a certain year.
5%/10% Increase in the price of electricity	Increase in domestic tax rates
5%/10% Increase in the price of natural gas	Increase in domestic tax rates
5%/10% tax on fossil fuels	Energy or carbon tax on top of ETS

SWIM results for flows coming in and out of the groundwater table were upscaled separately for Grand Est and Baden-Württemberg and finally added. Ex : Aquifer recharge (Grand Est+Baden Württemberg) = aquifer_recharge(Grand Est) + aquifer_recharge(Baden Württemberg).