GoNEXUS
Tools and solutions for governing the nexus

Deliverable D3.2: Global and continental scale interconnected WEFE model setup and baseline scenario

WP3

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Deliverable D3.2: Global and continental scale interconnected WEFE model setup and baseline scenario

Lead by E3M

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Abstract

This deliverable describes, per global and continental model, the interlinkages performed with the rest of models involved. It also includes the baseline scenarios run for them as well as a summary of their results. This deliverable is the main outcome of Task 3.2 and provides input for Tasks 3.3, 3.4, 5.2 and 5.3.

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Version History

Version	Date	Authors	Description
V0.1	09/11/2022	Kristina Govorukha (E3M)	Very first draft meant to guide the global modelling groups sharing model setup and defining the baseline scenario
V0.2	29/03/2022	Kristina Govorukha (E3M)	Changes to the chapters 1 and 3: Baseline scenario description – adding Tier 1 and 2 scenario assumptions' templates
V0.2.1	29/06/2022	Marc F. P. Bierkens (UU); Maria Blanco (UPM); Imen Arfa (UPM); Hylke Beck (JRC); Berny Bisselink (JRC); Kostas Kavvadias (E3M); Kristina Govorukha (E3M), Zoi Vrontisi (E3M), Dimitris Fragkiadakis (E3M), Panagiotis Fragkos (E3M); Aafke Schipper (PBL)	Chapter 2; model protocol revision. Chapter 4: dedicated model reports.
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V0.3	15/07/2022	Kostas Kavvadias (E3M), Kristina Govorukha (E3M)	Final comments and revision. Submission for internal revision.
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V1.0	25/07/2022	Kristina Govorukha (E3M)	Final comments and revision. Submission for internal revision.

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List of Acronyms

CMIP	Common Management Information Protocol
COP	Conference of the Parties
CS	Case Study
D	Deliverable
EEA	European Environment Agency
ETS	Emissions Trading System
FAO	Food and Agriculture Organization
GDP	Gross domestic product
IAM	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre - European Commission
LUISA	Land-Use based Integrated Sustainability Assessment modelling platform
RCP	Representative Concentration Pathways
RED	Renewable Energy Directive
SSP	Shared Socioeconomic Pathways
WEFE	Water-Energy-Food-Environment
WFD	Water Framework Directive

1 Introduction

In order to simulate the current and future WEFE nexus at the global scale, GoNEXUS has been set up with the following models: water model PCR-GLOBWB, the global energy system model PROMETHEUS, the agriculture and food model CAPRI, the biodiversity model GLOBIO, and the economic model GEM-E3. At the continental (European) scale, GoNEXUS will assess the WEFE using the integrated water resource and crop model LISFLOOD-EPIC, the European energy system model PRIMES, CAPRI (global but with higher resolution for the Europe), and biodiversity model GLOBIO for Europe.

These models will provide simulations of future trajectories of the WEFE nexus combining the global and European scale. The interconnections made between the global models and continental models will provide simulations of the different elements of the WEFE embedded in the global macro-economic context (GEM-E3), focusing on the interconnections between Water (PCR-GLOBWB, LISFLOOD-EPIC), Energy (PRIMES, PROMETHEUS), Food (CAPRI) and Ecosystems (GLOBIO).

Simulations consist of two set of runs:

- the first scenario runs (Tier 1), standalone model runs forced with SSP-RCP scenarios are based on common inputs from WP2. Some models have already utilized the links between the models at this step, see Table 1;
- the second scenario runs (Tier 2), the global and European scale models utilise the new interlinkages identified in the Deliverable 3.6. The interlinkages are presented in the Table 2.

Table 1- Model interlinkages utilised for TIER 1 runs

To: / From:	PCR-GLOBWB/ LISFLOOD-EPIC	CAPRI	PRIMES	GEM-E3	PROMETHEUS	GLOBIO
PCR-GLOBWB/ LISFLOOD-EPIC						x
CAPRI						
PRIMES				x		
GEM-E3			x		x	
PROMETHEUS				x		
GLOBIO						

Tier 1 runs. At the preparation step for the first scenario runs, some models utilised the interlinkages. Global and European scenario frameworks were harmonised between the energy model PRIMES, the global energy model PROMETHEUS and general equilibrium model GEM-E3. GLOBIO and LISFLOOD models shared the common information on river dam locations, water temperatures and discharge. Tier 1 runs were essential to analyse and evaluate the potential interlinkages between the models: including data exchange, its formats, common definitions and preprocessing requirements.

Tier 2 runs. Based on the Tier 1 runs, interlinkages between the models have been analysed and agreed between the modelling teams (see Table 2). Linkages between the models are complex and are not limited to the data exchange. Implementation of the links requires introduction of the model improvements and data preprocessing.

Table 2 - Model interlinkages planned for TIER 2 runs

To: / From:	PCR-GLOBWB/ LISFLOOD-EPIC	CAPRI	PRIMES	GEM-E3	PROMETHEUS	GLOBIO
PCR-GLOBWB/ LISFLOOD-EPIC		x	x		x	x
CAPRI	x		x			
PRIMES	x	x		x		
GEM-E3			x		x	
PROMETHEUS	x			x		
GLOBIO						

The deliverable is organised as follows. Chapter 2 presents the detailed protocol of model interlinkages, including: parameters delivered to other models, as well as parameters received from other models, and information on the availability of the data and its access. Chapter 3 provides the definition of the scenarios used in the project, as well as details on the Baseline scenario, the core of this deliverable. Chapter 3 and 4 provide the description of the Baseline scenario in sections dedicated to each model and focusing on the core expertise of the modelling.

Links and dependencies on other deliverables in the pipeline. The setup of the global models and interlinkages is reported in D3.6. The global scenario definitions are reported in D2.1. The policy relevant WEFE scenarios are presented in D2.3. The current deliverable focuses on the *Baseline Scenario*. This deliverable collects the protocols on the data exchange between the models and presents the results of the coupled *Baseline Scenario*, which will be used as a baseline case for the policy and solutions runs in task 3.4. The policy and solutions run focus on the European scale (LISFLOOD-EPIC, PRIMES, CAPI, GLOBIO), and where necessary refer to globally applicable measures (PCR-GLOBWB, PROMETHEUS, CAPRI, GLOBIO, GEM-E3).

The work on the development of the new interconnections between the individual global models and continental scale models for the simulations of the different elements of the WEFE has two main steps:

1. Tier 1 for global and European scale, as well as policy scenarios, have been uploaded in the data server YODA or documented the data access if output data is available via other platforms. Global and continental model setup has been/ will be described in deliverables 3.1, 3.4 and 3.6. The interlinkages between the models are being proved. The *Baseline Scenario* is defined, enabling the interpretation of the WEFE nexus at the global and continental level.
2. The interlinked global and European scale models Tier 2 runs are/will be uploaded to YODA. The detailed assessment of the *Baseline Scenario* run of the interlinked model setup that includes the model improvements.

2 Global and continental model interlinkages: protocol

2.1 Protocol description

For the development of the *Baseline Scenario*, it was necessary to incorporate the results of the global models into the continental scale models. Global WEFE groups should ensure that their Tier 1 results are available on the continental scale and are shared through YODA. The interlinkages below are utilized for the interconnected Tier 2 runs used for the Baseline and Policy scenarios. The following procedure is suggested:

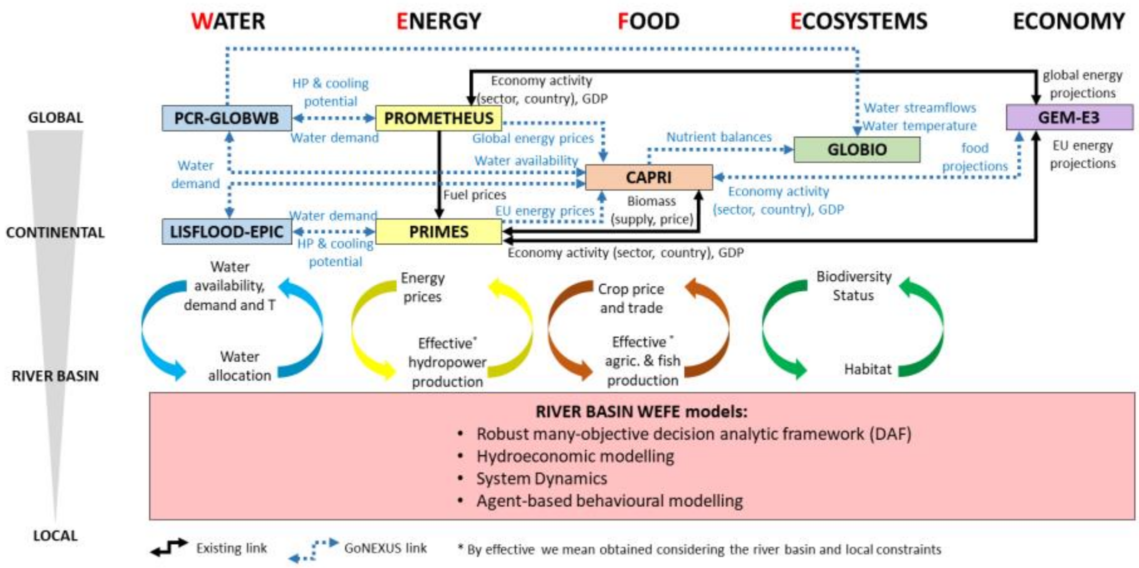


Figure 1 - GoNEXUS' Model Toolbox and model interlinkages

1. The global and continental scale model groups provide the following information to the WP3:
    a. a shapefile at the continental scale (Europe) (and or a lat-lon grid of the centre coordinates of the model cells);
    b. meta-info about models (grid size, time step, type of processes modelled etc)
2. The global modelling groups provide information (via a link to a repository such as YODA) to the continental model groups. The first data exchange between the global and continental model groups is based on the Tier 1 runs.
3. Global and continental-scale model results are integrated via the identified data interlinkages available from the D3.6.
4. The *Baseline Scenario* is developed using the results from interlinked global and continental scale model runs in the Tier 2.

data consistency: some models, the output table data is not identified in the input table of the target model (e.g., GEM-E2 -> CAPRI). Some data linkage is in progress and flags that it was considered but not implemented. agricultural water demand coming from CAPRI, PCR or GEM-E3 should be similar. n data exchange is agreed between the model, as format requirements may indeed differ between the models for the same parameter. I will add this to the introduction of the section 2 we focus on integrating model links, and comparison of model Tier 2 runs and results metrics will follow.

2.2 PCR-GLOBWB2/ LISFLOOD-EPIC

2.2.1 Description of outputs and interlinkages with other global and continental models

Table 3 - Model interlinkages and data delivered by PCR-GLOBWB/ LISFLOOD-EPIC to other models

From PCR-GLOBWB/ LISFLOOD-EPIC	**Format**					**To Model:**
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
Discharge (irrigated crops)	m^3s^{-1}	ncdf	Monthly	1979-2100	5 arc-minute	CAPRI
Groundwater pumping capacity for irrigation	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	CAPRI
Soil moisture content (rainfed crops	m^3 water pro m^3 soil	ncf	Monthly	1979-2100	5 arc-minute	CAPRI
Ea/Ep fraction (rainfed crops)	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	CAPRI
Effective precipitation	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	CAPRI
Discharge	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	PROMETHEUS/PRIMES
Surface water temperature	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	PROMETHEUS/PRIMES
Dam locations	Coordinates (m)	ncd	Yearly	1979-2100	5 arc-minute	GLOBIO
Discharge	m^3 m^{-2} $month^{-1}$	ncf	Monthly	1979-2100	5 arc-minute	GLOBIO
Surface water temperature	ºC	ncf	Monthly	1979-2100	5 arc-minute	GLOBIO

Note: Data from PCR-GLOBWB/ LISFLOOD-EPIC is available at YODA.

2.2.2 Description of the inputs from other global and continental models

Table 4 - Model interlinkages and data needs of PCR-GLOBWB/ LISFLOOD-EPIC from other models

To PCR-GLOBWB/ LISFLOOD-EPIC		**Format**		**Model**
Variables:	*unit*	*time resolution*	*spatial resolution*	
Crop area	ha	Annual	As available	CAPRI
Energy demand by sector - thermoelectric	Wh	Annual	As available	Prometheus/ PRIMES
Energy demand by sector - hydropower	Wh	Annual	As available	Prometheus/ PRIMES
Energy demand by sector – energy crops	Wh	Annual	As available	Prometheus/ PRIMES

2.3 CAPRI

2.3.1 Description of outputs and interlinkages with other global and continental models

Table 5 - Model interlinkages and data delivered by CAPRI to other models

From CAPRI	Format					To Model
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
Feedstock potential by feedstock type	t/yr	csv	[annual/2020 - 2050]	2020-2050	MS(NUTS0)	PRIMES
Crop area	Ha	csv	[annual/2020 - 2050]	2020-2050	MS(NUTS0)	PCR-GLOBWB
Crop yield	t DM/ha		[annual/2020-2070]	2020-2070	NUTS0	GEM-E3 PRIMES
Cultivated land (Starch crops, Oil crops, Sugar Crops, Annual Lignocellulosic crops, Perennial Lignocellulosic crops)	Ha	csv	[annual/2020 - 2050]	2020-2050	MS(NUTS0)	PRIMES

Data from CAPRI is available at YODA

2.3.2 Description of the inputs from other global and continental models

Table 6 - Model interlinkages and data needs of CAPRI from other models

To CAPRI		Format		From Model
Variables:	*unit*	*time resolution*	*spatial resolution*	
energy prices	Euro/toe	[annual/2020 - 2050]	[MS/NUTS0]	PRIMES
energy demand by sector	ktoe	annual, [2020-2050]	[MS/NUTS0]	PRIMES
domestic production of bioenergy	ktoe	annual, [2020-2050]	[MS/NUTS0]	PRIMES
domestic production of bioenergy	ktoe	annual, [2020-2050]	[MS/NUTS0]	PRIMES
fuel consumption in bioenergy production	ktoe	annual, [2020-2050]	[MS/NUTS0]	PRIMES
bioenergy consumption by sector	ktoe	annual, [2020-2050]	[MS/NUTS0]	PRIMES
irrigation water efficiency	coefficient	annual, [2020-2050]	National (NUTS0)	PCR-GLOBWB/ LISFLOOD-EPIC
Water use per sector	1000m3	annual, [2020-2050]	National (NUTS0)	PCR-GLOBWB/ LISFLOOD-EPIC
Water availability per source	1000m3	annual, [2020-2050]	National (NUTS0)	PCR-GLOBWB/ LISFLOOD-EPIC

2.4 PRIMES

2.4.1 Description of outputs and interlinkages with other global and continental models

The PRIMES model delivers the energy related variables for the EU to other global and continental level models, see Table 7.

Table 7 - Model interlinkages and data delivered by PRIMES to other models

From PRIMES	**Format**					**To Model:**
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
energy demand by sector	[ktoe]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	PCR-GLOBWB/ LISFLOOD-EPIC, GEM-E3
hydropower generation	[MWh]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	PCR-GLOBWB/ LISFLOOD-EPIC
hydropower installed capacity	[GW]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	PCR-GLOBWB/ LISFLOOD-EPIC
energy prices	[Euro/toe]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	CAPRI
domestic production of bioenergy [1]	[ktoe]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	CAPRI
fuel consumption in bioenergy production	[ktoe]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	CAPRI
bioenergy consumption by sector	[ktoe]	[csv]	[annual, hourly]	[2015-2070]	[NUTS0]	CAPRI
[1] incl. bio-solids, biogas, biofuels						

Note: Data from PRIMES is available at YODA.

Among the outputs for other models, for the *Baseline Scenario* PRIMES model delivers the following outputs (including model improvements noted in the D3.6):

- Hydropower generation and capacity hydropower (including run of river (RoR) and pumped storage)
- Water withdrawal for cooling for thermal power plants
- Water consumption for cooling for thermal power plants

2.4.2 Description of the inputs from other global and continental models

For the development of the Baseline Scenario, PRIMES relies on the outputs of other global level (GEM-E3, PROMETHEUS, PCR-GLOBWB) and continental models (LISFLOOD-EPIC).

Table 8 - Model interlinkages and data needs of PRIMES from other models

To PRIMES **Variables:**	**Format**			**From the Model**
	unit	*time resolution*	*spatial resolution*	
Cultivated land (Starch crops, Oil crops, Sugar Crops, Annual Lignocellulosic crops, Perennial Lignocellulosic crops)	[ha]	[annual/2020 - 2070]	[grid/MS]	CAPRI
Feedstock potential by feedstock type	[t/yr]	[annual/2020 - 2070]	[grid/MS]	CAPRI
Energy inputs per input type, per feedstock type, where applicable	[toe/t]	[annual/2020 - 2070]	[grid/MS]	CAPRI
River discharge	[m3/yr]	[annual/2020 - 2070]	[grid/MS]	LISFLOOD/LISFLOOD-EPIC
Water temperature	[degC]	[annual/2020 - 2070]	[grid/MS]	PCR-GLOBWB
EU economic activity (GDP and sectoral production)	[Euro]	[annual/2020 - 2070]	[MS]	GEM-E3
Global energy prices	[Euro/toe]	[annual/2020 - 2070]	[Europe]	PROMETHEUS

2.5 GEM-E3

2.5.1 Description of outputs and interlinkages with other global and continental models

Table 9 - Model interlinkages and data delivered by GEM-E3 to other models

From GEM-E3	**Format**					**To Model:**
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
GDP|MER (EU level)	[Euro]	[csv]	[5-year period]	[2015-2070]	[NUTS0]	CAPRI, PRIMES
GDP|MER (Global level)	[Euro]	[csv]	[5-year period]	[2015-2070]	[NUTS0]	CAPRI
Expenditure|Household	[Euro]	[csv]	[5-year period]	[2015-2070]	[NUTS0]	CAPRI
Expenditure|Household|Food	[Euro]	[csv]	[5-year period]	[2015-2070]	[NUTS0]	CAPRI

Note: Data from GEM-E3 is available at YODA.

2.5.2 Description of the inputs from other global and continental models

Table 10 - Model interlinkages and data needs of GEM-E3 from other models

To GEM-E3		**Format**		**From Model**
Variables:	*unit*	*time resolution*	*spatial resolution*	
Crop yield	t DM/ha	[annual or 5- year period/2020-2070]	[NUTS0]	CAPRI
Water Requirements per activity	Km3	[annual or 5- year period /2020-2070]	[NUTS0]	CAPRI
Energy demand by sector	[ktoe]	[5-year period/2020-2070]	[EU MS]	PRIMES
Fuel consumption by sector	[ktoe]	[5-year period/2020-2070]	[EU MS]	PRIMES
Fuel prices	[Euro/toe]	[annual or 5- year period /2015-2070]	[NUTS0/ Global]	PROMETHEUS

2.6 PROMETHEUS

2.6.1 Description of outputs and interlinkages with other global and continental models

The PROMETHEUS model delivers the energy related variables at the global and regional level to other global and continental level models, see Table 11.

Table 11 - Model interlinkages and data delivered by PROMETHEUS to other models

From PROMETHEUS	**Format**					**To Model:**
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
energy demand by sector (domestic, manufacturing industry, transport)	[ktoe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	PCR-GLOBWB/ LISFLOOD-EPIC
energy mix: energy crops need, hydropower needs	[ktoe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	PCR-GLOBWB/ LISFLOOD-EPIC
global energy prices for oil, gas and coal	[Euro/toe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	CAPRI
energy prices	[Euro/toe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	GEM-E3
energy demand by sector	[ktoe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	PRIMES
energy production by source	[ktoe]	[csv]	[annual, hourly]	[2015-2050]	[NUST0]	PRIMES

Note: Data from PROMETHEUS is available at YODA.

2.6.2 Description of the inputs from other global and continental models

For the development of the Baseline scenario, PROMETHEUS relies on the outputs of other global level models (GEM-E3, PCR-GLOBWB).

Table 12 - Model interlinkages and data needs of PROMETHEUS from other models

To PROMETHEUS Variables:		Format		Model
	unit	*time resolution*	*spatial resolution*	
EU and global economic activity (GDP and sectoral production)	[Euro]	[annual/2020 - 2070]	[NUST0]	GEM-E3
Water use for thermal power generation	[m³/MWh]	[annual/2020 - 2050]	[Global regions]	LISFLOOD

2.7 GLOBIO

2.7.1 Description of outputs and interlinkages with other global and continental models

Table 13 - Model interlinkages and data delivered by GLOBIO to other models

From GLOBIO	Format					To Model:
Variables:	*unit*	*data format*	*time resolution*	*time horizon*	*spatial resolution*	
Potentially lost range (PLR) per freshwater fish species	%	csv	2021-2040; 2041-2060	2030; 2050	5 arc-min	[tba]
Potentially affected fraction (PAF) of species	Dimensionless (0-1)	csv	2021-2040; 2041-2060	2030; 2050	5 arc-min	[tba]NA

Note: Data from GLOBIO is available at YODA.

2.7.2 Description of the inputs from other global and continental models

Table 14 - Model interlinkages and data needs of GLOBIO from other models

To GLOBIO		Format		Model
Variables:	*unit*	*time resolution*	*spatial resolution*	
Maximum weekly water temperature	ºC	2021-2040; 2041-2060	5 arc-min	PCR-GLOBWB
Maximum weekly water temperature	ºC	2021-2040; 2041-2060	5 arc-min	PCR-GLOBWB
Maximum weekly streamflow	m^3/s	2021-2040; 2041-2060	5 arc-min	PCR-GLOBWB
Minimum weekly streamflow	m^3/s	2021-2040; 2041-2060	5 arc-min	PCR-GLOBWB
Number of zero-flow weeks	#	2021-2040; 2041-2060	5 arc-min	PCR-GLOBWB
Presence of dams	NA	Present and future	NA (point records) for lat/lon	GRaND, GOODD, FReHD (Tier 1); PCR-GLOBWB (Tier 2)

3 Baseline Scenario

3.1 Scenarios used in the project

The GoNEXUS projects a variety of scenarios to assess the WEFE nexus. The global climate scenarios are defined and reported in D2.1. The policy relevant WEFE scenarios and narratives are presented in D2.3. The following section defines the *Baseline Scenario*, that will be used as an outline for the dedicated policy scenarios. The results of the policy scenarios and their comparison to the Baseline will be presented in the D5.4

The *Reference Scenario* is used to define the historical periods. For most of the climate and impact models the historic period covers the timeframe form 1979 (1960) to 2019. The Reference scenario is used to assess changes in the future climate conditions relative to the historic period, simulations and comparison to the observations data. Comparison of Future Scenarios to the Reference Scenario, contributes to the understanding of the changes in climate and hydrologic conditions. Comparison to the real observation data allows to assess parametric and structural uncertainty related to the model design. An overview of climate, socio-economic and policy scenarios are discussed in the preparation of the Tier 1 and Tier 2 runs of the global and continental scale models is provided in Table 15.

Future Scenarios include the integrated assessment (IAM) models' scenarios for the period from 2015 (2020) to 2100 (2070) Table 15. The scenarios integrate representative concentration pathways (RCPs) with shared socioeconomic pathways (SSPs). RCPs are harmonized emission trajectories that align IAMs with climate models (van Vuuren et al., 2011). Land use and socioeconomic scenarios, driven by socioeconomic factors, are represented by SSPs (O'Neill et al., 2014). The integration of SSPs and RCPs provides a broad range of future climate projections and allows for more consistent and coherent modelling of climate impacts and policy analysis.

Table 15 - Summary of the scenarios used by GoNEXUS project models

1979 (1960) - 2019 Reconstructed land use and water demand								***Type***
Observed weather	*W5E5*							Validation
Climate	*GFDL-ESM4 IPSL-CM6A-LR MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL*							Reference
2015 (2020) – 2100 Projections								
Socio-economic scenarios, projected land use and water demand								
RCP2.6	*SSP1*							*Impact*
RCP7.0	*SSP3*							*Impact*
RCP8.5	*SSP5*							*Impact*
Identified policy relevant scenarios, availability for WEFE nexus projections								
Simulations	**Models**							
	CAPRI	GLOBIO	GEM-E3	LISFLOOD	PCR-GLOBWB2	PRIMES	PROMETHEUS	
Emissions neutrality (SSP1-1.9)								
Sustainable development (SSP1-2.6)	x	x	x		x	x	x	*Baseline (current policies)*
Weak cooperation (SSP3-7.0)	x				x			
The wrong way (SSP5-8.5)	x	x	x	x	x	x	x	*Baseline (net zero)*
Global risk (SSP5-8.5+)								

GoNEXUS obtained CMIP5 and CMIP6 scenarios from the Coupled Model Intercomparison Project (CMIP)[2]. The use of CMIP5 together with the scientific advance posed by CMIP6 and their explicit link with SSP scenarios allows for comprehensive analysis of the WEFE nexus at the global scale (O'Neill, 2016).

For the European Union, GoNEXUS will utilize land use and socioeconomic scenarios from the Land-Use based Integrated Sustainability Assessment (LUISA)[1] modelling platform developed by the Joint Research Centre (JRC). This platform is used by the European Commission to evaluate current EU policies. The population projections, as well as the economic activity projections are based on the available European statistics and projections.

The Future scenarios may include or not include the chosen SSP-RCP combinations, see policy scenarios in Table 15. The comparison of the runs with and without climate scenarios allows to illustrate the impacts of climate change on the food, water and energy availability (see for example, the dedicated chapter 4.4 for the CAPRI model).

3.2 The Baseline scenario description

The *Baseline Scenario* is used to compare alternative future projections, that include impact on the WEFE sectors under the projected climate conditions. This scenario is chosen to reflect expectations about the trends and patterns of the projected socio-economic conditions at the global level, and at European scale in reference to relevant EC policies (Green Deal and Fit-for-55 policy package, Common Agricultural Policy). The Baseline Scenario will be used to identify benefits of additional measures and polices, to mitigate the effects of climate change and changes in the water availability for WEFE dimensions. Since the effect of the policies and initiatives is to be compared to the existing policies (*current polici*es) and to the planned but not yet implemented policies (*net zero*), the Baseline Scenario covers two climate and socio-economic scenarios, from the available scope of policy relevant scenarios listed in the Table 15. For its running process, the following scenarios are proposed: Sustainable development (SSP1-2.6) as "net zero" scenario, and Weak cooperation (SSP3-7.0), as "current policies" scenario. The goal is to quantify the impact on the WEFE sectors and policies under the projected climate conditions. Global and European scale modelling teams are progressing to the implements model developments and integrate interlinkages. The availability of scenario runs is summarised in Table 15.

Sustainable Development: the scenario aims for net-zero global CO_2 emissions after 2050, with a projected temperature increase of approximately 1.8°C above pre-industrial levels by the end of the century. This scenario focuses on sustainable development and inclusive growth, driven by awareness of environmental and social costs. It envisions reduced inequality, improved well-being, and modest population growth. A global trend towards eliminating import tariffs and export subsidies will favour regional agricultural products. The scenario presents low adaptation challenges and intermediate mitigation challenges.

At the European level, policies will promote renewable energy, reducing greenhouse gas emissions, and improving water efficiency to secure water resources. Strategies like Farm to Fork and organic farming will mitigate environmental impacts, protect biodiversity, and ensure food security. Research will enhance crop yields and minimize food waste, supporting the EU Biodiversity Strategy. The EU Green Deal and underlying policy packages are on track to deliver the EU Net Zero emissions target in 2050.

Weak Cooperation: the scenario depicts a fragmented world where national security is prioritized over sustainable development, leading to increased greenhouse gas emissions and a projected 3.6°C rise in global temperatures by 2100. This scenario is marked by economic and geopolitical tensions, hindering international cooperation and climate change mitigation. Developed regions experience rapid growth, while developing countries face slow growth and high population increases, resulting in income disparity and extreme poverty.

[1] https://data.jrc.ec.europa.eu/collection/luisa

Agriculture remains intensive, with crop yield and irrigation efficiency rising only with GDP, while livestock productivity stagnates. Consumption of animal products and food waste continues as usual, and protected areas for land use remain unchanged. Unsustainable agricultural practices reduce ecosystem services, affecting yields and efficiencies.

Water scarcity and insecurity worsen due to high population growth, increased water use, and more frequent droughts. Economic activity remains tied to high energy demand, with a preference for carbon-based technologies and slow adoption of renewable energy. The scenario presents high challenges for mitigation and intermediate challenges for adaptation, with growing resource intensity, fossil fuel dependency, environmental degradation, and slow technological progress.

At the European level, policies and activities directed to promote renewable energy, reduction of greenhouse gas emissions, and improvement of water efficiency are limited to the current policies landscape. The 2050 emissions reduction target is not met, and near term 2030 targets for renewable energy and energy efficiency are not met.

The following sections present the models' dedicated sections that describe the Baseline Scenario developments in the context of the chosen scenarios, as well as details on the utilised interlinkages between the models.

4 Model-based Baseline scenario results

Below each model defines specific assumptions about the implementation of the *Baseline Scenario*.

4.1 PCR-GLOBWB2 – Global scale Baseline scenario and results

Tier 1 scenarios have been prepared with inputs obtained from the ISI-MIP3b experiment (https://www.isimip.org/protocol/3/) extended with socioeconomic scenarios derived from the IMAFE3 model. These are the combinations SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5. Meteorological forcing comes from the 5 ISI-MIP CMIP6 model selected (GFDL-ESM4 IPSL-CM6A-LR MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL). These are bias-corrected and downscaled results at 5 arcminute resolution with the following variables at daily scale and over the period 1979-2100: precipitation, 2m atmospheric temperature and reference crop potential evapotranspiration. The latter is computed based on temperature, relative humidity, net radiation and wind speed. The socioeconomic scenarios include yearly maps of land use and land cover (including crops), domestic and domestic livestock and industrial water demand, the latter split into manufacturing and cooling (including powerplants).

Tier 2 scenarios differ from Tier 1 by the model interlinkages. The following variables are taken from the other GONEXUS models and are replacing other sources used in Tier 1 (e.g. IMAGE model): changes in crops (CAPRI); energy demand by sector needed for sectoral water demand calculations (Prometheus); demand for hydropower needed to include future dams following Gernaat et al (2017) (Prometheus), demand for thermo-electric power, needed to extent the cooling water use in the temperature modelling following Jones et al. (2023) (Prometheus). The Tier 2 scenarios are done for the following combinations: SSP1-RCP2.6 (emission neutrality) and SSP3-RCP7.0 (weak cooperation).

4.2 LISFLOOD-EPIC – EU scale Baseline scenario and results

For the Tier 1 simulations, LISFLOOD simulations were performed at 5 × 5 km^2 resolution grid over the extended European domain, which includes all the EU countries, as well as some neighbouring ones such as Albania, Bosnia Herzegovina, Iceland, Moldova, Montenegro, North Macedonia (FYROM), Norway, Serbia, and Switzerland at a daily time step.

The LISFLOOD water resources model is forced with two (RCPs): RCP4.5 and RCP8.5. The first one may be viewed as a moderate-emissions-mitigation-policy scenario and the second one as a high-end emissions scenario. For each RCP an ensemble of 11 EURO-CORDEX combinations of Global Climate Models (GCM) and Regional Climate Models (RCM) were used (Jacob et al., 2014) up to 2100 (Table 16). The reference scenario spans the period 1981-2010.

In LISFLOOD, the future projections of land use in Europe are derived from the LUISA modelling platform (Jacobs-Crisioni et al., 2017). LUISA translates socio-economic trends and policy scenarios into processes of territorial development. Among other things, it allocates (in space and time) population, economic activities and land use patterns which are constrained by biophysical suitability, policy targets, economic criteria, and many other factors. Except from the constraints, LUISA incorporates historical trends, current state and future projections to capture the complex interactions between human activities and their determinants. Key outputs of the LUISA platform are fine resolution maps (100m) of accessibility, population densities and land-use patterns covering all EU member states and the United Kingdom, Serbia, Bosnia Herzegovina and Montenegro until 2050 as described in WP2. For this reason, LISFLOOD is not forced with SSP socio-economic scenarios.

Table 16 - Climate projections used for Tier 1 and Tier 2 simulations.

	Institute	GCM	RCM	Tier 1	Tier 2
1	CLMcom	CNRM-CM5	CCLM4-8-17	X	
2	CLMcom	EC-EARTH	CCLM4-8-17	X	X
3	IPSL	IPSL-CM5A-MR	INERIS-WRF331F	X	X
4	SMHI	HadGEM2-ES	RCA4	X	
5	SMHI	MPI-ESM-LR	RCA4	X	
6	SMHI	IPSL-CM5A-MR	RCA4	X	
7	SMHI	EC-EARTH	RCA4	X	
8	SMHI	CNRM-CM5	RCA4	X	X
9	DMI	EC-EARTH	HIRHAM5	X	X
10	KNMI	EC-EARTH	RACMO22E	X	X
11	CLMcom	MPI-ESM-LR	CCLM4-8-17	X	X

Water demand in LISFLOOD consists of five components from which in Tier 1, the irrigation water demand is estimated dynamically within the model only based on climate conditions. The other four sectorial components are used as input data. These are (manufacturing) industrial water demand, water demand for energy and cooling, livestock water demand and domestic water demand. In general, water use estimated for these four sectors are derived from mainly country-level data (EUROSTAT, AQUASTAT) with different modelling and downscaling and regression techniques for future projections.

For the Tier 2 simulations both the climate forcing and socio-economic data are similar to Tier 1, but we modified LISFLOOD by dynamically integrating the EPIC crop growth module (LISFLOOD-EPIC; Task 3.1) to obtain more realistic estimates of irrigation water abstractions.

CAPRI

For the interlinkage between the models, we used a scenario of the crop distribution from the CAPRI model, which reflect a business-as-usual scenario with the current CAP and no climate change for 2020, 2030, 2040 and 2050. The irrigated area map from Wriedt et al. (2009) is used to distinct the CAPRI crop distribution between irrigated and rainfed agriculture.

For validation, a simulation with LISFLOOD-EPIC under current weather forcing for 2010 is performed including the CAPRI crop distribution of 2020. The year 2010 is used due to the availability of reported abstraction values (Farm Structure Survey, 2010). In Figure 2 the annual water abstraction for irrigation in LISFLOOD (Figure 2a) and the crop-specific water abstraction for irrigation in the modified LISFLOOD-EPIC including the CAPRI crop distribution (Figure 2b) is shown. A large increase in water abstraction for irrigation in the countries around the Mediterranean Sea is observed in the LISFLOOD-EPIC simulation compared to the LISFLOOD simulation. For validating these results, Figure 3presents the simulated water abstractions for irrigation with LISFLOOD (Figure 3a) and LISFLOOD-EPIC (Figure 3b) against reported values aggregated for NUTS2 regions.

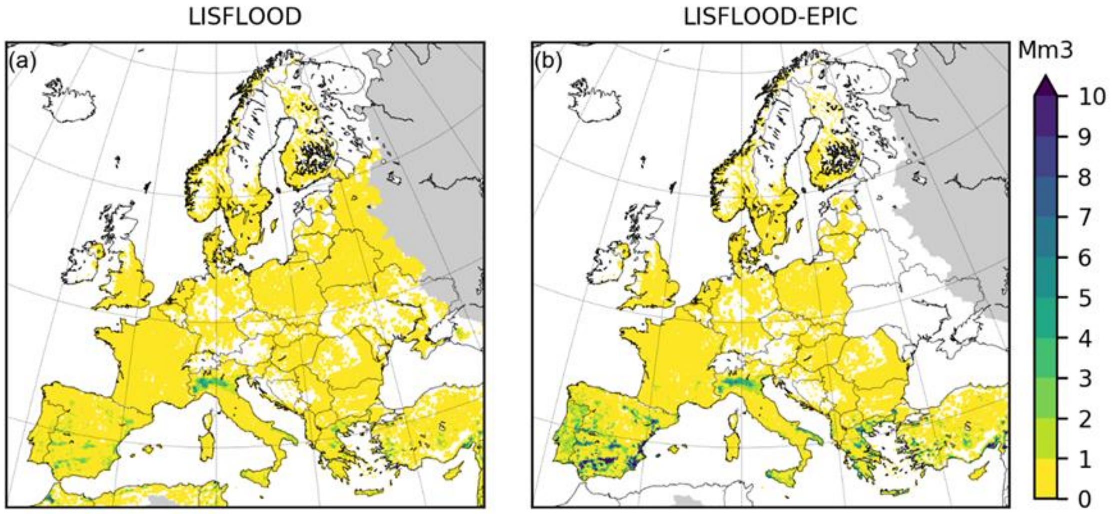


Figure 2 – Water abstraction for irrigation (Mm3) simulated with a) LISFLOOD and b) LISFLOOD-EPIC for the year 2010. LISFLOOD is used for the Tier 1 simulations and LISFLOOD-EPIC for the Tier 2 simulations.

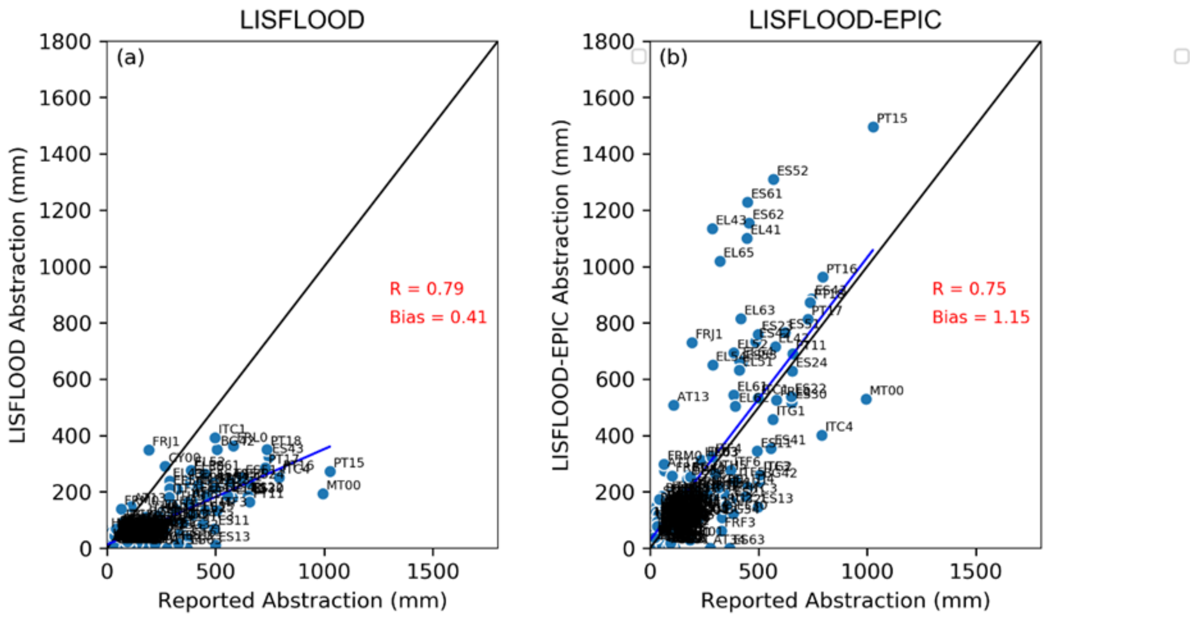


Figure 3 - Simulated water abstraction for irrigation for 2010 compared with reported values for a) LISFLOOD and b) LISFLOOD-EPIC.

The water abstractions for irrigations simulated with LISFLOOD are underestimated compared to the reported values (Figure 3a), while the simulated abstraction in LISFLOOD-EPIC shows an improvement in the bias compared with the reported values. In some of the NUTS2 regions in Spain, Portugal and Greece the simulated abstraction is overestimated compared to the reported values or under-reporting occurred in these regions.

PRIMES

For the Tier 2 simulations, the annual total water withdrawals and water consumption from solid, gas fired and nuclear power plants from PRIMES are taken to fulfil the energy demand up to 2070. As the PRIMES output is at country scale, we used the EC Energy Reference Scenario 2016 for projected fresh water use from the European energy sector (Medarac et al., 2018) disaggregated from country to NUTS2 level as a starting point. The projections are then estimated by the water withdrawals and consumption factors for every 5 years up to 2070 from PRIMES. The water withdrawals and consumption of 2006 (downscaled EUROSTAT, AQUASTAT country statistics), which are used as input for the Tier 1 simulations, are compared with the computed values of 2020 based on PRIMES ratios. Large differences are observed between the water withdrawals (Fig. 4a) and consumption (Fig. 4b) of 2006 and 2020. Note that the water consumption is a small fraction from the water withdrawals in the energy sector, and moreover a small fraction compared to the water consumption for irrigation (not shown).

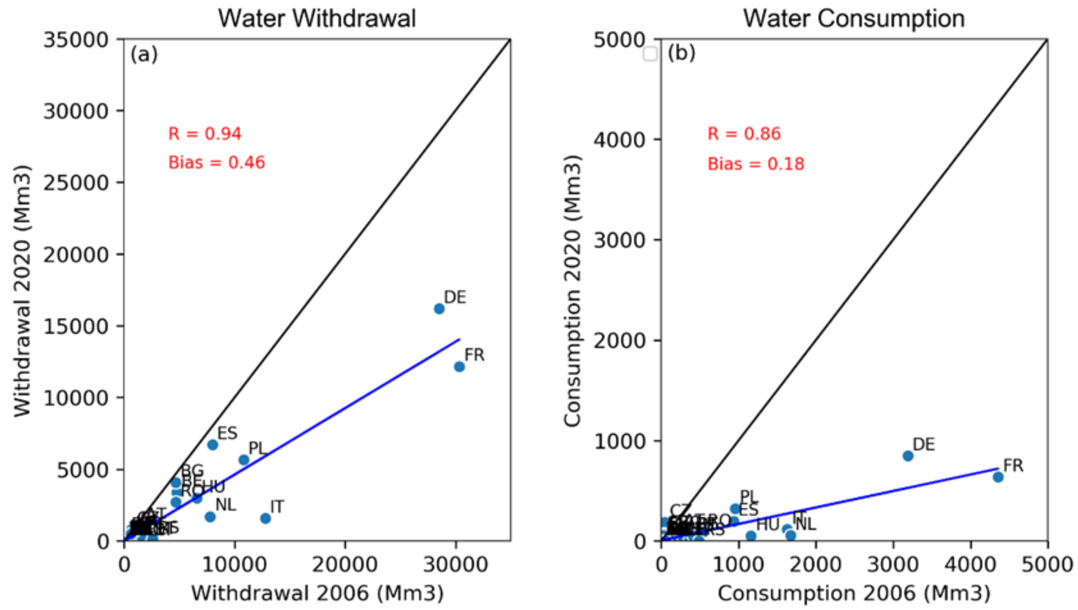


Figure 4 – Comparison of a) water withdrawal and b) water consumption between 2006 (used in Tier 1) and 2020 (used in Tier 2).

The Tier 2 simulations with LISFLOOD-EPIC includes CAPRI crop distribution according the business-as-usual scenario with the current CAP and no climate change, and PRIMES Current Policy scenario. The simulations are performed for 6 EURO-CORDEX combinations of GCMs and RCMs for RCP4.5 and RCP8.5 (Table 16) instead of the 11 models used for Tier 1 due to the heavy computational time using the EPIC crop growth module.

The impact on water resources using the WEFE Nexus approach by implementing agricultural and energy demand in Tier 2, and the resulting WEFE Nexus Evidence are presented in D5.4.

4.3 PRIMES

4.3.1 PRIMES – EU scale Baseline scenario implementation

The scenarios developed with PRIMES model were designed for the Tier 1 runs and represent the Current Policies and Net Zero scenarios. Scenarios have been calibrated to the available EU statistics for 2010 to 2020 reference years, and future projections from 2025 to 2070 with five-year steps.

PRIMES is a large-scale energy system model for the EU, UK as well as 10 non-EU countries including the EFTA countries Norway, Switzerland and Iceland.

For Tier 1 scenarios, PRIMES model does not use climate data directly. For the projections on agriculture, forestry, biomass potential PRIMES energy system model relies on the data provided by biophysical models.

Tier 2 runs: Tier 1 scenarios for the energy sector have been developed with respect to the available statistics and projections at the level of EU and its member states. Projections for the aggregate GDP of EU countries are based on the Ageing Report, European Commission (2021). For the period 2020 to

2050, EU population projections are based on the European Population Projections, base year 2019 (EUROPOP 2019). The population projections and GDP projections are compatible due to their common starting point. The following interlinkages with the global models on socio-economic assumptions are utilised for the Tier 1 scenarios:

- PRIMES model is interlinked with the GEM-E3 model, to harmonise the framework assumptions as population growth and GDP, as well as sector specific added value and industrial activity levels.
- PRIMES model is interlinked with the PROMETHEUS model, to harmonise the framework assumptions about the international fuel prices.

In the Tier 1, preliminary modifications to the PRIMES model were introduced to assess the needs for water consumption and withdrawal by thermal power plants. These preliminary results were shared with the project partners and compared with the Tier 1 results from the PCR-GLOBWB model performing sector specific projections for water use.

Table 17 - Summary of the scenarios used for Baseline Scenario by the PRIMES model

Simulations	***Socio-economic conditions at the EU scale***
2015 (2020) – 2100 Projections	
Policy relevant scenarios	
Net Zero	EU socio-economic projections, Ageing Report, European Commission (2021), European Population Projections (EUROPOP 2019)
Current Policies	

Tier 2 runs: Climate adjusted scenarios and comparison to the EU energy Baseline Scenario. EU energy scenarios, see Table 17,in the Tier 2 runs will be enriched by taking into account the climate change effects through linking with dedicated biophysical models. The Tier 2 runs include the following linkages to consider climate change effects by:

- linking data on biomass potential with CAPRI
- linking the data on water temperatures in RCP scenarios from PCR-GLOBWB
- linking the data on river discharge in RCP scenarios from LISFLOOD/LISFLOOD-EPIC

For this experiment, the Current Policy and Net Zero scenarios are put in the context of global climate change scenarios: with +3.6°C towards the end of the century in the Weak Cooperation global scenario and +1.5 – 2°C temperature increase in Emissions Neutrality scenario in line with the Paris Agreement goals (Figure 5).

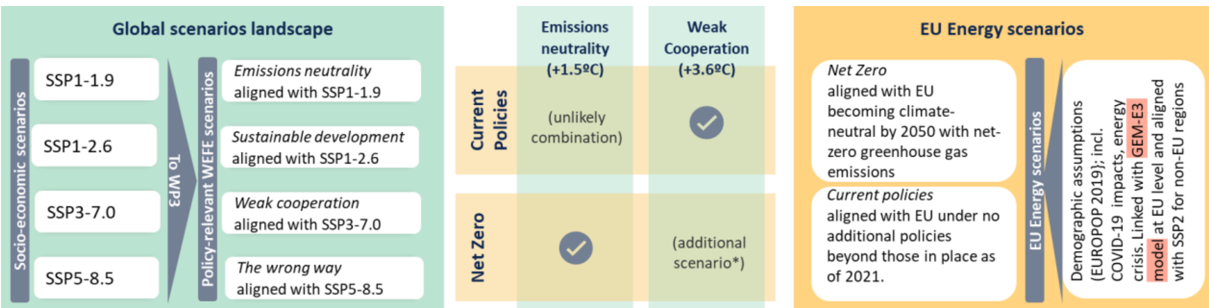


Figure 5 - Implementation of the EU energy Baseline scenario.

Linking PRIMES Biomass Supply Model and CAPRI: Expected impacts of climate change in Tier 2 runs on land availability, affecting the potential for energy crops, which in turn will impact biomass utilization pathways for bioenergy.

Crop yield of food and energy crops by Member State

The PRIMES Biomass Supply model incorporates crop yields and incremental crop yield improvements over time, that is used to estimate the amount of feedstock that can produced in the available land. Crop yields in combination with crop production cost curves (energy inputs, machinery, land rent, labour costs, agrochemical costs) ultimately determine the feedstock cost-supply curves that participate in the optimization problem. The impact of climate change on crop yields will ultimately affect cost-supply curves of the different land-produced feedstock categories, thus diverging impacts between Tier 1 and Tier 2 scenarios.

Agricultural residues feedstock potential for bioenergy use by Member State

Agricultural residues from primary crop production, whether for food, feed, or bioenergy, are an important (primarily) lignocellulosic type of feedstock in PRIMES Biomass Supply that is used for bioenergy purposes. The maximum recoverable potential of agricultural residues that is available for bioenergy (e.g. excluding other competing uses such as bedding or other uses e.g. residues left on field for soil management or sustainability considerations) comprises an important part of the feedstock available, not only due to its lower costs (compared to e.g. primary lignocellulosic crops), but also due to the fact that this feedstock has no land requirements.

Tier 2 scenarios compared to Tier 1 scenarios may demonstrate differences on primary crop production and in turn on related agricultural residues, affecting the pathways deployed in the model. Potential feedback is that a reduction in available agricultural residues for may increase their average cost and in turn the price of related bioenergy commodities produced by agricultural residues, therefore reducing their competitiveness compared to their production by other feedstocks.

PRIMES energy (IEM) model and LISFLOOD / GLOBIO: linking the data on river discharge in RCP scenarios from LISFLOOD, and river water temperatures from GLOBIO.

Tier 2 runs will be enriched by taking into account the climate change effects on the water sector through linking PRIMES power plant performance with LISFLOOD and GLOBIO. This will allow an assessment of the operational impact on available water quantity and temperature to the performance of the power system. More specifically. Tier 2 runs will include the following enhancements due to linkages with other models:

- Link of available water for hydropower corrected for different RCP scenarios. A reduced potential for hydropower will be observed in scenarios and regions with high water scarcity.
- Link of temperature with power plants operational performance. A capacity reduction and a performance penalty have been observed in RCP scenarios and regions with high water scarcity or increased water temperature

The detailed comparison of the Tier 1 and Tier 2 results will be provided in D3.4.

4.3.2 PRIMES – EU scale Baseline scenario results

The socio-economic assumptions used in the model for Tier 1 runs are the same for both Net Zero and Current policies scenarios.

Current Policies scenario

We developed a policy baseline scenario for the EU energy sector that will project the no-climate and no-policy baseline for EU. The scenario includes policies already in place, without recent 2030 and 2040 targets that are not yet translated into policies. The scenarios were defined in 2022 and the cut-off date for the scope of policies can be associated with EU 2020 Reference Scenario. The policy baseline scenario does not include the following policies:

- An updated EU Effort Sharing Regulation (ESR) (European Parliament and the Council, 2023a) targets per Member State for 2030.
- The EU Emission Trading System reform of 2023 (European Commission, 2023a).
- The 42.5% EU RES target in 2030, envisaged in RED III (European Parliament and the Council, 2023b).
- -11.7% final energy consumption reduction relative to respective year in the EU Reference Scenario 2020, the target announced in the revised EED (European Commission, 2021d).

Net Zero scenario

The Net Zero scenario assumes the EU reaching net zero greenhouse gas emissions by 2050 in compliance with the European Green Deal agreement and Fit-for-55 policy package aiming to contribute to limit scenarios that ensure limit 1.5°C global temperature increase (see European Commission 2020). The scenario includes the target and policies foreseen by the proposals for the changes in the key directives announced within the Fit-for-55 package. As the scenarios were defined before the recent policy developments as discussed above, the following Proposals were included in the design of the scenario[2]:

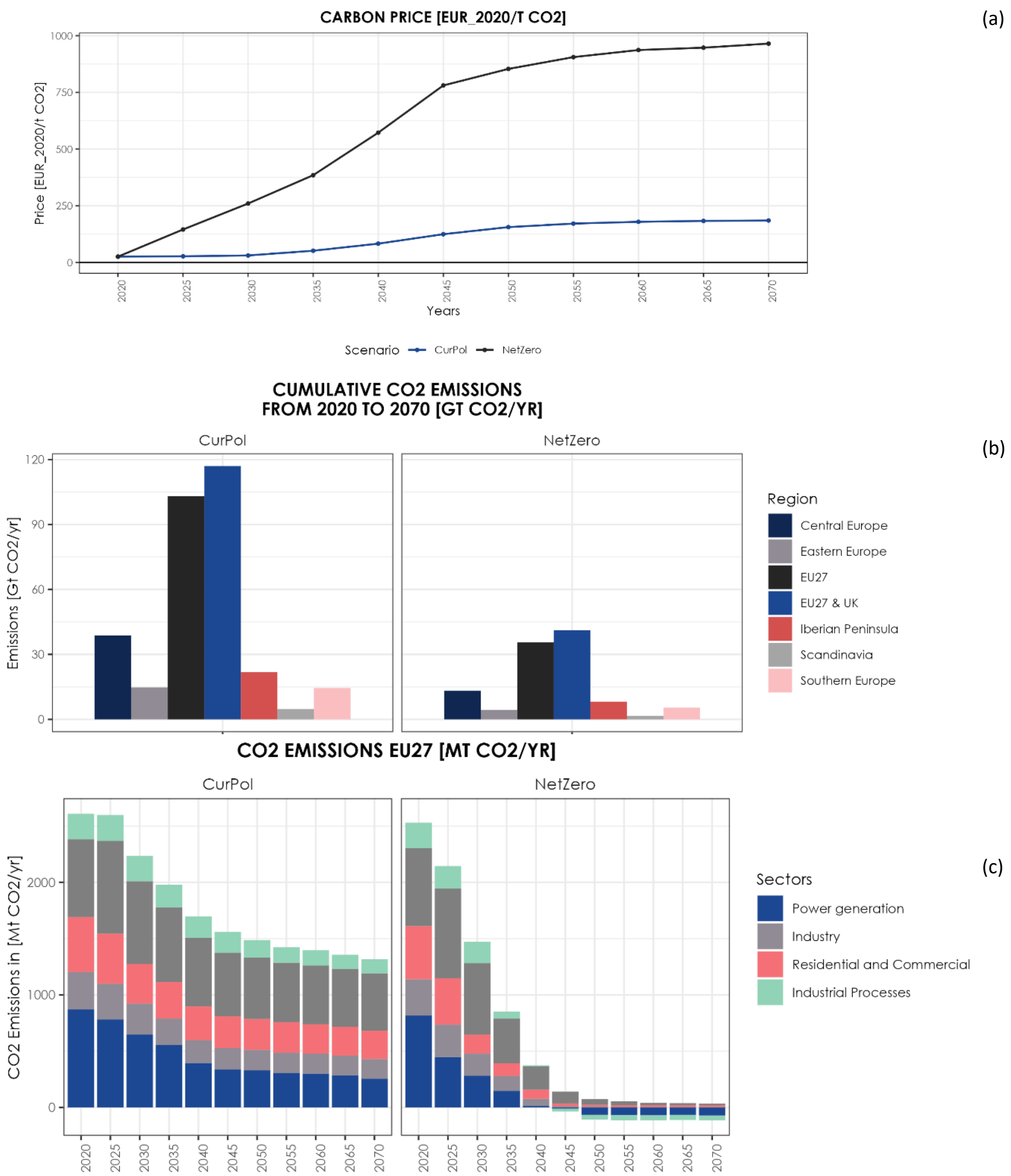
- 40% EU RES target in 2030 RED (European Commission, 2021e).
- -9% final energy consumption reduction relative to respective year in the EU Reference Scenario 2020, in the proposal for the energy efficiency directive (European Commission, 2021d).
- updated energy performance standards for buildings in EPBD (European Commission, 2021c).
- Proposal for ETS reform 2021.

Current Policies and Net Zero scenarios for the European Union (EU27) for the period from 2020 to 2050. Net Zero scenario shows significant CO_2 emissions reductions compared to Current Policies scenario, see Figure 6 (a). Particularly in power generation, transport, buildings, and industry sectors Figure 6 (c). Net Zero scenario shows negative emissions in the EU by 2050, benefiting from carbon capture technologies combined with biomass (BECCS), underscoring the EU's ambitious climate policy commitments aimed at achieving emissions neutrality target by 2050.

The primary energy mix is dominated by gas, oil, and nuclear, with moderate growth in renewables, particularly solar and wind power. However, the NetZero scenario for the EU27 shows a substantial rise in renewable energy, especially solar, wind, and biomass, and a reduction in fossil fuel use. In the primary energy mix under Current Policies, coal, oil, and gas remain dominant, with renewables seeing only limited growth Figure 7. However, the Net Zero scenario shows a substantial increase in renewable energy deployment, especially solar and wind, with a corresponding decline in fossil fuel use.

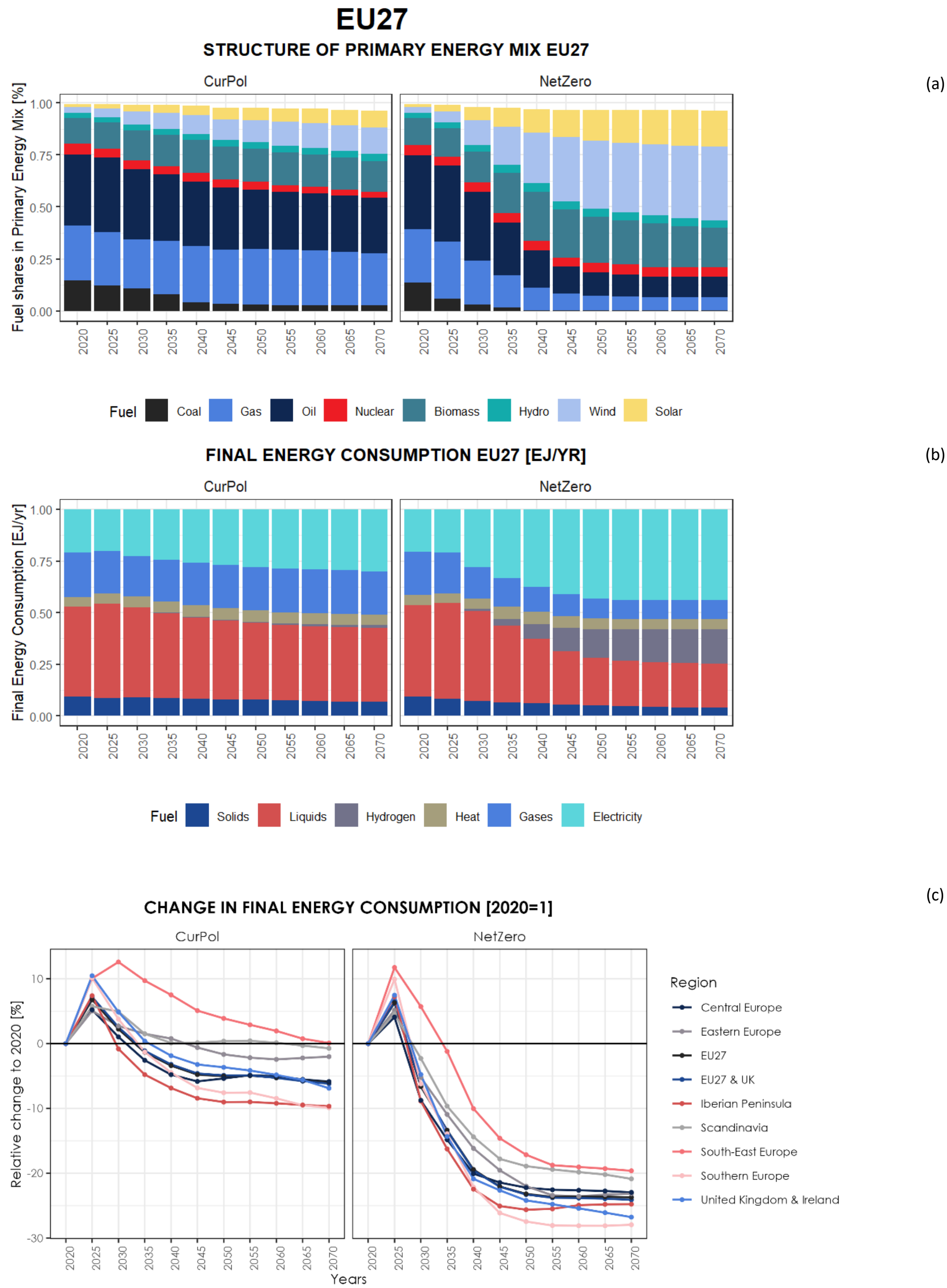
Under the Current Policies scenario, final energy consumption (FEC) remains dependent on liquids and solids, with modest increases in electricity and minimal hydrogen introduction Figure 7 (a) and (b). Another significant contribution to emissions reduction is reduction in FEC in the Net Zero scenario Figure 7 (c). The observed FEC reduction relative to year 2020 is driven by successful implementation of the energy efficiency and renewable policies across the economic sectors of the EU Member States.

[2] The EU policy framework for Tier 2 can be revised to include latest policy developments to the time of delivery.



Note: results for CO_2 emissions for the European regions can be found in the Annex 5.1.

Figure 6 - Net Zero and Current Policies scenarios EU27 scope: (a) EU ETS1 price; (b) Cumulative CO_2 emission; (c) CO_2 emissions per sector. Source: PRIMES model.



Note: results for primary and final energy mix for European regions can be found in the Annex 5.1.

Figure 7 - Net Zero and Current Policies scenarios EU27 scope: (a) Primary energy mix; (b) Final energy consumption mix; (c) Changes in final energy consumption relative to the FEC in year 2020 (different to the EED definition, the reference is year 2020, not the respective year of the EU Reference Scenario 2020).

4.4 CAPRI

CAPRI is a global spatial partial equilibrium model for the agricultural sector developed for ex-ante impact assessment of agricultural, environmental and trade policies with a focus on the European Union. It is a comparative static model solved by sequential iteration between supply and market modules (for a detailed description see Britz and Witzke, 2014). The CAPRI Water version is an extended version of the model integrating water-food interconnections as it accounts for irrigation water use, irrigation efficiency, water use by other sectors and water related policy impacts, among others.

4.4.1 CAPRI – Global scale Baseline scenario implementation and results

Senarios definiton

In this project, no climate scenarios and three baselines scenarios have been analysed:

- NoCC (no climate change effects): no climate change effects with Current Policies.
- Baselines with Climate change effects: Data on climate socioeconomic scenarios (SSP1-2.6, SSP3-7.0 and SSP5-8.5) has been processed at national level for all global regions and aggregated at the spatial scale in CAPRI for non-EU regions SSP1-2.6, SSP3-7.0 and SSP5-8.5 : shifters on crop yield (irrigated and rainfed), crop water requirements, water availability and non-agricultural water withdrawal coming from biophysical models.

CAPRI results and projection have been run from 2020 till 2050 with annual steps.

Results

At global level, in Figure 8, we can see that the production of the selected crops increases between in 2020 and 2050 in all scenarios. This increase in production due to increase in yields. These findings suggest that other factors, such as growth in food demand and population growth will have a bigger influence on food production globally.

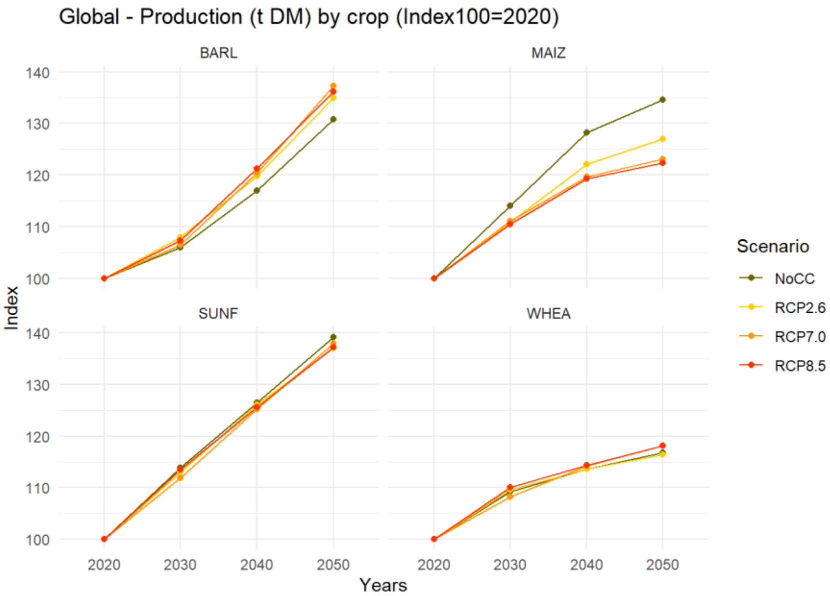


Figure 8 - Trends of global production by crop under NoCC and climate change (between 2020 and 2050)

Figure 9 presents percentage change of global producer prices results in 2050 under climate change SSP1-2.6, SSP3-7.0 and SSP5-8.5. We can see barley, maize and sunflower with the largest price increase. Exogenous decrease in crop yields leads to a negative supply shock and will thus be counterbalanced by an increase in crop prices under climate change.

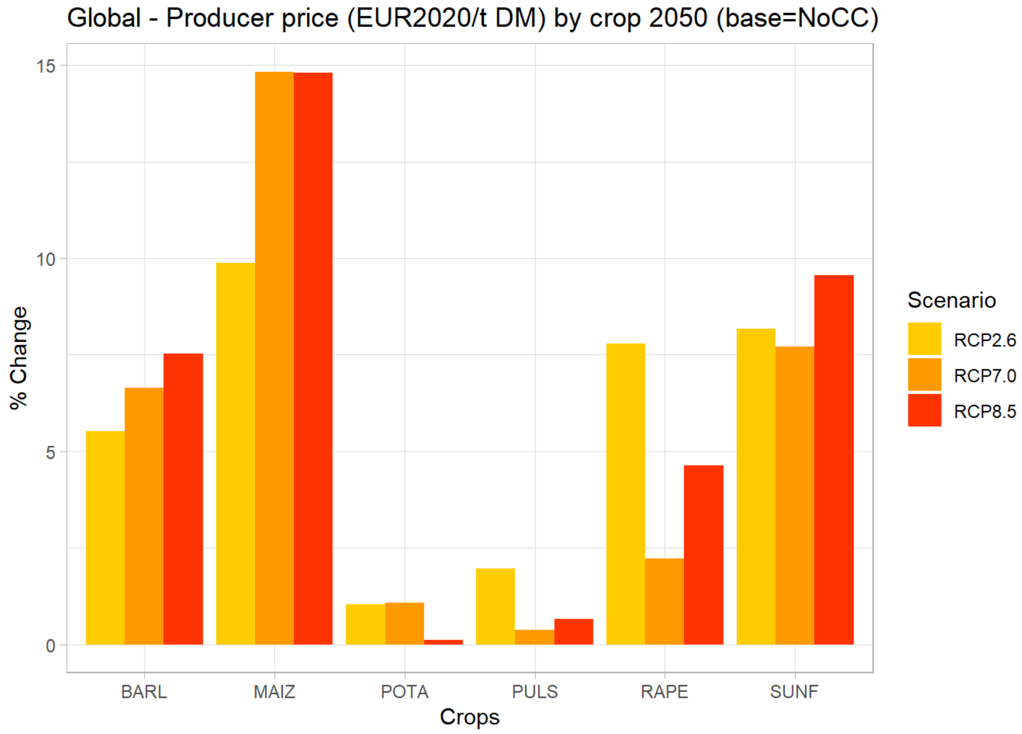


Figure 9 - Global producer prices changes result in 2050 under climate change(euro2020/t DM) (% change from no climate change in 2050)

Price increase will induce changes in cropland allocation as well as production intensity. This will most likely lead to more land allocated to crop with high prices as well as more input-intensive farming practices to market adjustments. As we can see in figure 10, rainfed area of all crops increase under more climate change and compared to no climate change in 2050. However, irrigated area decreases under more climate change. With a decrease in production and an increase in area, average yield decreases. These findings suggest that other factors, such as water availability for irrigation (figure 11) for irrigation and crop water requirements, will have a bigger influence on food production patterns under climate change in 2050.

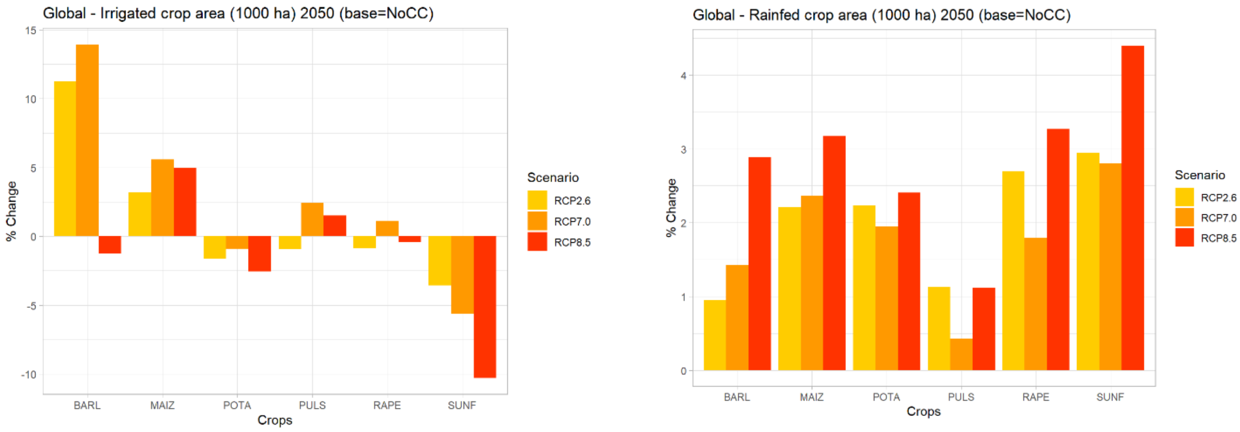


Figure 10 - Change of irrigated and rainfed area (1000 ha) under climate change in 2050 (relative to no climate change)

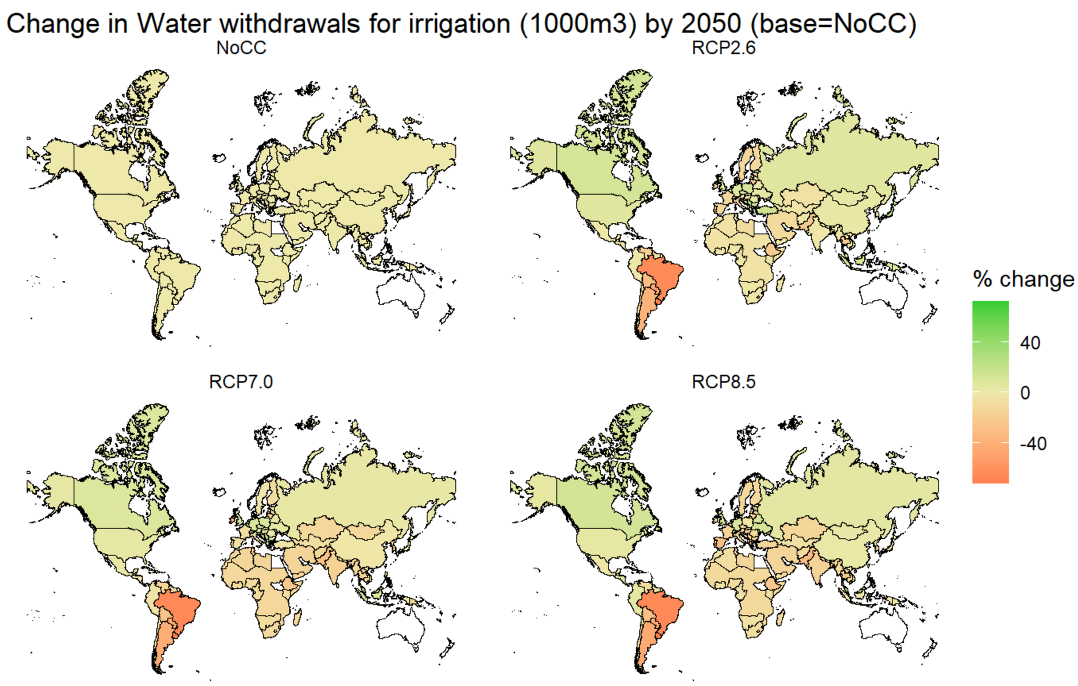


Figure 11 - Global change in water withdrawls for irrigation (1000m3) in 2050 (relative to NoCC)

4.4.1 CAPRI – EU scale Baseline scenario implementation and results

Senarios definiton

Similar to global scale, no climate scenarios and three baselines scenarios have been analysed:

- NoCC (no climate change effects): no climate change effects with Current Policies.
- Baselines with Climate change effects: Data on climate socioeconomic scenarios (SSP1-2.6, SSP3-7.0 and SSP5-8.5) has been processed at national level for all global regions and aggregated at the spatial scale in CAPRI for non-EU regions SSP1-2.6, SSP3-7.0 and SSP5-8.5 : shifters on crop yield (irrigated and rainfed), crop water requirements, water availability and non-agricultural water withdrawal coming from biophysical models.

CAPRI results and projection have been run from 2020 till 2050 with annual steps.

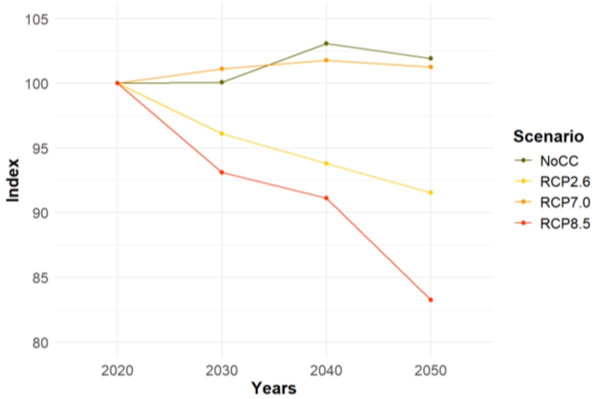
Results

From CAPRI results, under no climate change, EU total irrigated agricultural area is projected to increase under between 2020 and 2050. However, the total rainfed agricultural area is expected to decrease between the same period (Figure 12 A and B). At country level, the irrigated area is expected to decrease mainly in southern European regions with limited water availability in 2050 compared to 2020 (Spain shows a decrease between 10 and 20% in the majority of regions). However, irrigated cropland is expected to increase in some less water stressed regions in 2050 compared to 2020 (for example Germany shows an increase of irrigated area approximately between 0 and 10%) ().

Furthermore, production of the majority of crops is expected to increase between 2020 and 2050 under no climate change. This increase in production can be explained by increase in food demand following population growth. The increase in production compared to area (intensification) leads to an increase in crop yield. This increase in yields can be explained by an increase in technological factors and an increase in water withdrawals for irrigation (more water used for irrigation) between 2020 and 2050 (see Figure 13).

Looking at scenarios under climate change, EU total irrigated agricultural area is expected to decrease between 2020 and 2050 (especially under SSP5-8.5). The total rainfed agricultural area shows a small decrease between 2020 and 2050 compared to irrigated area (Figure 12 A and B). Under climate change scenarios, EU aggregated agricultural production mainly is projected to decline between 2020 and 2050 (especially under SSP5-8.5). Results confirm that the effects of climate change on EU production are a consequence of yield changes (mainly decrease of irrigated yield), increase in crop water requirements and less water availability for irrigation (less intensification and water use for irrigation).

Model results (Figure 14) show that climate change will reduce total water withdrawal compared to no climate change. This reduction will affect water withdrawal for irrigation (less water availability for irrigation especially under SPP5-RCP8.5 in 2050).



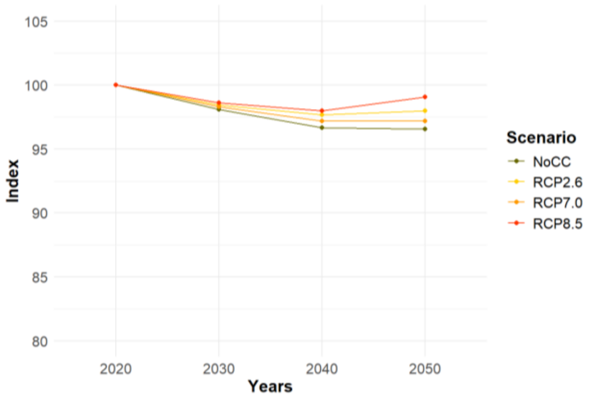


Figure 12 – (A) EU trends of irrigated agricultural area (B) EU trends of rainfed agricultural area (1000 ha) (Index 100=2020)

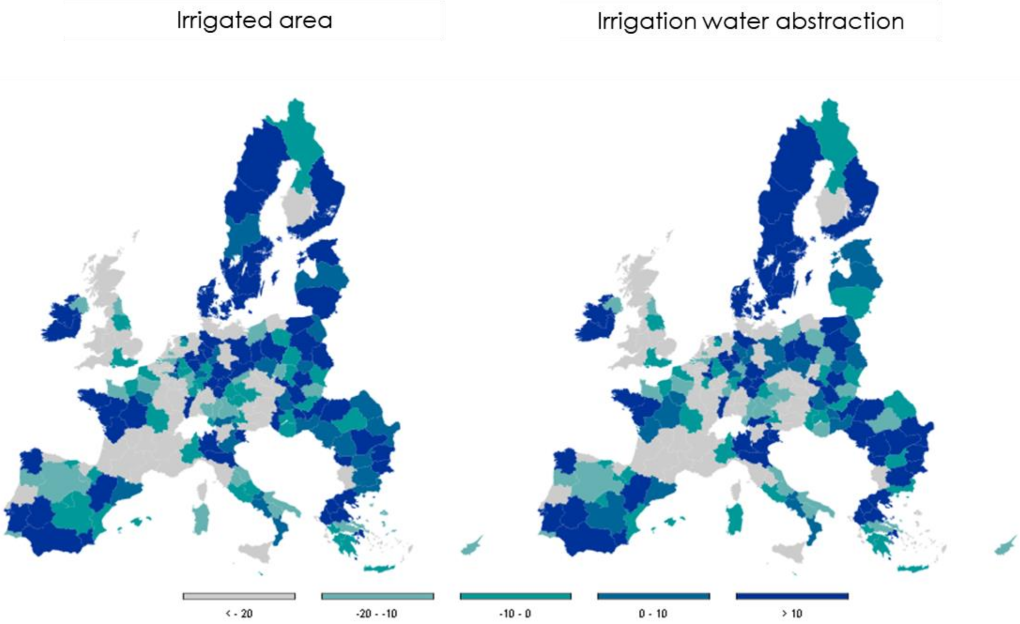


Figure 13 - Irrigation trends under no climate change in 2050 (relative to 2020)

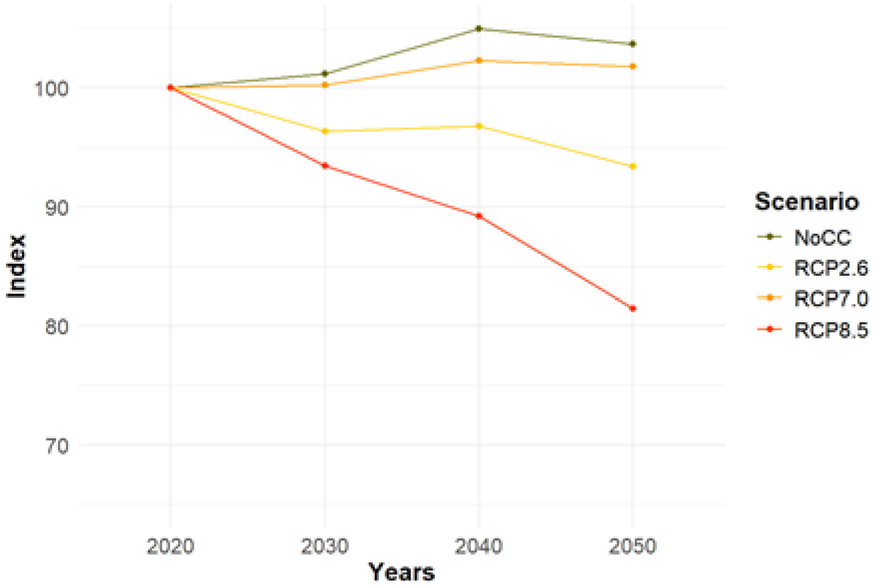


Figure 14 - EU trends of Water withdrawal for irrigation (1000m3) (Index 100=2020)

At crop level, in Figure 15, we selected seven crops that produced more at EU level (barley, maize, potato, pulse, rape, sunflower and soft wheat) to assess the impact of climate change on irrigated and rainfed area in 2050. Under more climate change and with less water availability for irrigation, irrigated area of barley, rape, sunflower is expected to decrease by around 55%, 48% and 48% respectively for SSP5-8.5 in 2050 compared to no climate change. However, for the same crops, the rainfed area at EU level is expected to increase in 2050 compared to no climate change scenario (by around 7.5% for barley, 10% for rape and 6% for sunflower under SSP5-8.5). This can be explained by less water availability for irrigation, there is a shift from irrigated to rainfed area for some crops (especially winter crops). For summer crops such as maize (need water for irrigation), even with less water availability under climate change, the irrigated area increases compared to no climate change scenario in 2050.

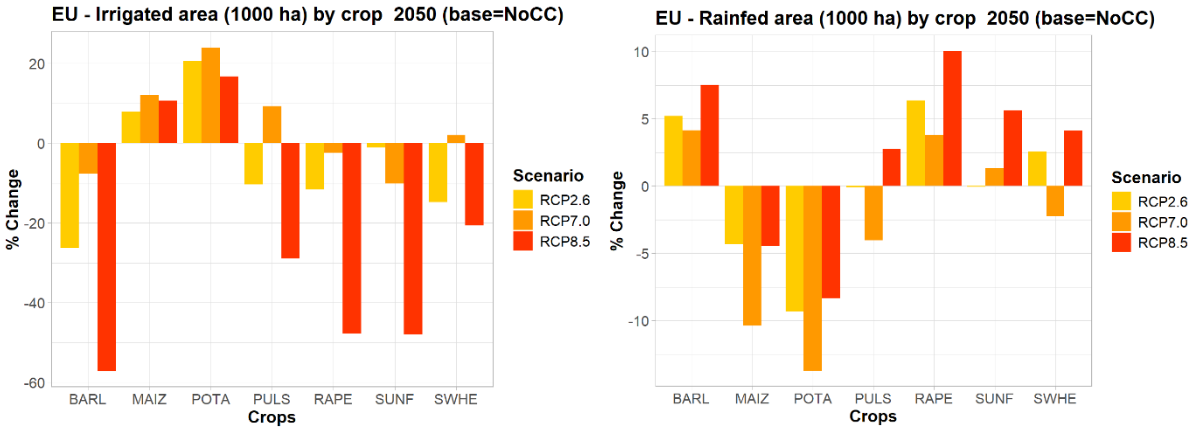


Figure 15 - EU changes of agricultural area (irrigated and rainfed) per crop (1000ha) in 2050 (base= NoCC)

From Figure 16, looking into country-level and under climate change "SSP5-8.5", the irrigated area will decrease for almost all EU country. With less water availability for irrigation under climate, there is less water use for irrigation and then decrease in irrigated areas. Hence, when the impact of climate change leads to a reduction in freshwater availability, treated water becomes a mitigation option for most of the member states to alleviate the climate change impact especially for countries with high level of water scarcity (Spain, France, Italy…).

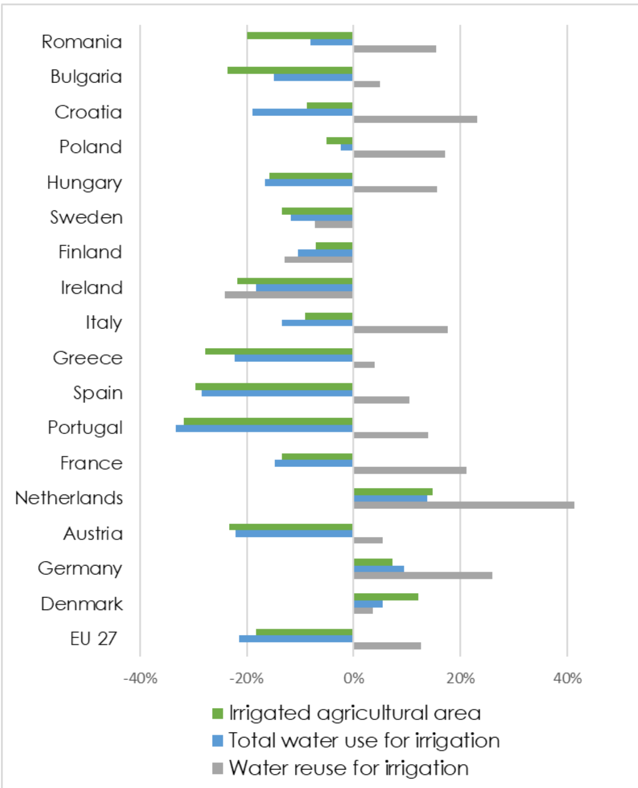


Figure 16 - EU changes of water use and reuse for irrigation by EU country under SSP5-8.5 (relative to NoCC in 2050)

4.5 GEM-E3

GEM-E3 has prepared the Current Policies and Net Zero scenario for the Tier 1 runs. The GEM-E3 model is a global model, with the detailed representation of the global regions, European countries, and the EU. The Current policies scenario takes into account climate policies legislated up to March 2022 while the Net Zero scenario considers in the NDC pledges up to 2030 and the mid-century strategy pledges (net-zero) announced at COP26 in Glasgow up to 2050. In more detail:

Socioeconomic assumptions in Current Policies scenario

In GEM-E3 model all major socioeconomic components are calibrated to replicate exogenous projections for the reference (Current Policies) scenario, based on extraneous information regarding GDP growth and population.

For the EU27, the macroeconomic projections are updated to account for the impacts of the war in Ukraine (European Commission, DG Economic and Financial Affairs, 2022). For the EU GDP growth rates, population and employment projections are drawn from DGECFIN's Ageing Report (2022).

For the non-EU countries, socio-economic projections combine IMF, OECD, and ILO statistics. Global GDP is projected to grow at an average annual rate of 2.7% for the period up to 2050; EU GDP is projected to increase at an annual rate of 1.7% while the unemployment rate falls from approximately 7.9% in 2020 to 5.7% in 2050.

Climate and energy policies in Current Policies scenario

This scenario considers only currently implemented climate and energy policies. Policies incorporated in GEM-E3 model are described in detail in the NewClimate2 database, where current policies are defined as currently implemented policies adopted by governments (through legislation) or non-binding targets backed by effective policy instruments. Ambitions and pledges are not included. These policies are mostly with a time horizon up to 2030. After 2030, the ambition levels should remain at least constant throughout the rest of the time frame (2050/2100). We thus introduce an "equivalent" carbon price, taking the equivalent of 2030 and extrapolation to the post-2030 period by using the GDP growth rate of each model regions to 2100. 4.5.2 Net Zero scenario

Climate and energy targets in Net Zero scenario

This scenario considers the implementation of the NDC pledges and the mid-century strategy pledges (net-zero) announced at COP26 in Glasgow. In particular, the following targets have been achieved as in presented in Table 18 and Table 19.

GEM-E3 has prepared the Current Policies and Net Zero scenario for the Tier 1 runs. The GEM-E3 model is a global model, with the detailed representation of the global regions, European countries, and the EU.

Table 18 - NDC targets in the GEM-E3 Net Zero scenario

Region	NDC target for 2030
Argentina	GHG emissions 349 $MtCO_2e$
Australia	GHG emissions 43% below 2005 levels
Brazil	GHG emissions 48% below 2005 levels
Canada	GHG emissions 40-45% below 2005 levels
China	- Reduction in CO_2 emissions intensity (emissions per unit of GDP) by 60% to 65%, compared to 2005 levels (excl. LULUCF) - Peaking CO_2 emissions before 2030 - Increase in the share of non-fossil fuel in primary energy to around 25% - New renewable wind and solar installed capacity target of 1,200 GW - Increase in forest stock volume by 6 billion m3, relative to 2005 levels
EU-27	GHG emissions 55% below 1990 levels
India	- GHG emissions intensity 45% below 2005 levels (excl. LULUCF) - Increase in the share of non-fossil energy in total power capacity to around 50% by 2030 - Increase the carbon sink volume with 2.5 to 3 $GtCO_2$ equivalent through additional forest and tree cover by 2030
Indonesia	GHG emissions 43.2% below BAU
Japan	GHG emissions 46% below 2013 levels
Republic of Korea	GHG emissions 40% below 2018 levels
Mexico	GHG emissions 40% below BAU
Russian Federation	GHG emissions 70% below 1990 levels
Saudi Arabia	GHG emissions of 715 – 958 $MtCO_2e$
South Africa	GHG emissions of 350-420 $MtCO_2e$
Thailand	GHG emissions 40% below BAU
Turkey	GHG emissions 41% below BAU
USA	GHG emissions 50-52% below 2005 levels
Viet Nam	GHG emissions 43.5% below BAU

Table 19 - Net-zero GHG or CO_2 target in the GEM-E3 Net Zero scenario

Country	Official net-zero target year	Emission type		Country	Official net-zero target year	Emission type
Canada	2050	GHG		Russia	2060	CO_2
USA	2050	GHG		Saudi Arabia	2060	CO_2
Costa Rica	2050	GHG		Israel	2050	CO_2
Panama	2050	GHG		UAE	2050	GHG
Brazil	2050	GHG		India	2070	GHG
Chile	2050	GHG		South Korea	2050	CO_2
Ecuador	2050	GHG		China	2060	GHG
Uruguay	2050	CO_2		Thailand	2050	CO_2
Nigeria	2060	CO_2		Viet Nam	2050	CO_2
South Africa	2050	CO_2		Malaysia	2050	CO_2
EU	2050	GHG		Indonesia	2060	GHG
UK	2050	GHG		Japan	2050	GHG
Turkey	2053	CO_2		Australia	2050	GHG
Ukraine	2060	GHG		New Zeeland	2050	GHG
Kazakhstan	2060	CO_2		Sri Lanka	2060	GHG

Linking GEM-E3 model in the Tier 2 runs the scenarios will be enriched by taking into account the climate change effects through linking GEM-E3 model with other models (PRIMES, PROMETHEUS and CAPRI). This will allow an assessment of the socioeconomic implications of the examined climate impacts. The Tier 2 runs include the following linkages with other models:

1. Energy demand by fuel in buildings, transport and industrial are soft linked with PRIMES fuel consumption.

2. Crop yield of the agricultural sector in GEM-E3 is soft-linked with the CAPRI model.
3. Energy prices are taken by PROMETHEUS model.

The detailed comparison of the TIER 1 and TIER 2 results will be provided in D3.4.

4.5.1 GEM-E3 – Global scale Baseline scenario implementation and results

At the global level GDP implications are of a moderate magnitude, as results indicate a GDP loss of less than 2% of cumulative GDP for the 2020-2100 period. The low-carbon transition entails the transformation of the production and consumption system and involves all economic actors and sectors. This is a capital-intensive process that depends strongly on the financial availability that will allow a smooth funding of new low-carbon investments. This is a technology-intensive process that leads to lower operational costs, due to less expenditure on fossil fuels, but to higher demand for capital. The source of financing of the new, low-carbon investments is a key driver of the socioeconomic implications of the transition. In our scenarios, we assume that the low-carbon investments substitute (or crowd-out) other types of investments, thus total along with the negative effect on demand, total investments fall. Further, production costs increase as the transition to climate neutrality entails the adoption of more expensive energy carriers and low-carbon processes, while emissions are taxed with a carbon price. Country-level results depend on the country-specific target as described in the Section above and on the i) level of investments and energy saving expenditures associated with the implementation of policies, ii) dependence on coal or other fossil fuel- related activities, iii) export intensity and iv) manufacturing potential of clean energy equipment and clean energy potential. Figure 17 shows that the highest losses are in seen in fossil-fuel producing countries. Countries such as Russia, Saudi Arabia, and South Africa are anticipated to encounter the most significant GDP reductions. This is primarily attributed to the decarbonization process decreases the demand for their primary export commodities, namely fossil fuels.

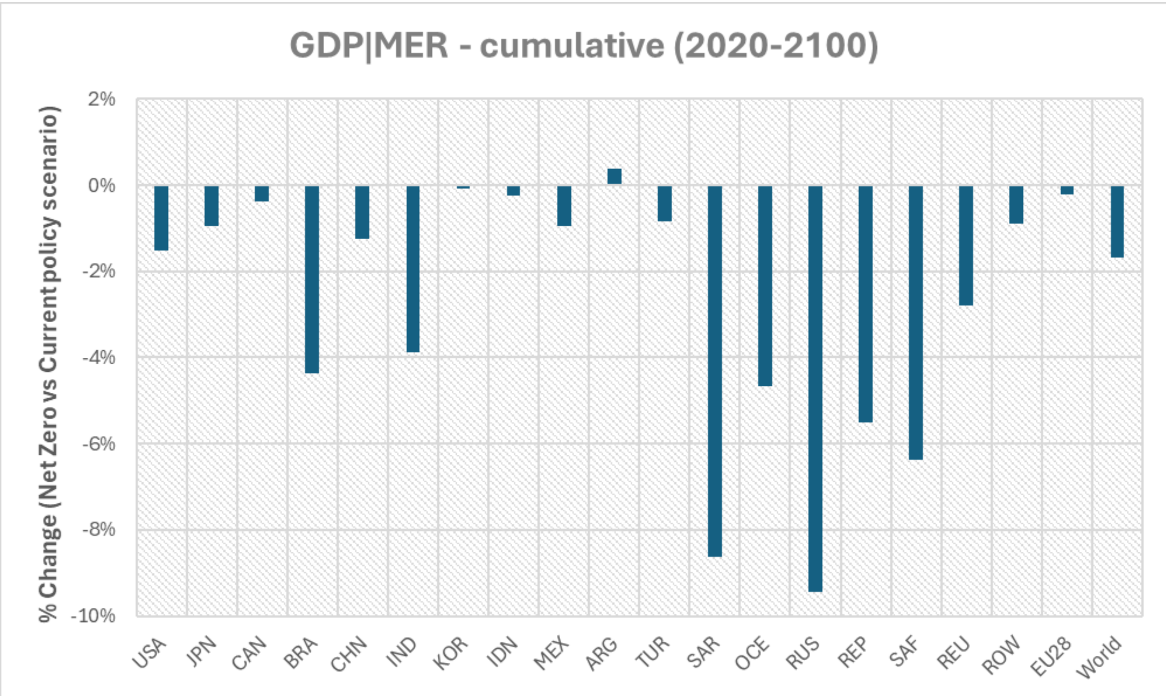


Figure 17 - % Change of GDP cumulative 2020-2100 (Net Zero vs Current Policy scenario); source: GEM-E3 model

Figure 18 shows the % change of household consumption in the Net Zero scenario compared to the Current Policy scenario, while Figure 19 for the consumption of food in particular. According to the results from the GEM-E3 model, the decreased economic activity in the decarbonization scenario results in a net loss of jobs, leading to reduced household incomes and subsequently lower consumption of goods and services.

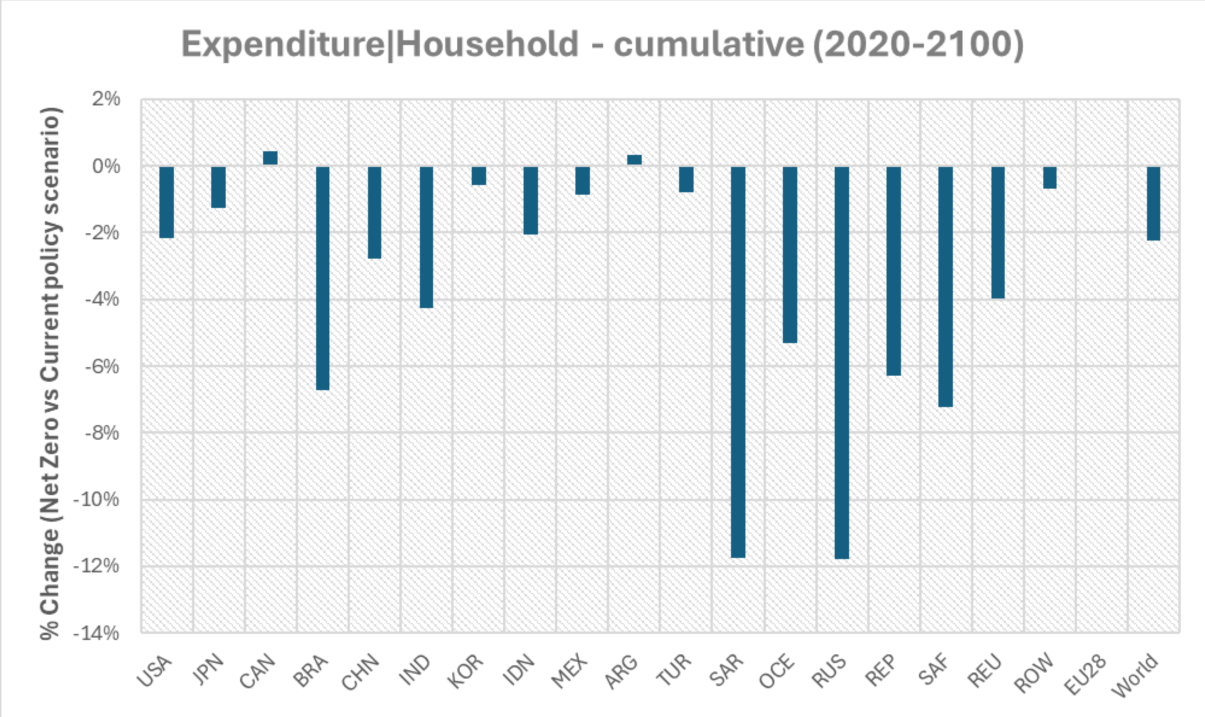


Figure 18 - % Change of household consumption cumulative 2020-2100 (Net Zero vs Current Policy scenario); source GEM-E3

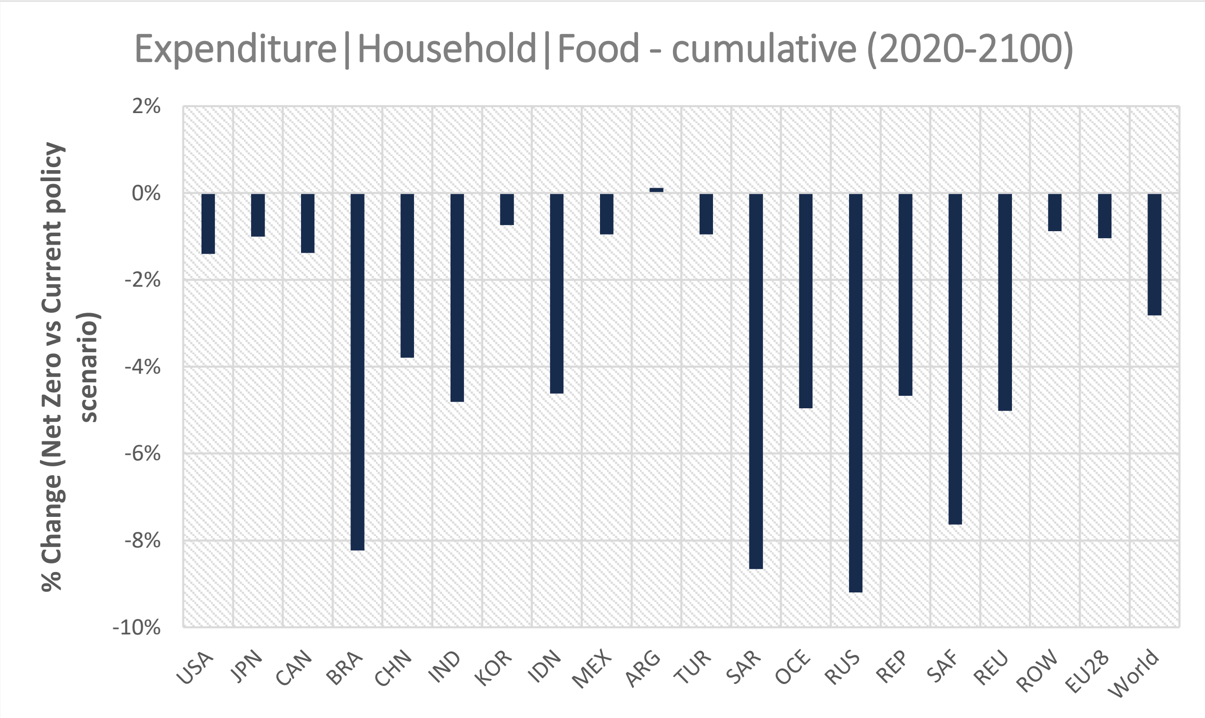


Figure 19 - % Change of household consumption | Food, cumulative 2020-2100 (Net Zero vs Current Policy scenario); source GEM-E3

4.5.4 GEM-E3 – EU scale Baseline scenario implementation and results

GEM-E3 has prepared the Current Policies and Net Zero scenario for the TIER 1 runs. The GEM-E3 model is a global model, with the detailed representation of the global regions, European countries, and the EU. The EU scale is described in the section above.

4.6 PROMETHEUS

4.6.1 PROMETHEUS – Global and EU scale Baseline scenario implementation

The scenarios developed with PROMETHEUS model were designed for the Tier 1 runs and represent the Current Policies and Net Zero or PA scenarios (in line with the Paris Agreement goals of keeping global temperature increase to well-below 2C and pursue efforts towards 1.5C). The Current Policies scenario takes into account energy and climate policies implemented and known up to 2021 both in the EU (in line with the PRIMES scenarios) and globally. Implementation at the EU level is discussed in detail below. Assumptions for PROMETHEUS scenarios at the EU level are harmonised with the PRIMES energy scenarios. The interlinkage is discussed in detail in the section for PRIMES scenarios.

Current Policies (CurPol) scenario, after the mid-century is lower than RCP8.5 (and closer to RCP 6) but differences are not large until 2050 and assumptions are the following:

- For global regions:
  - the main socioeconomic scenario assumptions used is the SSP2 scenario, including the GDP and population assumptions, but updated to include the impacts of COVID-19 and recent trends from IMF and the World Bank.
  - Current Policies scenario represents a Baseline scenario where only the currently implemented climate policies are introduced (details in Van Soest et al 2021) without the national climate targets and pledges (i.e. Nationally Determined Contributions, Long-Term net-zero targets) that are not translated into concrete policies.
- For the EU level:
  - EU GDP and population projections are derived from the Ageing Report, European Commission (2021). For the period 2020 to 2050, EU population projections are based on the European Population Projections, base year 2019 (EUROPOP 2019). The projections include the effects of COVID-19 and the energy crisis, with the Russian war in Ukraine.
  - For the EU, targets and policies that are not yet translated into concrete policies should not be included (as ESR targets for 2030). The ETS GHG emissions cap for 2020-2030 is included (without considering the ETS reform in 2023 and introduction of the ETS2 system). Some national policies translated in national regulations are included: e.g., coal phaseout in Germany by 2038.

Net Zero scenario (NetZero) is close to RCP 2.6 “Sustainable Development" scenario SSP1-2.6 with the following assumptions:

- The same levels of GDP and population assumptions as the Current Policy scenario are used
- For global regions, the scenario imposes a global peak budget constraint (1100 Gt CO_2 from 2011 to peaking year) leading to rapid emission reductions.
- For the EU, the main target is reaching net zero emissions by 2050.
- For global regions, the scenario implements global harmonized carbon pricing throughout all regions after 2020 so as to reach the global peak carbon budget constraint. This represents an idealized policy implementation.
- For the EU, a different approach is taken: the GHG neutrality target for 2050 is driven by the carbon pricing under EU emissions trading system combined with ambitious regulatory policies (e.g. CO_2 standards, efficiency regulations etc).

Linking PROMETHEUS model in TIER 2 runs: the PRMOMETHEUS model is utilising the existing link with GEM-E3 model (see Table 11 and Table 12): GDP of the global regions as an input to the model, and global energy prices for the GEM-E3. Water use for power generation is assessed from LISLFOOD model. This will inform the water use needs for global regions under the two policy scenarios.

4.6.2 PROMETHEUS – Global and EU scale Baseline scenario results

The results are provided for global regions: World, North America, Western Pacific, China, India, Commonwealth of Independent States, Europe and Other Economies, Emerging Economies, Rest of the World, European Union (28 countries).

Global cumulative CO_2 emissions for the period from 2020 to 2050, in Net Zero scenario are driven by the strong climate and emissions neutrality policies adopted in some global regions as in EU27 & UK, North America region including USA and Canada, see Figure 20 (a) and (b). Net Zero scenario projects significant emissions reductions across all sectors, emphasizing the impact of stringent climate policies on achieving net-zero targets. This comparison highlights the crucial role of policy interventions in driving the shift to a low-carbon economy and mitigating climate change.

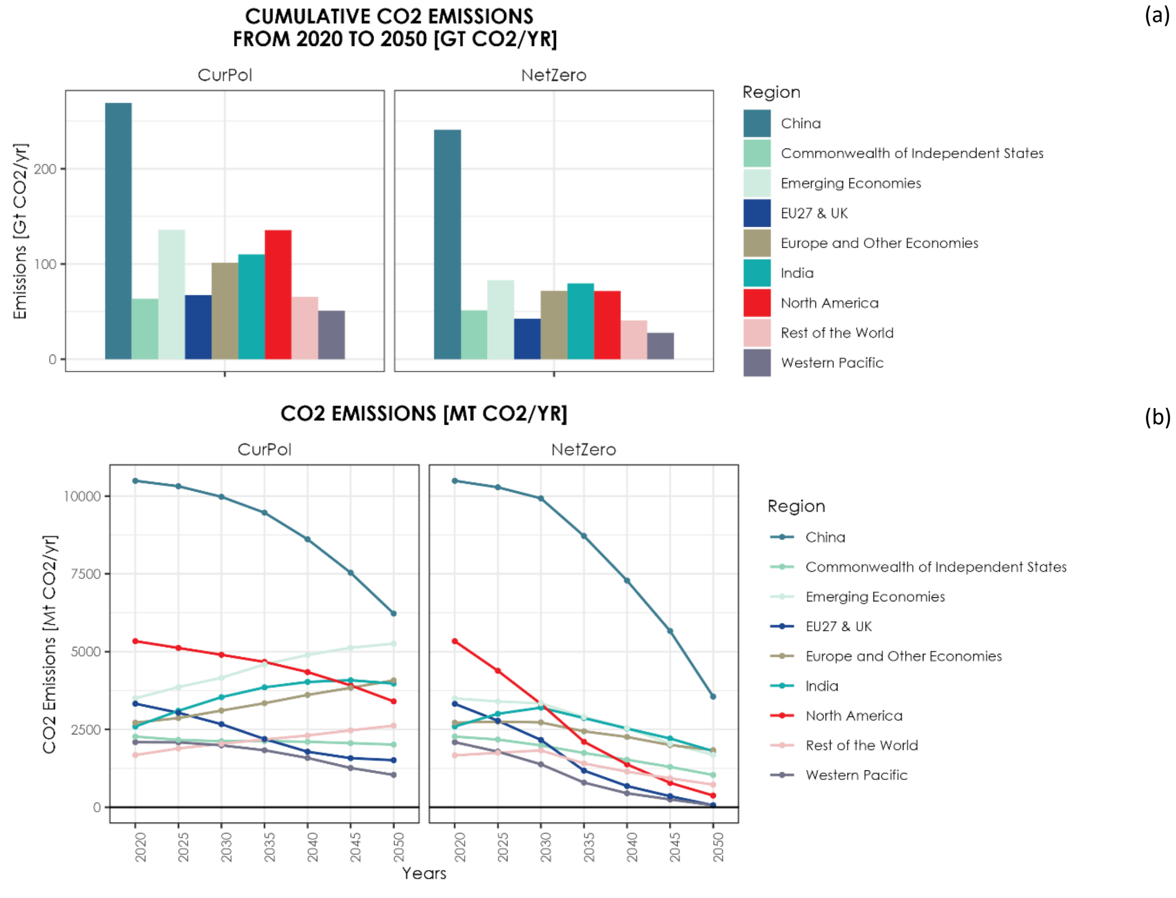


Figure 20 - CO_2eq emissions in global regions cumulative (a) and emissions trajectory (b). Source: PROMETHEUS model.

Figure 21 demonstrates the anticipated changes in global final energy consumption (FEC) mix, under the Current Policies and Net Zero scenarios from 2020 to 2050. In the Current Policies scenario, energy consumption remains largely dependent on traditional fuels like solids and liquids, with only a modest rise in electricity use, indicating a continued reliance on fossil fuels without strong climate policies. Conversely, the Net Zero scenario depicts a major shift towards increased use of renewable-based electricity and green hydrogen, alongside a decrease in solids and liquids, marking a transition to cleaner energy sources. Not only the structure of the FEC undergoes changing, but the overall energy consumption is lower in the Net Zero scenario, compared to the Current Policies Figure 22 (a). Lower FEC is achieved by using more energy efficient processes in industry, higher building standards in residential and services sectors. Higher energy efficiency is reliant on the electrification of the economic sectors on one side Figure 22 (c), as well as higher share of renewable energy in the power generation, industry and transport sectors Figure 22 (b).

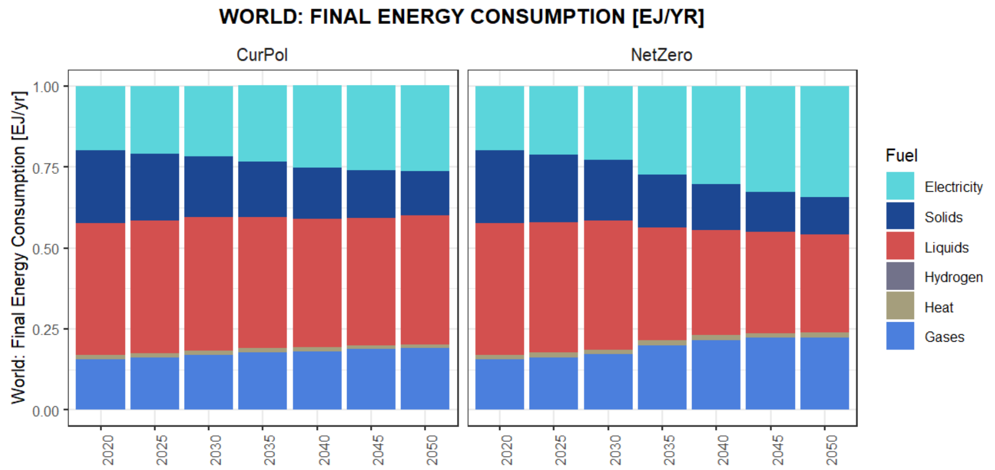
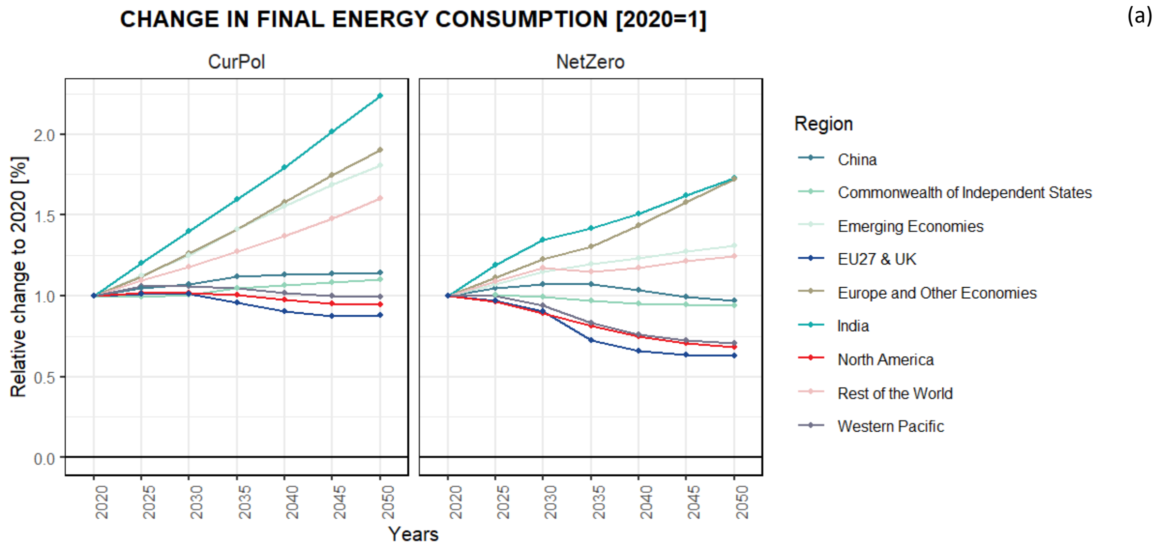
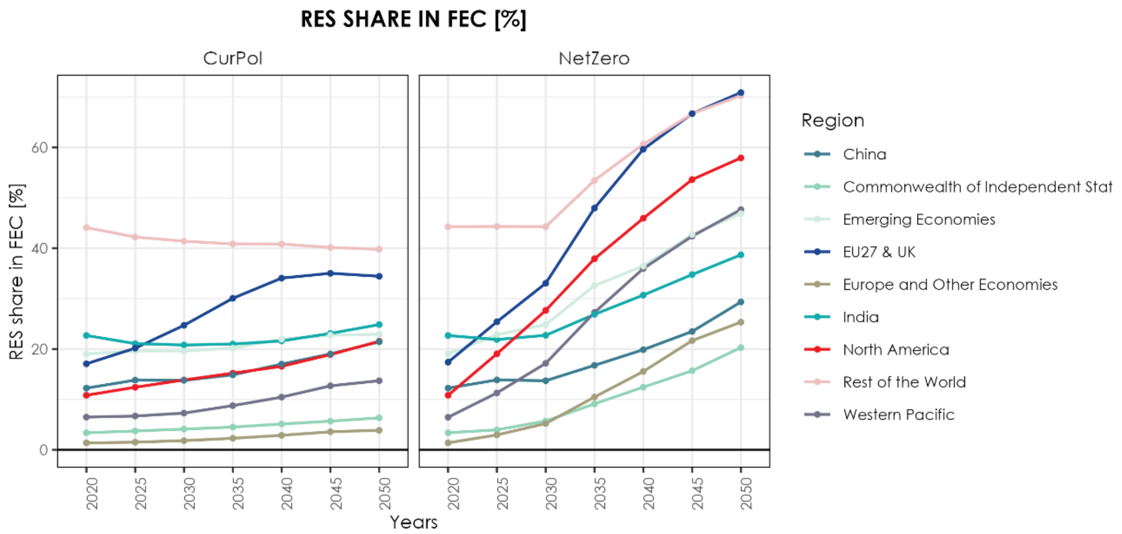


Figure 21 - Final energy consumption mix [%]: Source: PROMETHEUS model.

Comparing both scenarios, it can be illustrated the effectiveness of stringent climate policies in transforming energy consumption patterns and significantly reducing CO_2 emissions. This underscores the critical role of stringent climate policies in transforming energy landscapes and achieving significant emissions reductions. Among the risks to the Net Zero scenario, is the availability of water for the needs of the power generation sector. With linkage to the LISFLOOD model in Tier 2, we can assess the water needs at the level of global regions. The detailed comparison of the Tier 1 and Tier 2 results will be provided in D3.4.



(b)



(c)

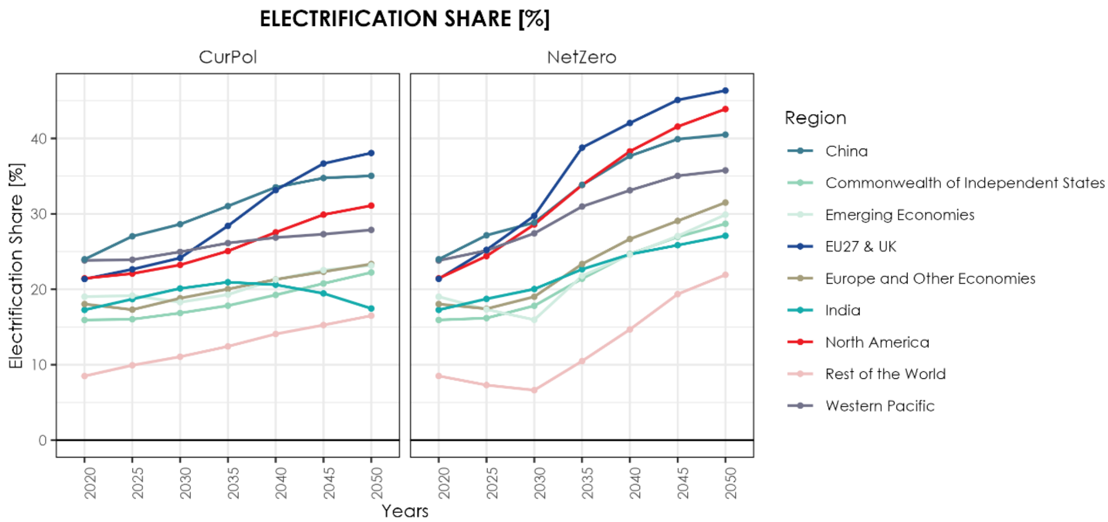


Figure 22 – Changes in the final energy consumption (FEC) for global regions. (a) changes in FEC until 2050, (b) renewable energy (RES) share in the final energy consumption, (c) electrification share in FEC. Source: PROMETHEUS model.

4.7 GLOBIO - Global and EU scale Baseline scenario implementation and results

Tier 1 scenarios were prepared for four Representative Concentration Pathways (RCPs; 2.6, 4.5, 6.0, 8.5), based on five Global Climate Models (GCMs; GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M), and for two scenario years (2030 and 2050). Data on weekly streamflow and water temperature (averaged over 2021-2040 and 2041-2060 for 2030 and 2050, respectively), required to run the GLOBIO model, were obtained from the FutureStreams dataset (Bosmans et al. 2022). The FutureStreams dataset, which is compiled based on outputs of PCR-GLOBWB, was preferred over Tier 1 outputs of PCR-GLOBWB produced in GoNEXUS, because it was already available at the start of GoNEXUS, hence preventing potential delays in the workflow. With FutureStreams data as input, the Tier 1 runs with GLOBIO comply with the GoNEXUS baseline scenarios for RCP2.6 and RCP8.5, but they deviate slightly by including RCP6.0 instead of RCP7.0 (so a mitigation rather than a baseline scenario). Results for RCP4.5 are extra. The RCPs were combined with three situations for the presence of dams: no dams (for comparison), current dams (from the GRanD and GOODD databases; Lehner et al. 2011; McMulligan et al. 2020), and current + future dams (adding dams from the FHReD database; Zarfl et al.

2015). Tier 2 scenarios are based on outputs of PCR-GLOBWB produced specifically for GoNEXUS (see section 2.7.1). Further, the input dataset on dams as used in PCR-GLOBWB is also used as input to the fragmentation module of GLOBIO, to ensure complete consistency.

For the Tier 1 and Tier 2 runs for the continental scale (Europe; EU27), the same set-up was used as for the global runs (see section 2.7.2).

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5 Annex

5.1 PRIMES results EU scale

Table A - Countries in the aggregated regions in the graphs

EU27 & UK	**EU27**	**Iberian Peninsula**	**Western Europe**	**Central Europe**
Ireland	Ireland	Spain	United Kingdom	Ireland
United Kingdom	Belgium	Poland	Luxembourg	Belgium
Belgium	Luxembourg		Netherlands	Italy
Luxembourg	Netherlands		Germany	Slovenia
Netherlands	Germany		Denmark	Slovakia
Germany	Denmark		France	Portugal
Denmark	France		Spain	Hungary
France	Spain		Poland	Liechtenstein
Spain	Poland		Slovakia	Romania
Poland	Slovakia		Finland	Bulgaria
Slovakia	Finland		Austria	Greece
Finland	Austria		Czech Republic	
Austria	Italy		Latvia	
Italy	Slovenia		Spain	
Slovenia	Czech Republic		Croatia	
Czech Republic	Slovakia			
Slovakia	Portugal			
Portugal	Hungary			
Hungary	Latvia			
Latvia	Spain			
Spain	Liechtenstein			
Liechtenstein	Croatia			
Croatia	Romania			
Romania	Bulgaria			
Bulgaria	Greece			
Greece				

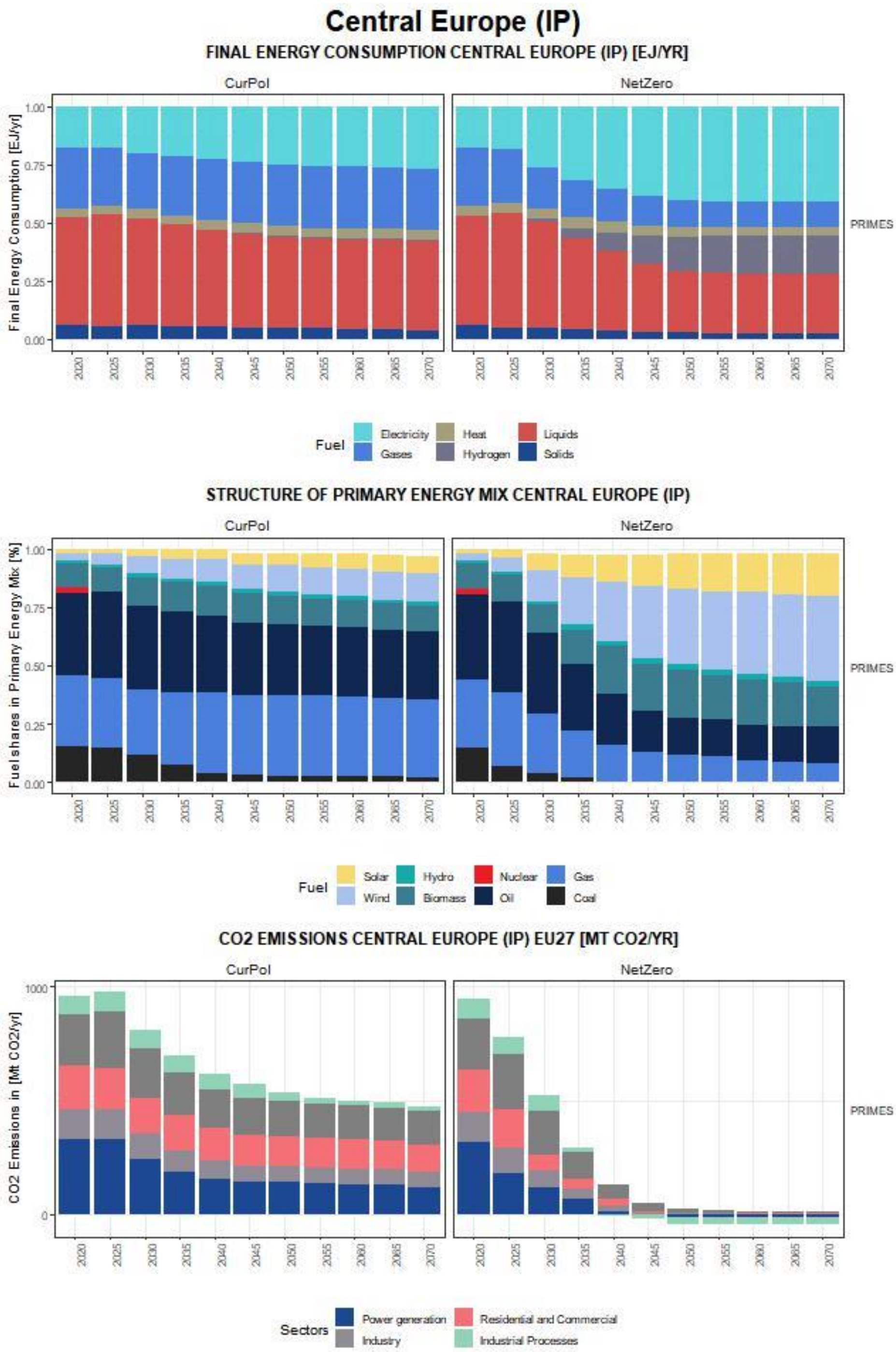

Figure A 1 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: Central Europe

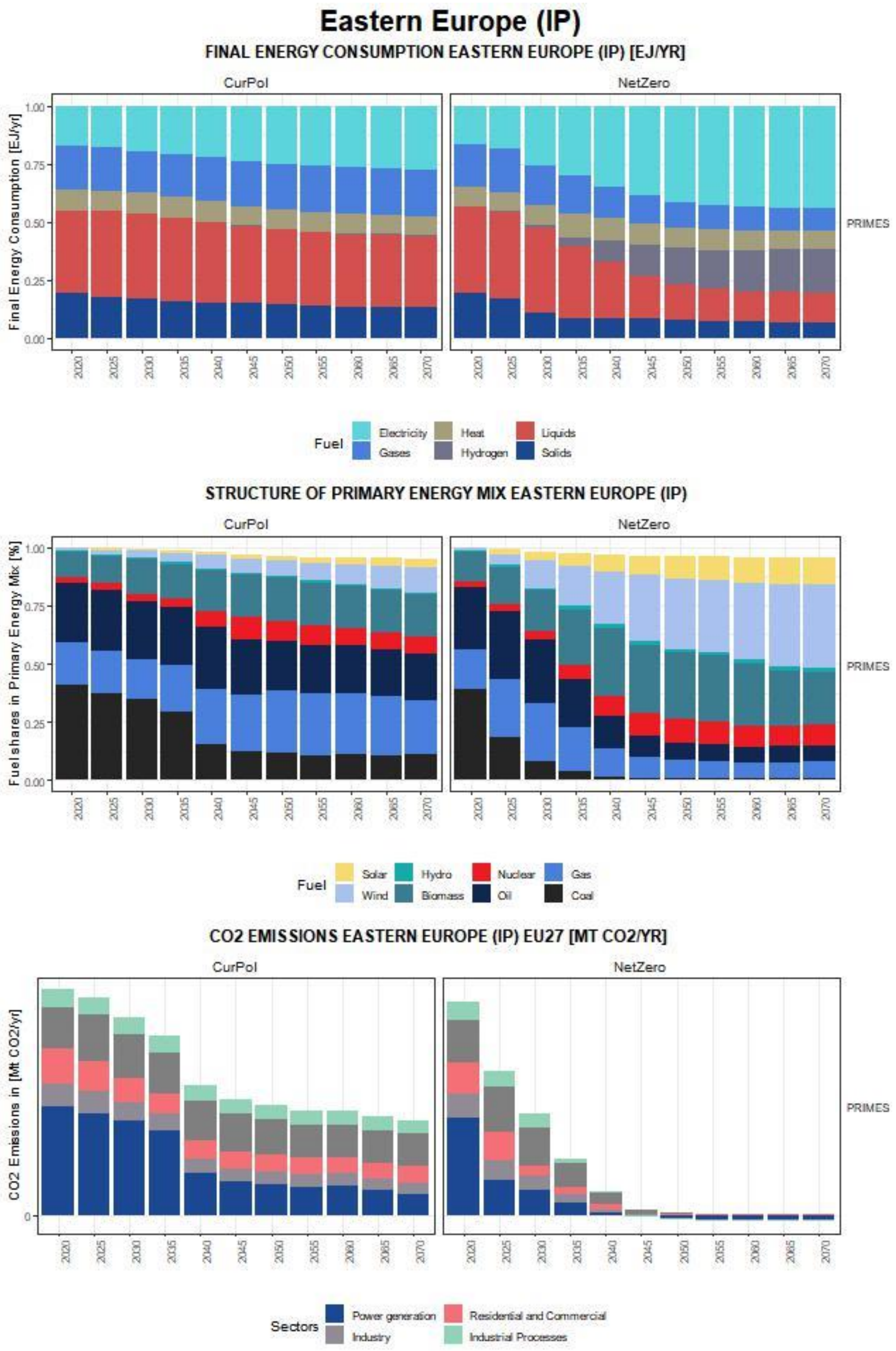

Figure A 2 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: Eastern Europe

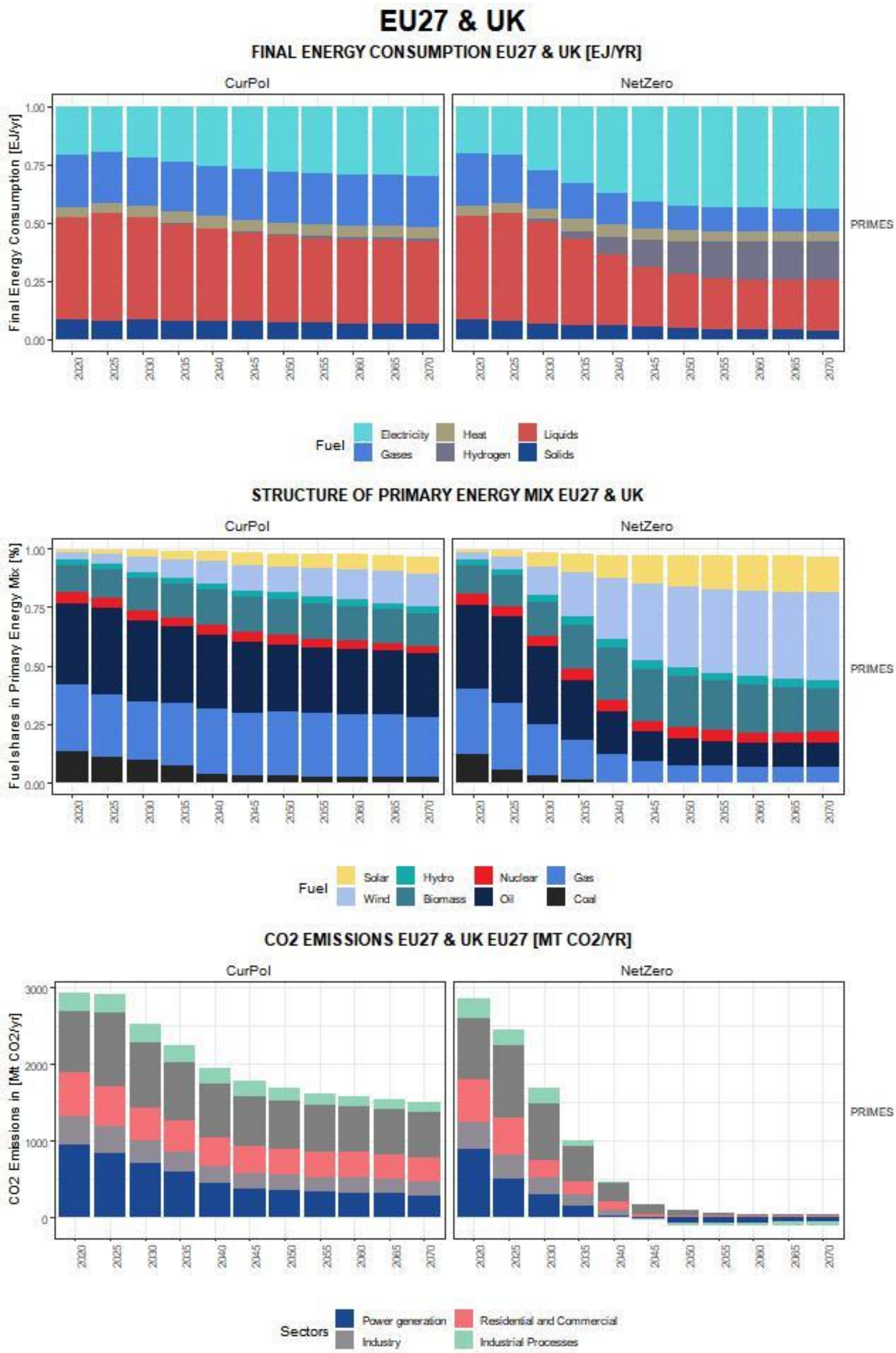

Figure A 3 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: EU27 & UK

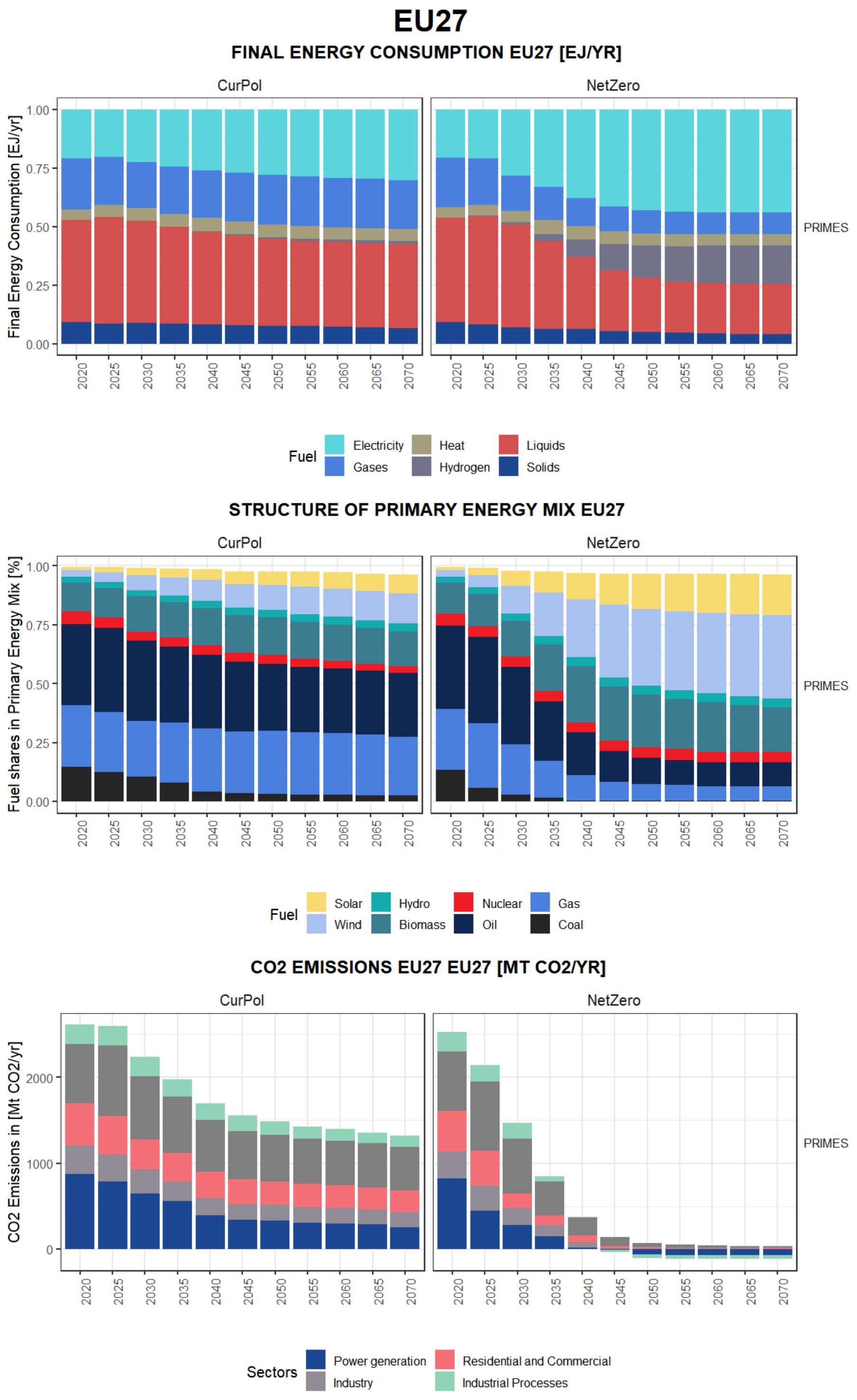

Figure A 4 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: EU27

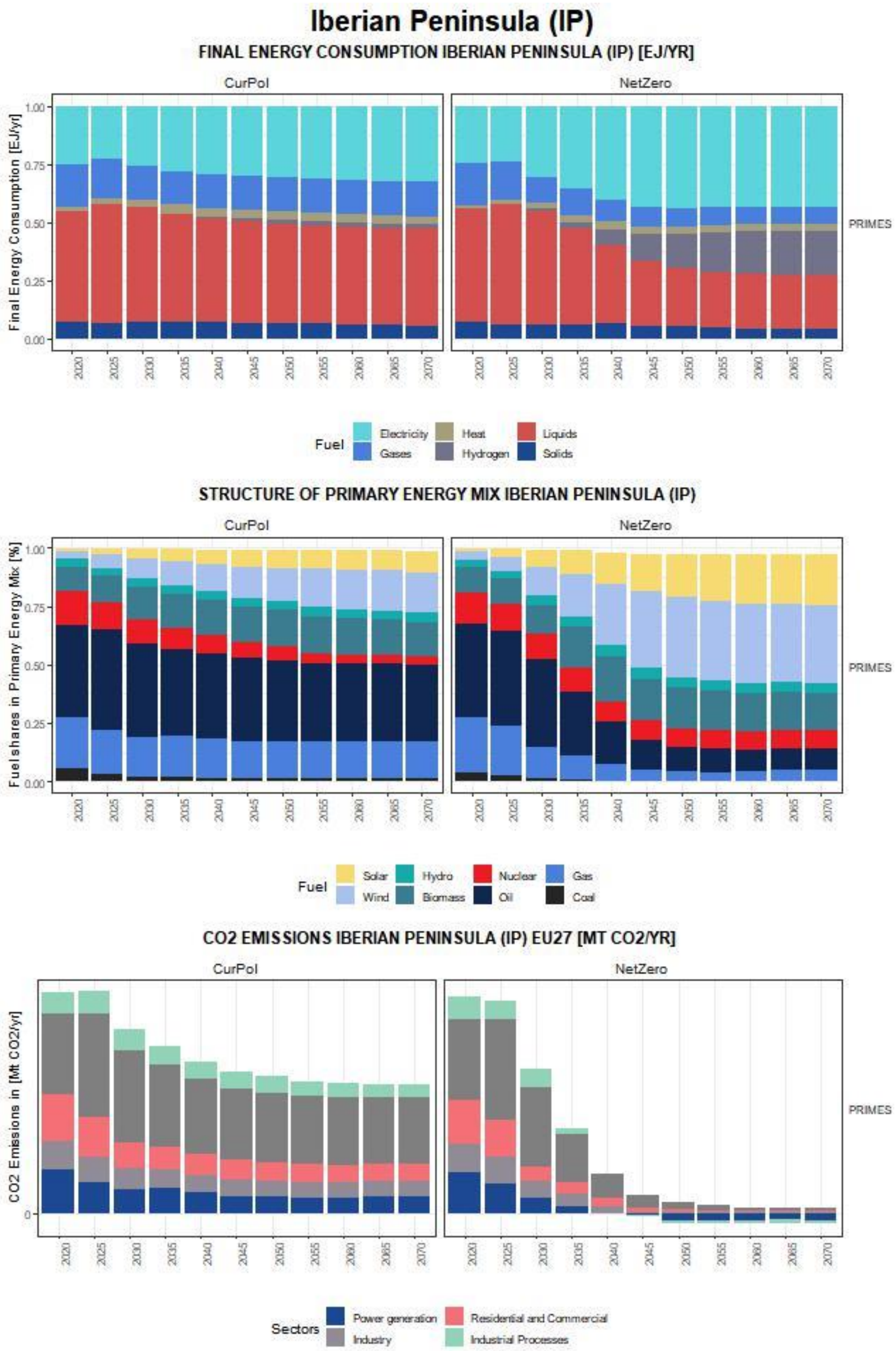

Figure A 5 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: Iberian Peninsula

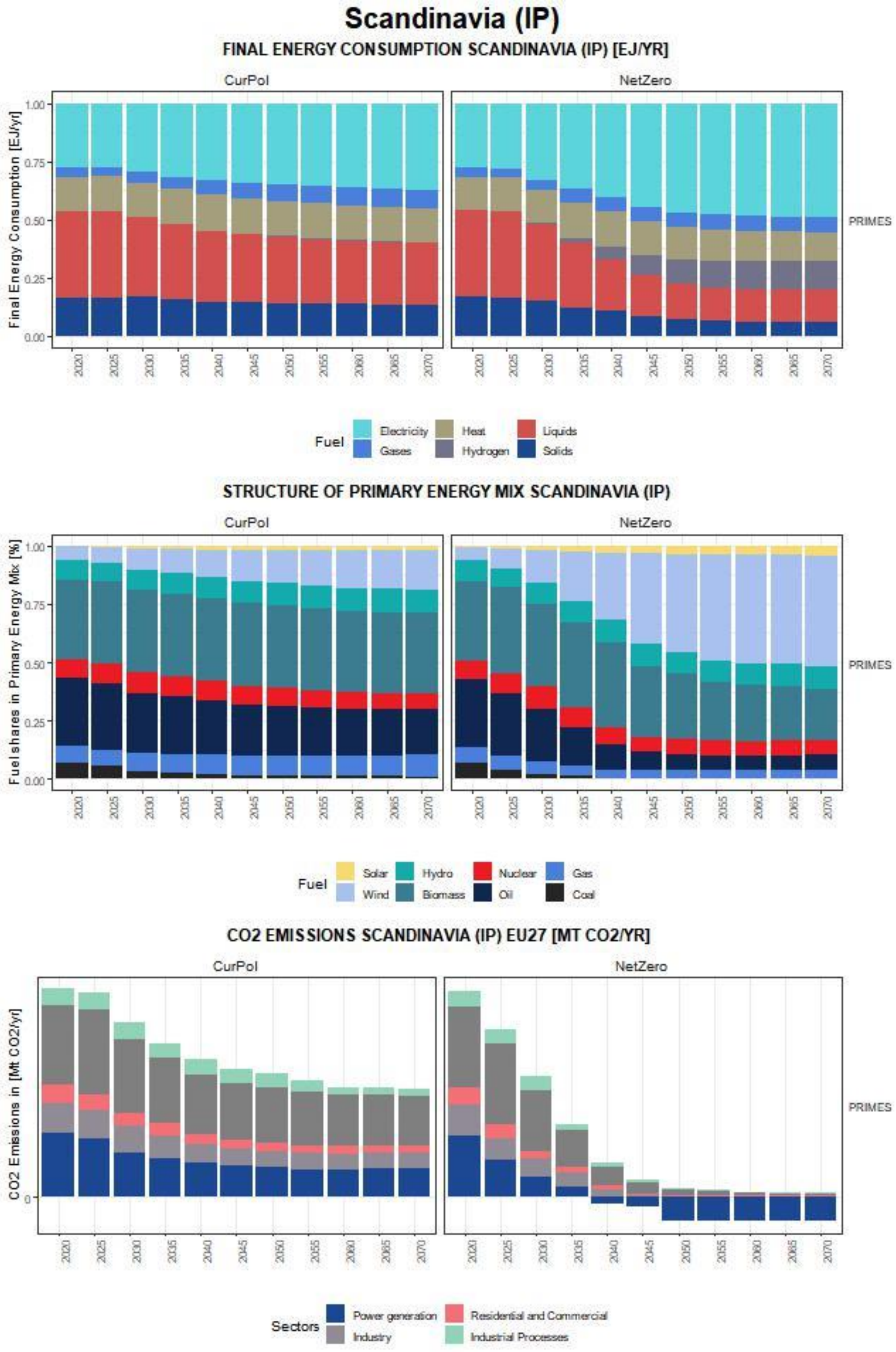

Figure A 6 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: Scandinavia

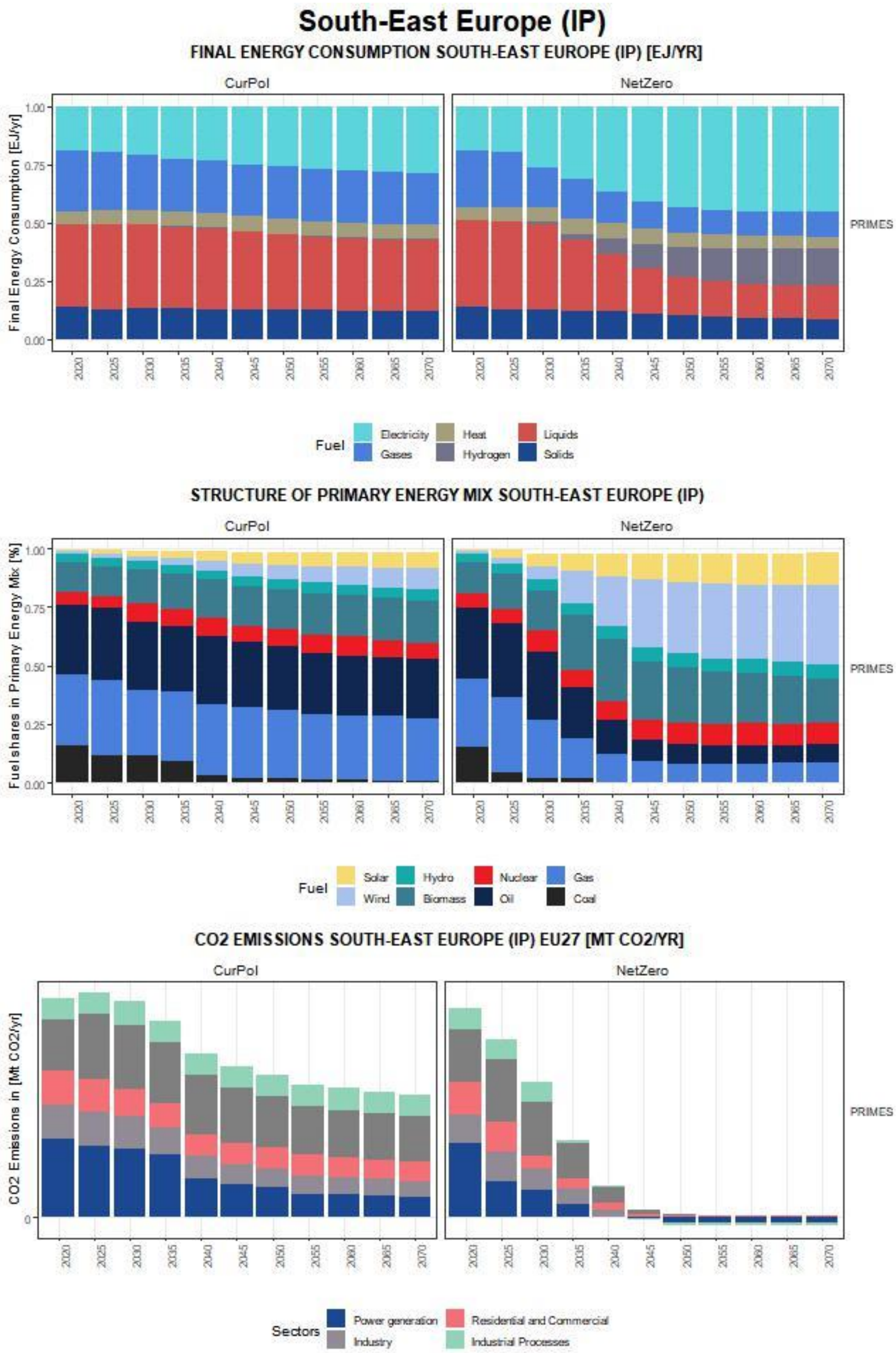

Figure A 7 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: South-East Europe

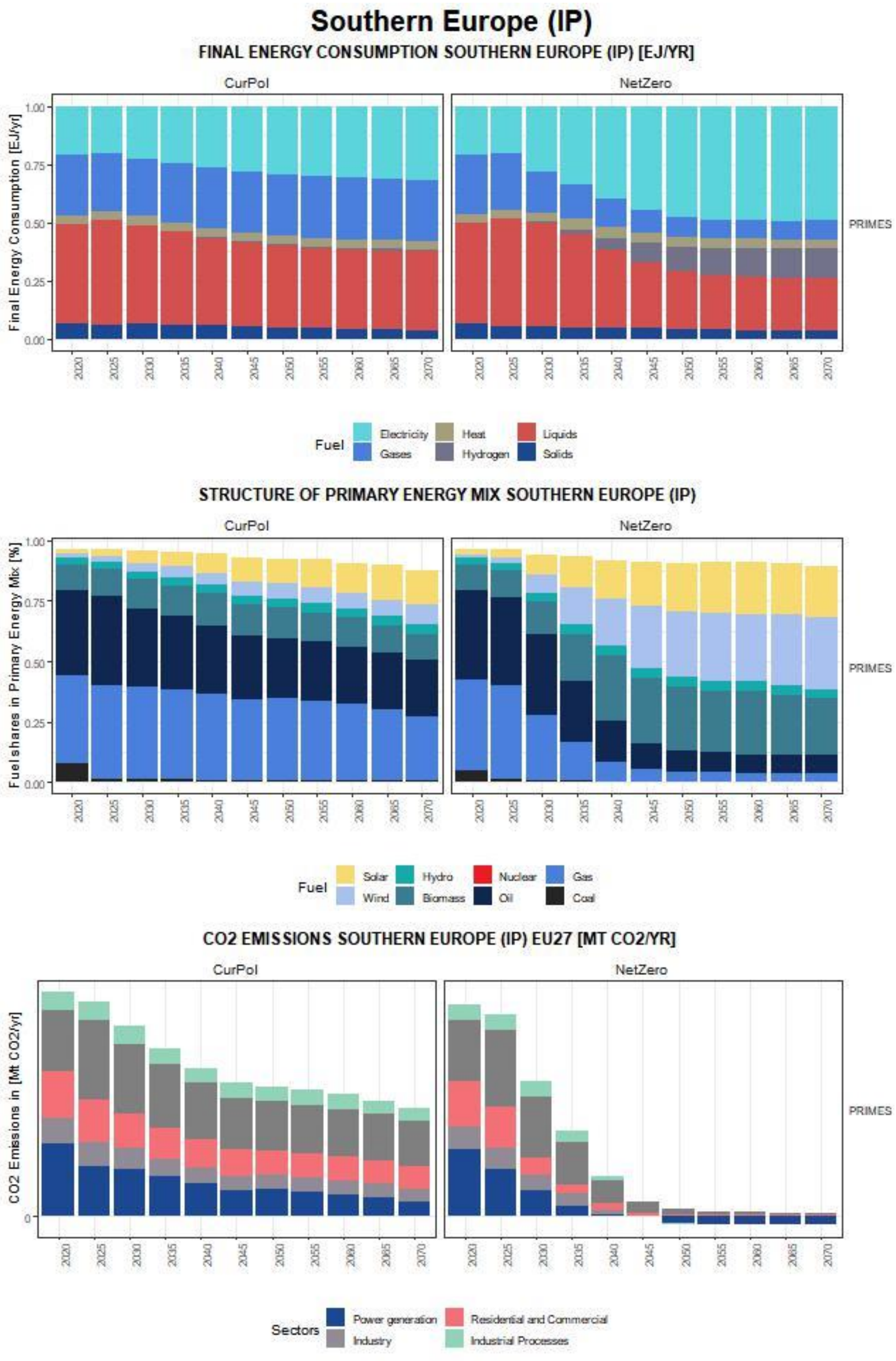

Figure A 8 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: Southern Europe

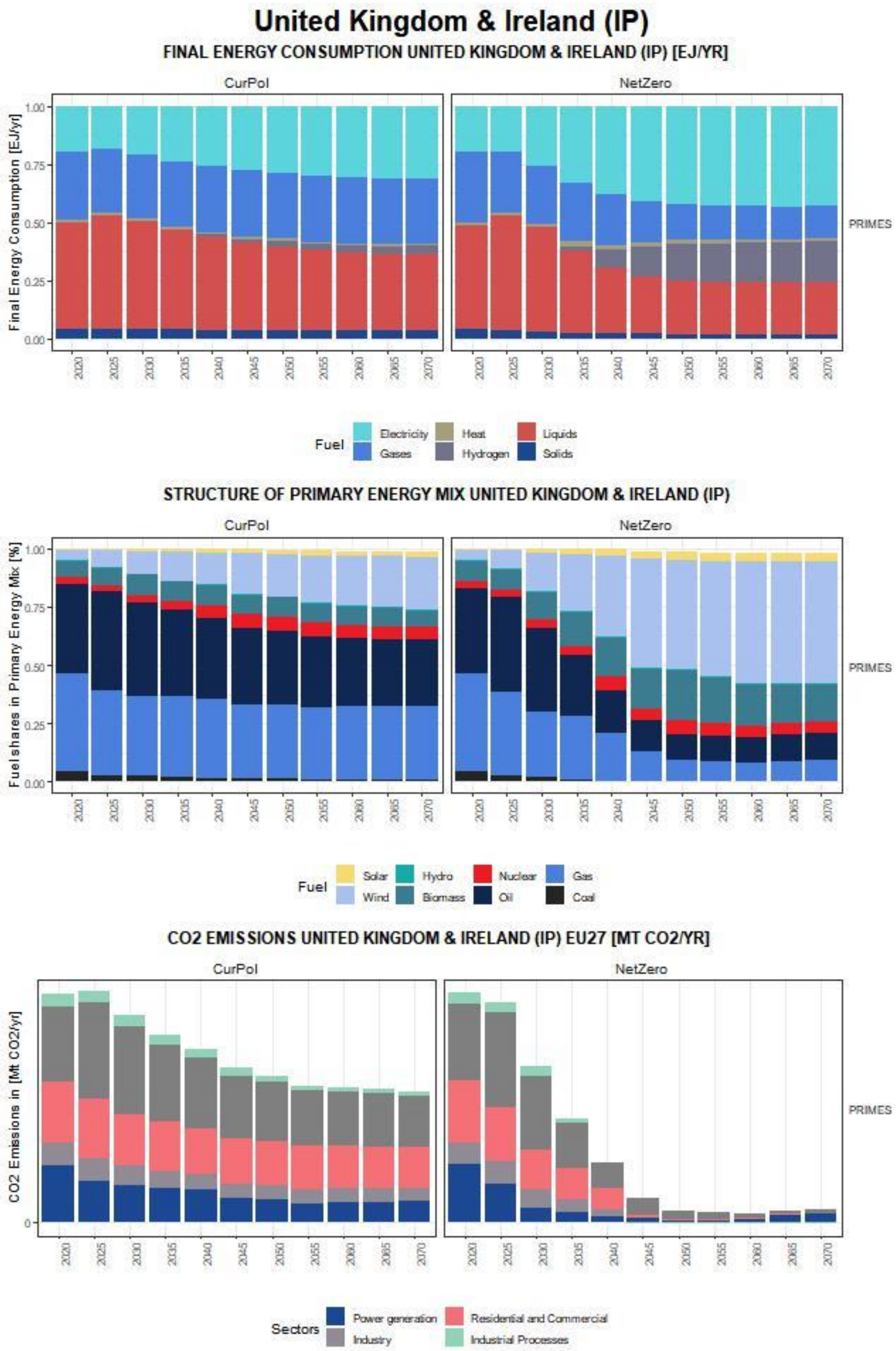

Figure A 9 – Primary and final energy consumption mix, emissions by sector. Source: PRIMES results: UK and Ireland

5.2 PCR-GLOBWB Tier 1 results at the global scale

An example of the Tier 1 runs at the global scale are given below. Further information on changes in water demand and water shortages by sectors are given in deliverable D5.2 on global evidence.

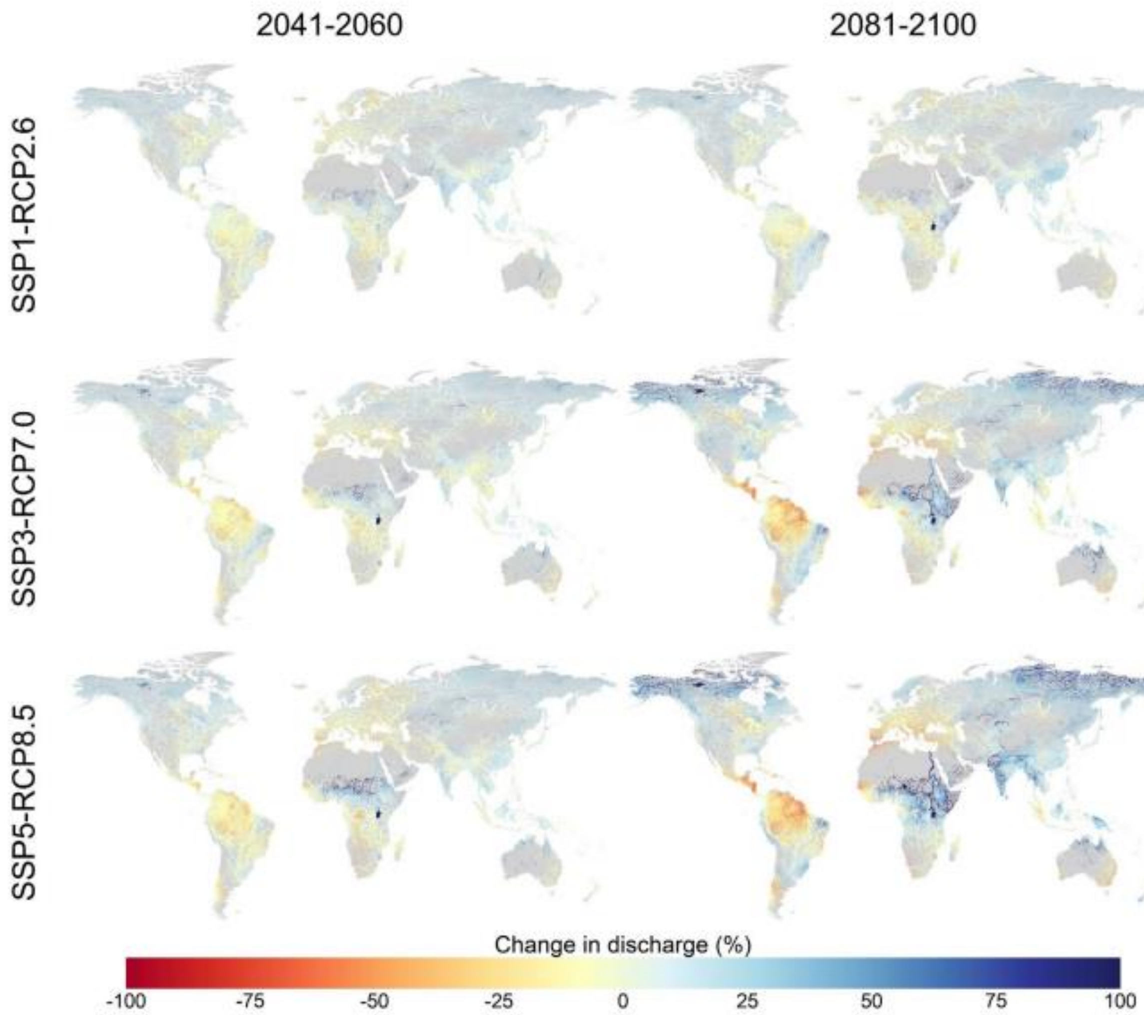

Figure A 10 - Percentage changes in discharge in the time periods 2041-2060 and 2081-2100 under three combined climate and socio-economic scenarios, relative to a historical reference period.

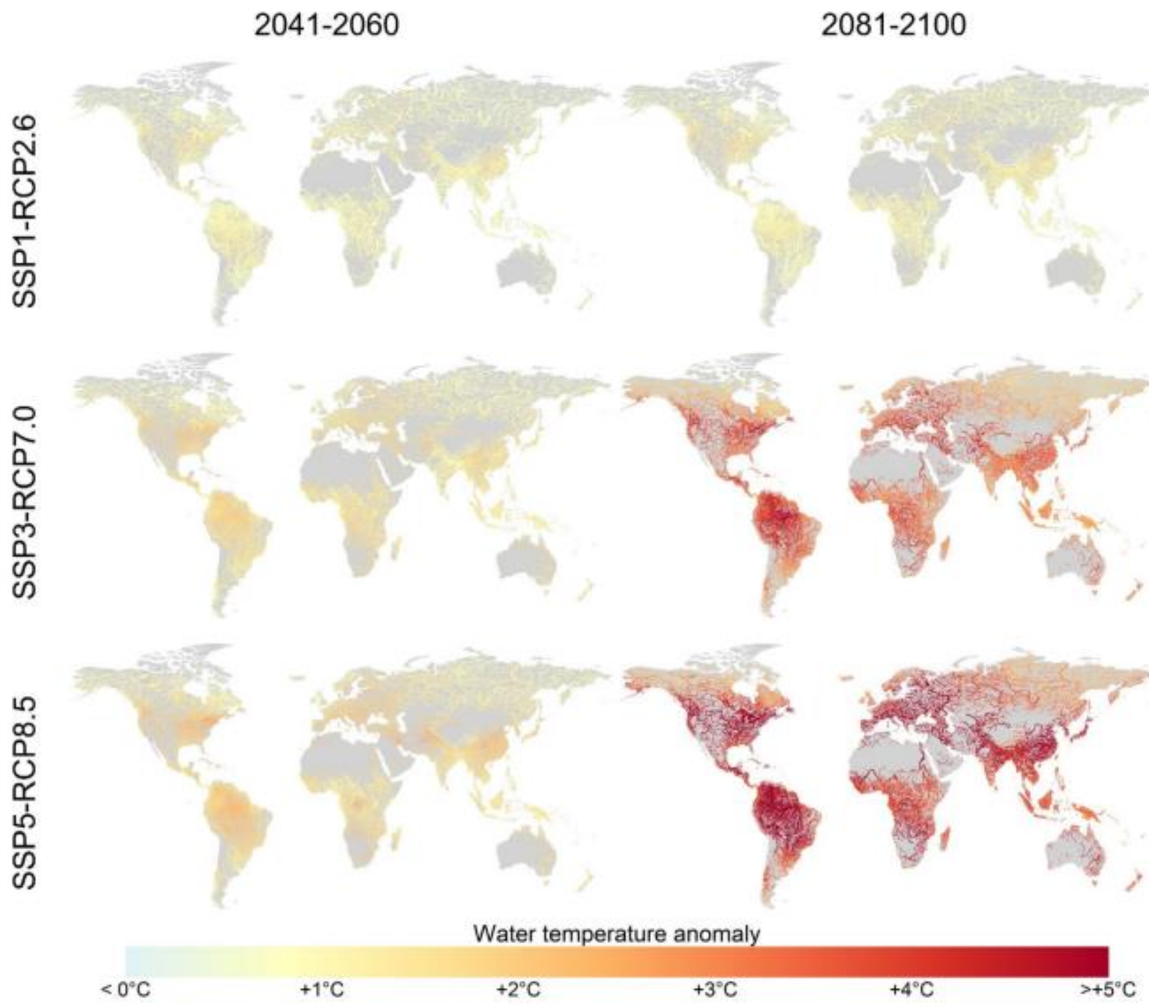

Figure A 11 - Changes in yearly average surface water temperature (℃) in the time periods 2041-2060 and 2081-2100 under three combined climate and socio-economic scenarios, relative to a historical reference period.