Deliverable D5.2: Baseline Global WEFE nexus evidence

Marc Bierkens (UU); Maria Blanco (UPM); Imen Arfa (UPM); Kristina Govorukha (E3M), Zoi Vrontisi (E3M), Dimitris , Panagiotis Fragkos (E3M); Aafke Schipper (PBL)

WP5

Version 3.0, July 2024

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Lead by UU
Marc Bierkens (UU)

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Abstract

This deliverable is the main result of task 5.2. It provides an overview of the WEFE nexus at the global scale for the baseline scenarios: SSP-RCP scenarios: Tier 1 (stand-alone) runs and selected indicators of the global WEFE nexus per model. The target audiences are the GoNEXUS partners, scientists working on global-scale WEFE modelling, and global institutions and NGOs interested in global assessments and policy support for Water, Energy, Food and the Environment (e.g., World Bank, UNESCO, UNEP, WRI). It is also relevant for WEFE EU directives such as the Water Framework Directive, the Common Agricultural Policy, the Energy Directive and the EU Green Deal. It will be used in Task 6.2.

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Version History

Version	Date	Authors	Description
V0.1 and V1.1	20/11/2023	Marc Bierkens (UU), Maria Blanco (UPM), Imen Arfa (UPM), Kristina Govorukha (E3M), Aafke Schipper (PBL)	Generation of first draft.
V2.1	28/02/2024	Marc Bierkens (UU), Maria Blanco (UPM), Imen Arfa (UPM), Kristina Govorukha (E3M), Aafke Schipper (PBL)	Second Draft.
V2.2	01/07/2024	Marc Bierkens (UU), Maria Blanco (UPM), Imen Arfa (UPM), Kristina Govorukha (E3M), Aafke Schipper (PBL)	Second draft version 2
V3.0	17/07/2024	Marc Bierkens (UU), Maria Blanco (UPM), Imen Arfa (UPM), Kristina Govorukha (E3M), Aafke Schipper (PBL)	Version submitted; after external review by Hector Macian Sorribes (UPV), Juan Manuel Carricondo Antón (UPV), Paolo Burlando (ETH) and Daniele Peano (CMCC)

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1 Introduction

The thematic models (water, energy, food, ecosystem) used for the global assessment of the WEFE nexus in GoNEXUS have been improved and are operational (see D5.1 and D5.6 for the description of the models and their improvements). They are currently employed by the consortium members for research and policy-making, including some of the models used by the European Commission (as well as other policy-making institutions such as the Organisation for Economic Co-operation and Development (OECD) or the World Bank), for impact assessments and the analysis of policy options. The model set includes operational climate-water, climate-energy, climate-biodiversity, and land use-economic models (e.g. agro-economic models), with most of them considering the interdependencies of only a few sectors and no single one taking into account all the four components of the nexus together with climate change.

At the global level this deliverable assesses the WEFE nexus using the global hydrology and water resources model PCR-GLOBWB, the agroeconomic model CAPRI the energy model PROMETHEUS and the global biodiversity model GLOBIO. These models provide a diagnosis of changes to the WEFE nexus at the global scale under the baseline scenario (SSP-RCP scenarios: Tier 1 runs). From the Tier 1 scenario results (reported in D3.2), indicators are calculated that will be used to characterize the WEFE nexus from a multi-attribute perspective.

2 Global models level WEFE

2.1 Global WEFE models used

Table 1. Global model models in GoNEXUS

Model feature	PCR-GLOBWB	CAPRI	PROMETHEUS	GEM-E3	GLOBIO
Model type	Global hydrology and water resources rainfall model	Global agro-economic model with regionalized EU detail	Global macro-econometric energy, environment and economy model	Multi-regional, multi-sectoral, general equilibrium (CGE) model	Global biodiversity model
Main topics	- climate and socioeconomic change impact assessment - water abstraction - water availability	- agricultural trade, - bioenergy - water policies, -climate impacts	-energy balances -CO_2 emissions -energy technology penetration, -prices and costs.	Macro-economy and its interaction with the environment and the energy system	Freshwater fish species distributions and diversity
Nexus components	Water, land, climate	Food, water, bioenergy, environment, climate	Energy, climate, environment	Energy, Environment, Economy	Environment, biodiversity
Geographic coverage	Global	Global	Global	Global	Global
Spatial resolution	5 arcminutes (about 10x10 km)	World regions	World regions	World regions	5 arcminutes (about 10x10 km)
Application to case studies	Global	Global and European	Global?	Global	Global
Time step	Daily	Annual	Annual	Decadal	decadal
Time frame	Until 2100	Until 2050	Until 2050	Until 2050	Until 2100
Partner	UU	UPM	E3M	E3M	PBL

Five global thematic models are used in GoNEXUS, the main features of which are presented in Table 1. For an extensive description of the model setup and model improvement we refer to deliverables 3.1 and 3.6. Figure 1 provides a schematic on how the models have been coupled in the Tier 2simulations. Results of these simulations will be presented in Deliverable D3.4.

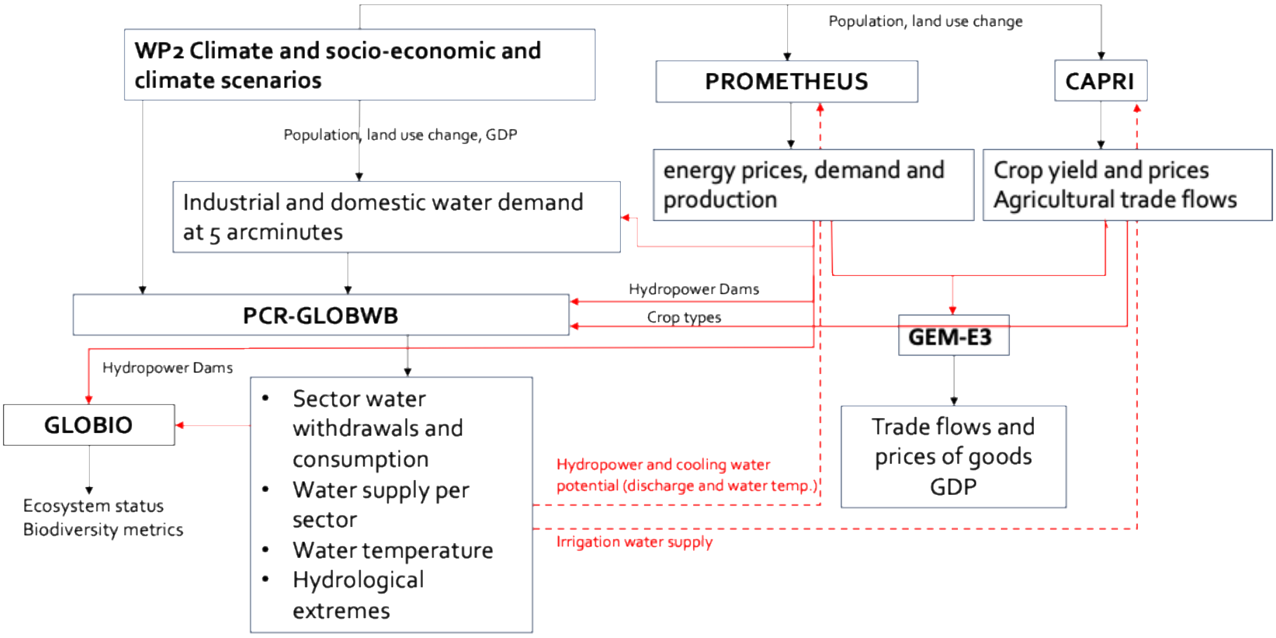

Figure 1. Model interdependencies across the WEFE nexus in Tier 2 simulations

2.2 Indicators reported

Table 2 provides a list of the indicators that will be reported per model. Together these indicators represent the nexus and its trade-offs.

Table 2. WEFE Indicators reported by each model

WEFE Element/Model	**Global Indicators**
Water/PCR-GLOBWB	Water demand per sector, water gap per sector, water stress index (maps plus global aggregates), water temperature (maps)
Energy/PROMETHEUS	Power generation (including hydropower generation), installed capacity (including hydropower; e.g., run of river, pumped storages), energy prices by sector and fuel, energy demand by sector and fuel, domestic production of bioenergy (incl. bio solids, biogas, biofuels), fuel consumption in bioenergy production, bioenergy consumption by sector.
Food/CAPRI	Irrigated and rain-fed agricultural area, food production, crop yields, water use for irrigation
Ecosystems/GLOBIO	Potentially lost range (PLR; %) for each freshwater fish species; potentially affected fraction (PAF; 0-1) of freshwater fish species per grid cell
Financial-economic/GEM-E3	Producer prices, income
Land/CAPRI	Irrigated and rain-fed agricultural area
Carbon emission/PROMETHEUS	GHG emissions by sector (energy, transport, buildings, services and industry)

3 Baseline scenarios

In this deliverable we will use three main scenarios named "Sustainable Development," "Weak cooperation," and "The Wong Way". These policies relevant WEFE scenarios align with the climate, socioeconomic, and land use scenarios used in CMIP6 (Eyring et al., 2016; O'Neil et al., 2016) as follows (See D2.1 for a more elaborate description of these scenarios):

- "Sustainable development" aligned with SSP1-2.6
- "Weak cooperation" aligned with SSP3-7.0
- "The wrong way" aligned with SSP5-8.5

The policy-relevant WEFE scenarios are baseline scenarios that represent future trends of the system assuming **no additional** policies beyond those already in place. A baseline scenario serves as a comparison or counterfactual scenario to assess impacts of alternative scenarios (e.g. policy changes), therefore, they will serve to assess the different solution (WP7) within the framework of the project. Figure 2 shows representative hypothetical trajectories of the three main policy-relevant WEFE scenarios and the reference period. In the "Sustainable development" scenario (depicted in green), more positive impacts (Less water scarcity, less ecosystem damage, reduced energy demands) on WEFE indicators are expected, while in "The wrong way" scenario (depicted in red), more negative impacts are expected.

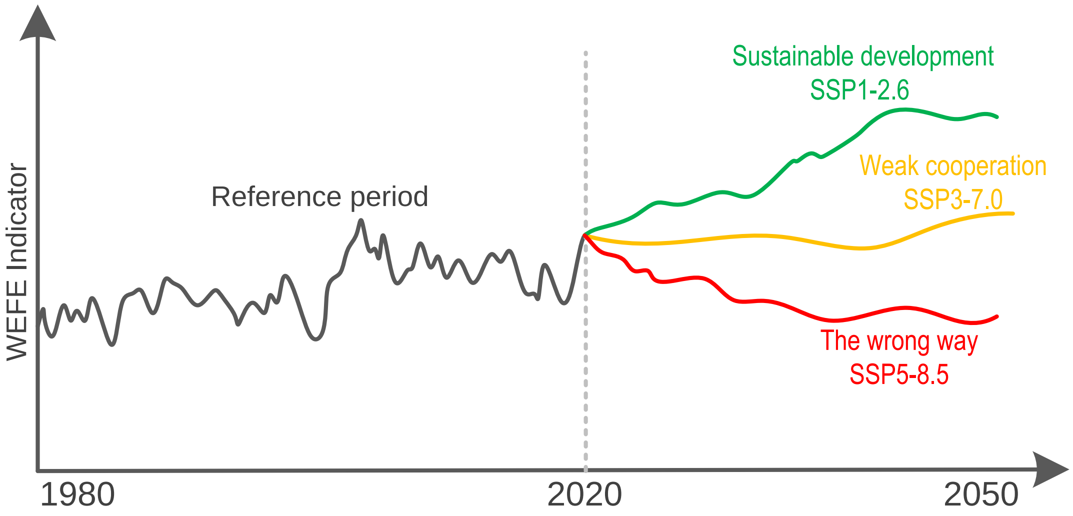

Figure 2. Illustration of the policy-relevant baseline WEFE scenarios in contrast and the reference period. The WEFE indicator could be any indicator related to a WEFE component, for instance Irrigation water gap when referring to the Water part of agricultural water use. Source: own elaboration.

The global scenario development is extensively described in D3.2. In this deliverable, two sets of scenario runs are made. In the Tier 1 runs, each global model is run separately with its own socioeconomic and climate forcing. In the Tier 2 runs the models have been interconnected (see D3.2 and Figure 1). The Tier 2 runs are still in production at the time of the calculation of the indicators, it proved not to be possible to have the global evidence ready for this deliverable. These will be presented in D3.4 along with a comparison with the Tier 1 runs. Therefore, the global indicators will be provided for the Tier 1 runs only for the following scenarios:

Table 3 Validation, reference and baseline scenarios (no additional policies) for the Tier 1 runs

Simulations	***Models***	***Scenario type** (time frame)*
Reconstructed land use and water demand		
Observed meteorological forcing	W5E5	Validation (1960-2019)
Historical climate simulations	GFDL-ESM4 IPSL-CM6A-LR MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL	Reference for impact (1979-2019)
	Socio-economic conditions	**Scenario**
Projections based on climate and socioeconomic scenario (baseline scanarios; no additional policies)		
Policy relevant scenarios	***Projected WEFE nexus***	
Sustainable development	SSP1-RCP2.6	Impact (2020-2100)
Weak cooperation	SSP3-RCP7.0	Impact (2020-2100)
The wrong way	SSP5-RCP8.5	Impact (not PROMETHEUS) (2020-2100)

4 Baseline scenario results

4.1 Water: PCR-GLOBWB

Figure 3 shows maps of river discharge (calculated with PCR-GLOBWB) and surface water temperature (calculated with DynQual) for the three combined SSP-RCP Tier 1 baseline scenarios. Figure 4 displays the water temperature. We see reductions in discharge in the Mediterranean, Northern South America and Southern Africa. High-end scenarios show large increases of water temperature, most notably in regions with decreasing discharge (Figure 4).

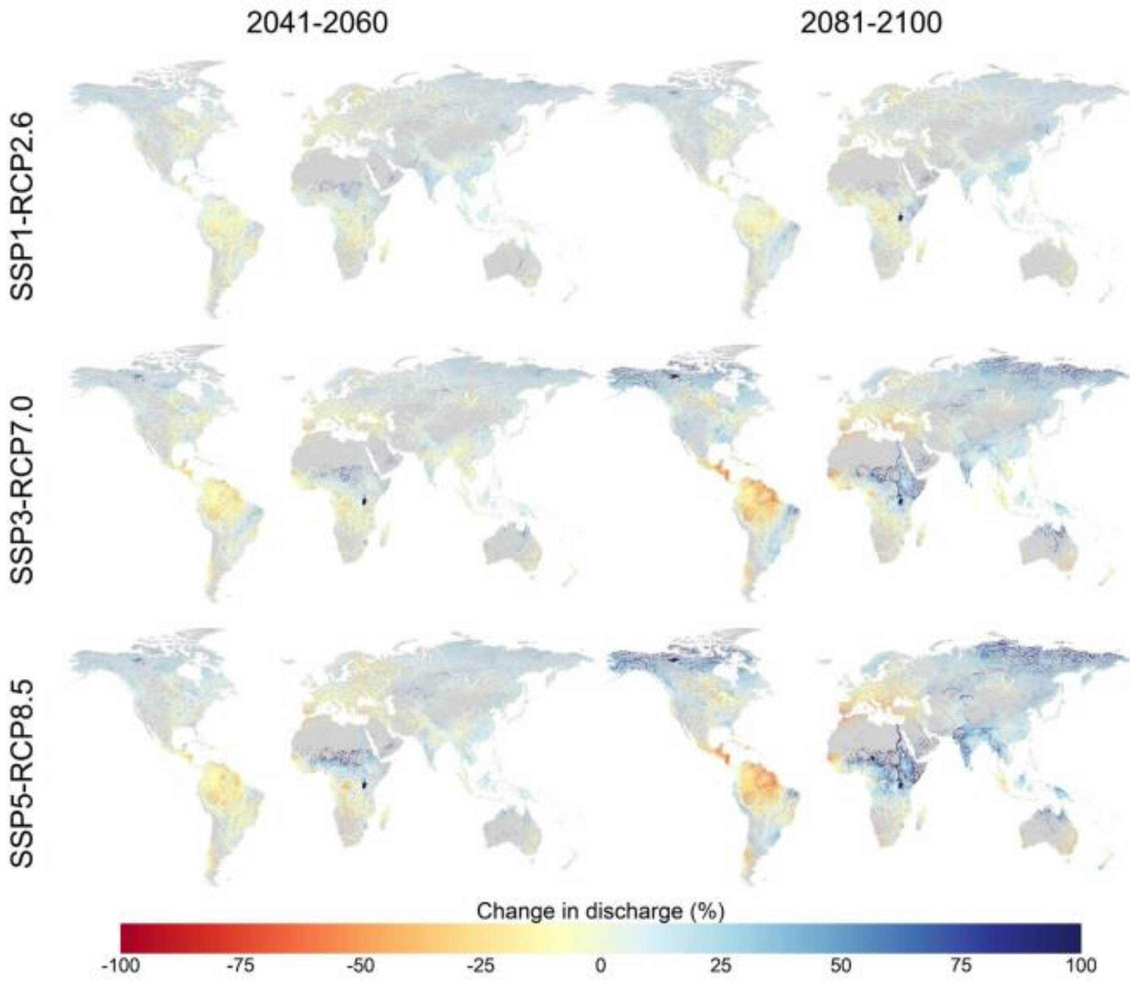

Figure 3. Percentage changes in discharge in the time periods 2041-2060 and 2081-2100 under three combined climate and socio-economic scenarios, relative to a historical reference period (1979-2019) as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

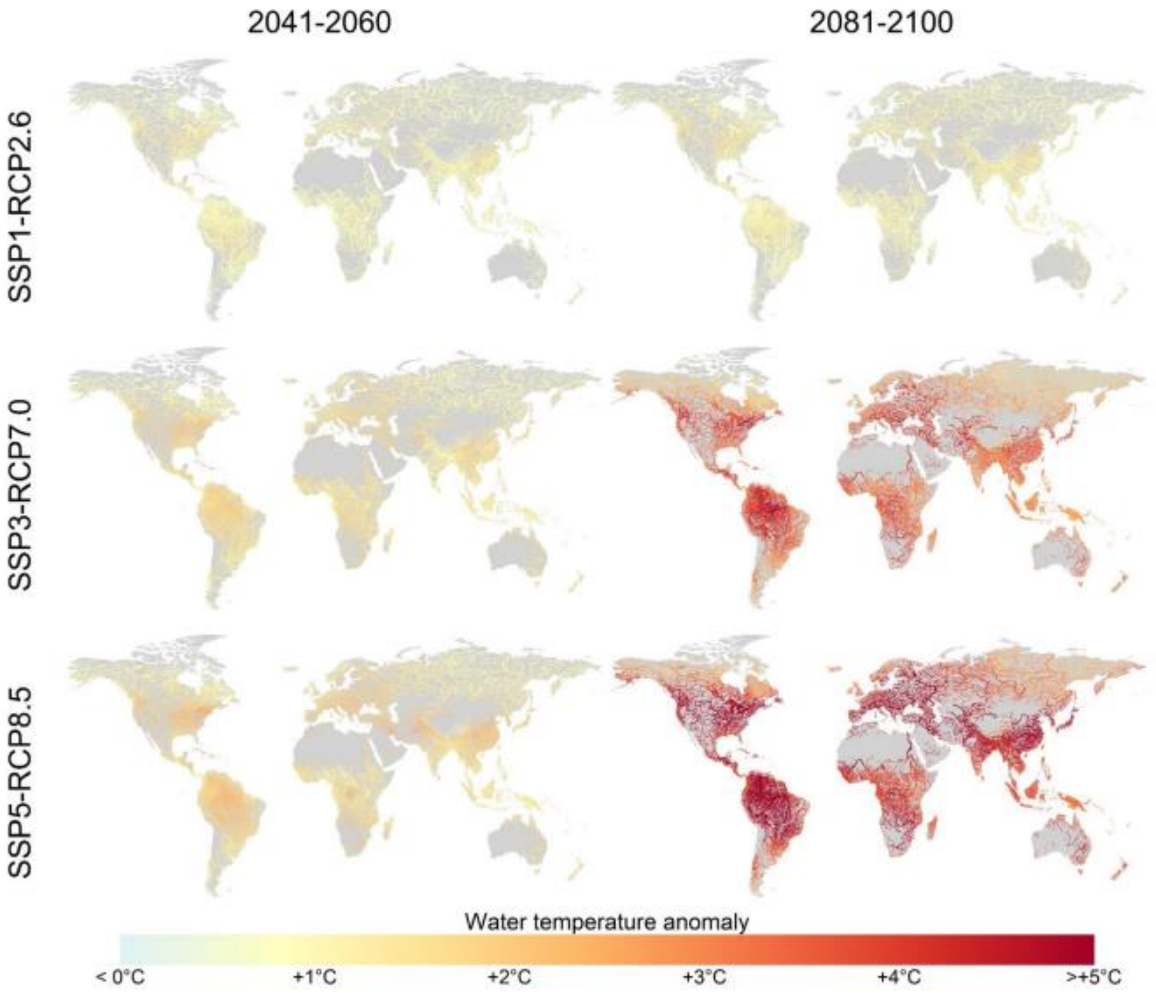

Figure 4. Changes in yearly average surface water temperature (℃) in the time periods 2041-2060 and 2081- 2100 under three combined climate and socio-economic scenarios, relative to a historical reference) period (1979-2019 as calculated with PCR-GLOBWB and DynQual (Tier 1 baseline scenarios).

Figure 5 shows the change in water withdrawal and water gap[1] with time under the three combined climate and socio-economic scenarios. In all scenarios, the water withdrawn is increasing, but mostly under the high-end scenarios SSP3-RCP7.0 and SSP5-RCP8.5. The water gap is increasing accordingly, but differences between scenarios are less clear.

Figure 6 shows for three time slices bar plots of water source and for which sector this water is supplied. Non-renewable groundwater use is increasing proportionally to total water withdrawal. Also, the proportion of domestic and industrial water withdrawal is increasing in the two high-end scenarios.

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[1] The water gap is the total sum of positive increments of (demand – withdrawal of renewable water). In Tier 1 this is set equal to non-renewable groundwater withdrawal.

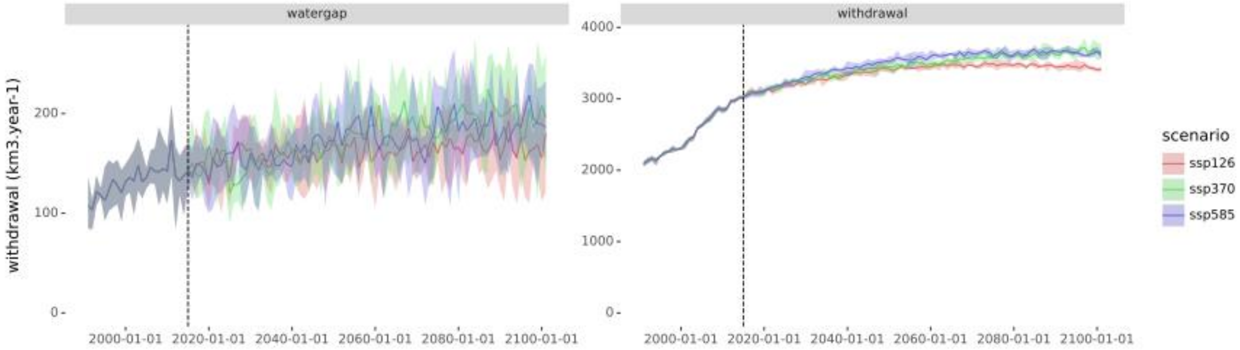


Figure 5. Evolution of water withdrawal (right) and water gap (left) from 1990-2100 under three combined climate and socio-economic scenarios as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

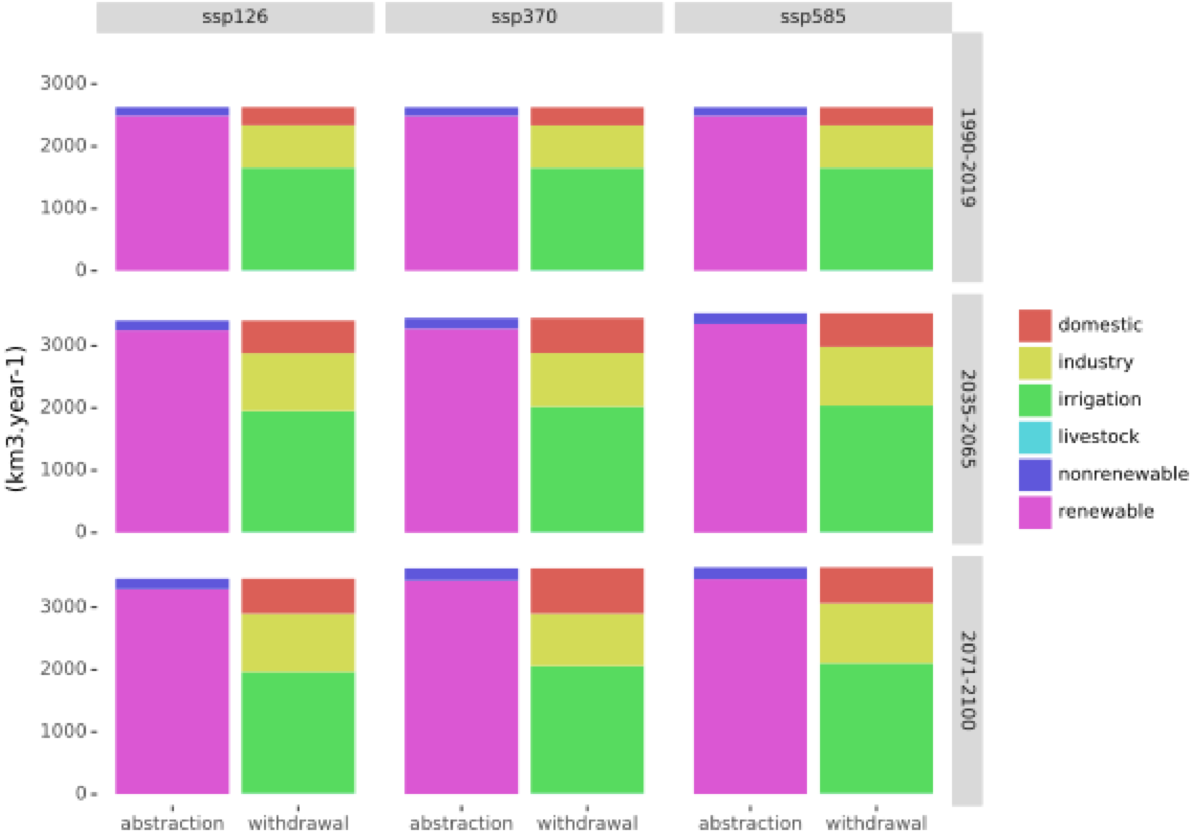


Figure 6. Sources of water withdrawal and sectoral water supply under three combined climate and socio-economic scenarios and calculate with PCR-GLOBWB (Tier 1 baseline scenarios).

Figures 7,8 and 9 show maps of the water gap for two time slices and two scenarios for the irrigation, industry and domestic sector respectively. The patterns of water gaps are different between sectors, but the totals are increasing, especially for the SSP3-RCP7.0 scenario. Note that to reduce the number of figures we have shown only the most likely scenario (SSP3-RCP7.0) and the scenario that is indicative for sustainable development (SSP1-RCP2.6). The SSP5-RCP8.5 results are available on the YODA data repository of the project.

Irrigation water gap

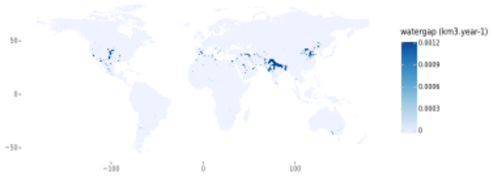
	1990-2019	2071-2100
SSP1-RCP2.6		
SSP3-RCP7.0		

Figure 7. Current water gap (1990-2019) and projected future water gap (2071-2100) for the irrigation sector under scenarios SSP1-RCP2.6 and SSP3-RCP7.0 as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

Industrial water gap

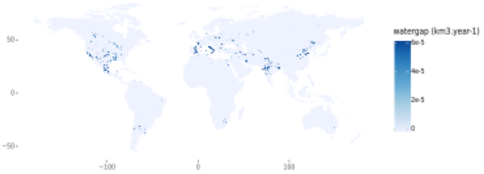
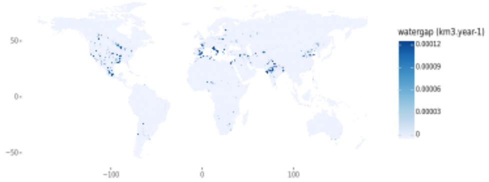
	1990-2019	2071-2100
SSP1-RCP2.6		
SSP3-RCP7.0		

Figure 8. Current water gap (1990-2019) and projected future water gap (2071-2100) for the industrial sector under scenarios SSP1-RCP2.6 and SSP3-RCP7.0 as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

Domestic water gap

	1990-2019	2071-2100
SSP1-RCP2.6		
SSP3-RCP7.0		

Figure 9. Current water gap (1990-2019) and projected future water gap (2071-2100) for the domestic sector under scenarios SSP1-RCP2.6 and SSP3-RCP7.0 as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

Figure 10 shows the change in the globally averaged water scarcity index[2] (cf. Wada et al., 2011) with time under the three combined climate and socio-economic scenarios. In all scenarios, the water scarcity index, a measure of water stress, is increasing, but mostly under the high-end scenarios SSP3-RCP7.0 and SSP5-RCP8.5.

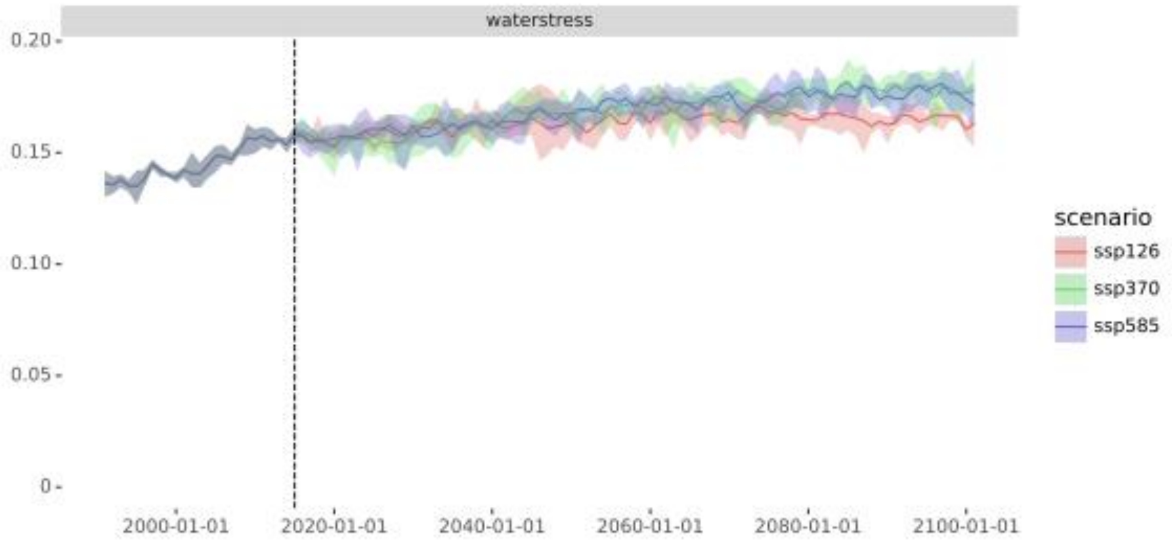


Figure 10. Evolution of the global average water scarcity index from 1990-2100 under three combined climate and socio-economic scenarios as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

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[2] The water scarcity index is obtained by 1) calculating per pixel per month the ratio of the total sectoral water demand and the renewable water availability (effectively discharge);2) calculating from the monthly ratios a yearly average value. If the water scarcity index exceeds 0.4, a region is presumed under water stress.

Figure 11 shows maps of the water scarcity index (WCI) for the current time and for two scenarios for the period 2071-2100. It shows that many areas experience water stress (WCI >0.4) and some of the heavily irrigated areas in semi-arid zones even severe water stress (WCI > 0.8).

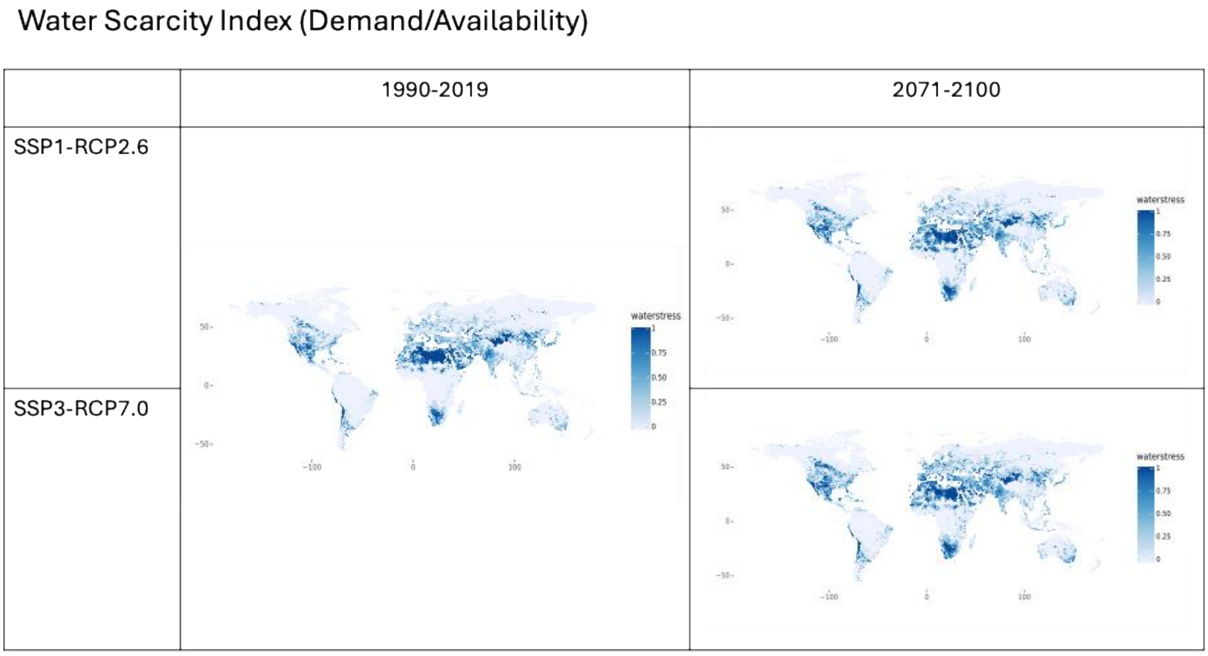


Figure 11. Current water scarcity index (1990-2019) and projected future water scarcity (2071-2100) under scenarios SSP1-RCP2.6 and SSP3-RCP7.0 as calculated with PCR-GLOBWB (Tier 1 baseline scenarios).

Looking at all the global results from PCR-GLOBWB it is evident that sectoral water demand, water scarcity and the use of non-renewable groundwater are increasing under all scenarios. However, the increase is largest under SSP3-RCP7.0 and SSP5-RCP8.5. The fact that there is still a significant increase under SSP1-RCP2.6 is due to the warming impact that is still there under this scenario and its effect on water demand, but also because in a world of reduced emissions, the demand for crops (food but also energy crops) is not reducing and irrigated agriculture is the largest water user. The differences between SSP3-RCP7.0 and SSP5-RCP8.5 are small. This is because the increased water demand under more warming under RCP8.5 is (partly) offset by reduced water demand by a more effective global trade under the globalized world of SSP5. The maps show that the increases in water gap and water scarcity are relatively small and occur mostly at the same regions of the world. This may also be a reflection of the fact that growth in sectoral water demand regions such as sub-Saharan Africa are not that well represented in the socioeconomic scenarios.

4.2 Food/Water: CAPRI

Description of the model

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 module focuses on water-related issues in agriculture, it provides essential insights into irrigation and sectoral water use, water efficiency, and water related policy impacts. CAPRI water is integrated into both the supply module and the market module.

For instance, the water module integrates irrigation for crops into the supply module at the NUTS 2 level, involving the following:

Land is categorized as irrigable (equipped for irrigation) where water input can be supplemented with irrigation and rain-fed which only receive water input from precipitation, and non-irrigated land. This categorization aligns with the land balance in the supply module.
Crop production activities are split into rain-fed and irrigated variants. Input-output coefficients are estimated for both irrigated and rain-fed crop variants.
Water for irrigated crop variants is included as a production factor by considering crop-specific water requirements, irrigation/rain-fed shares, irrigated to rain-fed yield ratio, irrigation efficiency and price/cost.

Also, in the water module, a water balance is computed. The approach balances the water withdrawal and use in the domestic, industrial, energy, irrigation and livestock sectors, with water availability. The water balance involves the following:

The total water use cannot exceed water availability
Water allocation usually give priority to urban and livestock uses compared to irrigation.
Irrigation water use cannot exceed the potential available water for irrigation at NUTS 2 level.
Livestock water use includes both daily drinking and service water requirements. While irrigation water availability is constraint, livestock water is not.

Furthermore, the water module in CAPRI differentiates irrigation water use by source. Several water sources have been considered, including surface water, groundwater, desalinated water and reused treated water.

Scenarios definition

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.

In this project, n climate scenarios and three baseline scenarios have been analysed:

NoCC (no climate changes effects): SSP1, SSP3 and SSP5 with no climate change effects on crop yields and crop water requirements.

Baselines with Climate change effects: SSP1-RCP2.6, SSP3-RCP7.0, and SSP5-RCP8.5. (using one GCM: UKESM-1-0-LL GCM): shifters on crop yield (irrigated and rainfed), crop water requirements and non-agricultural water withdrawal provided by IIASA.

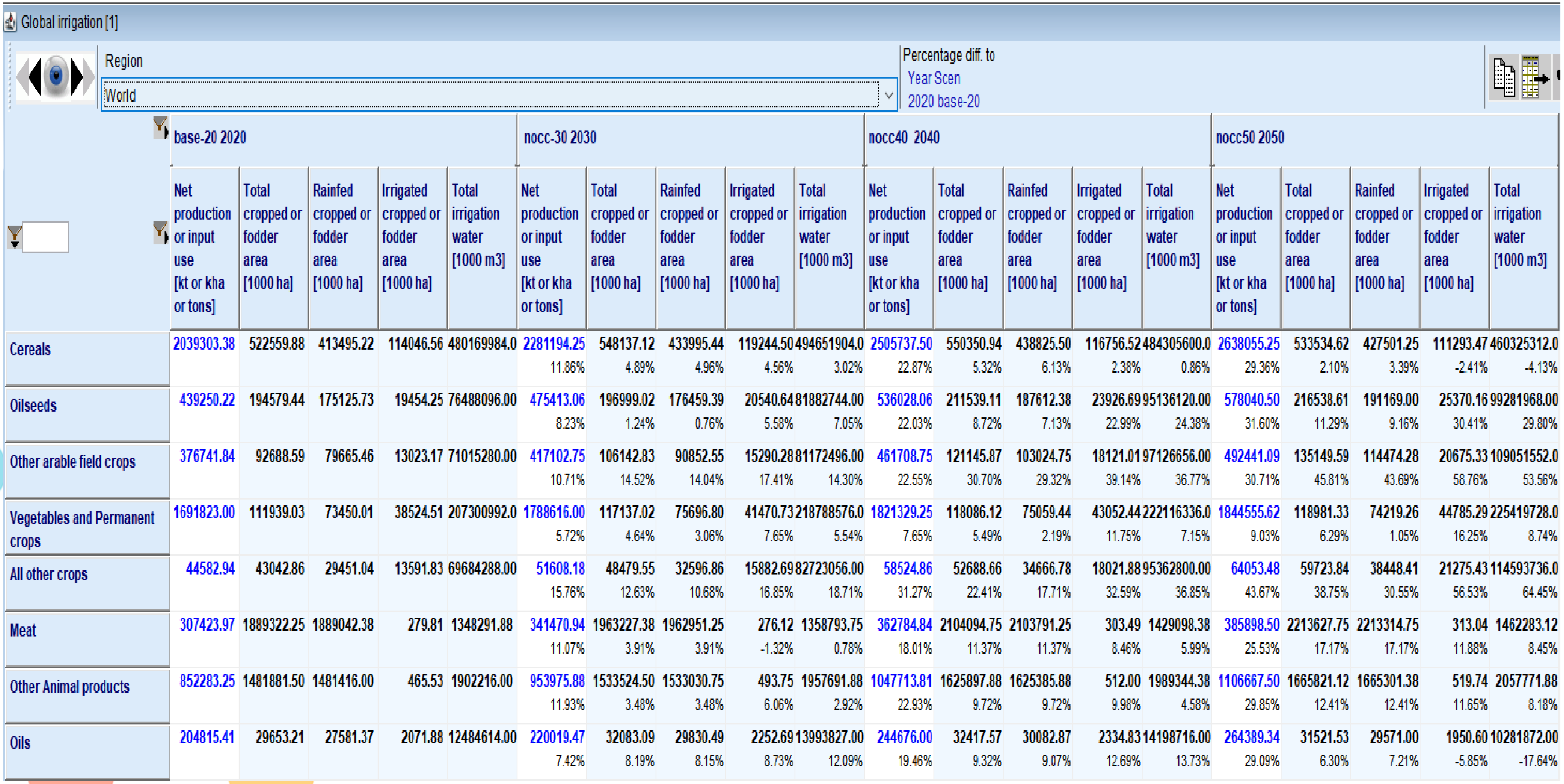
For this study, results from biophysical simulations were incorporated into the agro-economic model CAPRI, thus the integrated modelling approach allows for the analysis of the impacts of climate change on agriculture. Biophysical models project crop yield effects of climate change under various climate scenarios, and those yield effects are incorporated into agro-economic models to evaluate impacts on production and prices.

Scenarios have been run for 2020, 2030, 2040 and 2050.

- **CAPRI results without climate change**

At global level, in Table 4, we can see that the production of the selected commodities increases with the largest increase for cereals and oilseeds (29.36% and 31% respectively in 2050 compared to 2020). This increase in production is due to an 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. Water for irrigation increases for all commodities except for cereals and oils in 2050 compared to 2020 under no climate change effects.

Table 4. Global production, area and total water for irrigation under no climate change (value and % change from 2020)



Global irrigation [1]

Region: World

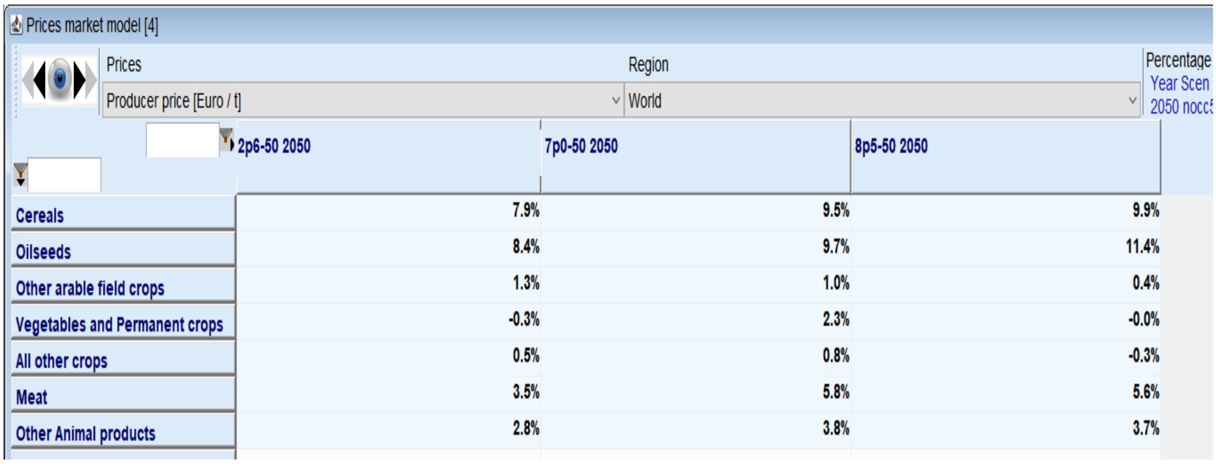
Percentage diff. to
Year Scen
2020 base-20

	base-20 2020					nocc-30 2030					nocc40 2040					nocc50 2050				
	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]
Cereals	2039303.38	522559.88	413495.22	114046.56	480169984.0	2281194.25 11.86%	548137.12 4.89%	433995.44 4.96%	119244.50 4.56%	494651904.0 3.02%	2505737.50 22.87%	550350.94 5.32%	438825.50 6.13%	116756.52 2.38%	484305600.0 0.86%	2638055.25 29.36%	533534.62 2.10%	427501.25 3.39%	111293.47 -2.41%	460325312.0 -4.13%
Oilseeds	439250.22	194579.44	175125.73	19454.25	76488096.00	475413.06 8.23%	196999.02 1.24%	176459.39 0.76%	20540.64 5.58%	81882744.00 7.05%	536028.06 22.03%	211539.11 8.72%	187612.38 7.13%	23926.69 22.99%	95136120.00 24.38%	578040.50 31.60%	216538.61 11.29%	191169.00 9.16%	25370.16 30.41%	99281968.00 29.80%
Other arable field crops	376741.84	92688.59	79665.46	13023.17	71015280.00	417102.75 10.71%	106142.83 14.52%	90852.55 14.04%	15290.28 17.41%	81172496.00 14.30%	461708.75 22.55%	121145.87 30.70%	103024.75 29.32%	18121.01 39.14%	97126656.00 36.77%	492441.09 30.71%	135149.59 45.81%	114474.28 43.69%	20675.33 58.76%	109051552.0 53.56%
Vegetables and Permanent crops	1691823.00	111939.03	73450.01	38524.51	207300992.0	1788616.00 5.72%	117137.02 4.64%	75696.80 3.06%	41470.73 7.65%	218788576.0 5.54%	1821329.25 7.65%	118086.12 5.49%	75059.44 2.19%	43052.44 11.75%	222116336.0 7.15%	1844555.62 9.03%	118981.33 6.29%	74219.26 1.05%	44785.29 16.25%	225419728.0 8.74%
All other crops	44582.94	43042.86	29451.04	13591.83	69684288.00	51608.18 15.76%	48479.55 12.63%	32596.86 10.68%	15882.69 16.85%	82723056.00 18.71%	58524.86 31.27%	52688.66 22.41%	34666.78 17.71%	18021.88 32.59%	95362800.00 36.85%	64053.48 43.67%	59723.84 38.75%	38448.41 30.55%	21275.43 56.53%	114593736.0 64.45%
Meat	307423.97	1889322.25	1889042.38	279.81	1348291.88	341470.94 11.07%	1963227.38 3.91%	1962951.25 3.91%	276.12 -1.32%	1358793.75 0.78%	362784.84 18.01%	2104094.75 11.37%	2103791.25 11.37%	303.49 8.46%	1429098.38 5.99%	385898.50 25.53%	2213627.75 17.17%	2213314.75 17.17%	313.04 11.88%	1462283.12 8.45%
Other Animal products	852283.25	1481881.50	1481416.00	465.53	1902216.00	953975.88 11.93%	1533524.50 3.48%	1533030.75 3.48%	493.75 6.06%	1957691.88 2.92%	1047713.81 22.93%	1625897.88 9.72%	1625385.88 9.72%	512.00 9.98%	1989344.38 4.58%	1106667.50 29.85%	1665821.12 12.41%	1665301.38 12.41%	519.74 11.65%	2057771.88 8.18%
Oils	204815.41	29653.21	27581.37	2071.88	12484614.00	220019.47 7.42%	32083.09 8.19%	29830.49 8.15%	2252.69 8.73%	13993827.00 12.09%	244676.00 19.46%	32417.57 9.32%	30082.87 9.07%	2334.83 12.69%	14198716.00 13.73%	264389.34 29.09%	31521.53 6.30%	29571.00 7.21%	1950.60 -5.85%	10281872.00 -17.64%

- **CAPRI results under climate and socioeconomic scenarios**

Table 5 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 those cereals and oilseed 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. This can lead to interregional adjustments in production, consumption and trade. This interconnection between production and price effects is illustrated in table 5 and 6, which summarizes the CAPRI simulated effects on global agricultural price, production and area for major commodities.

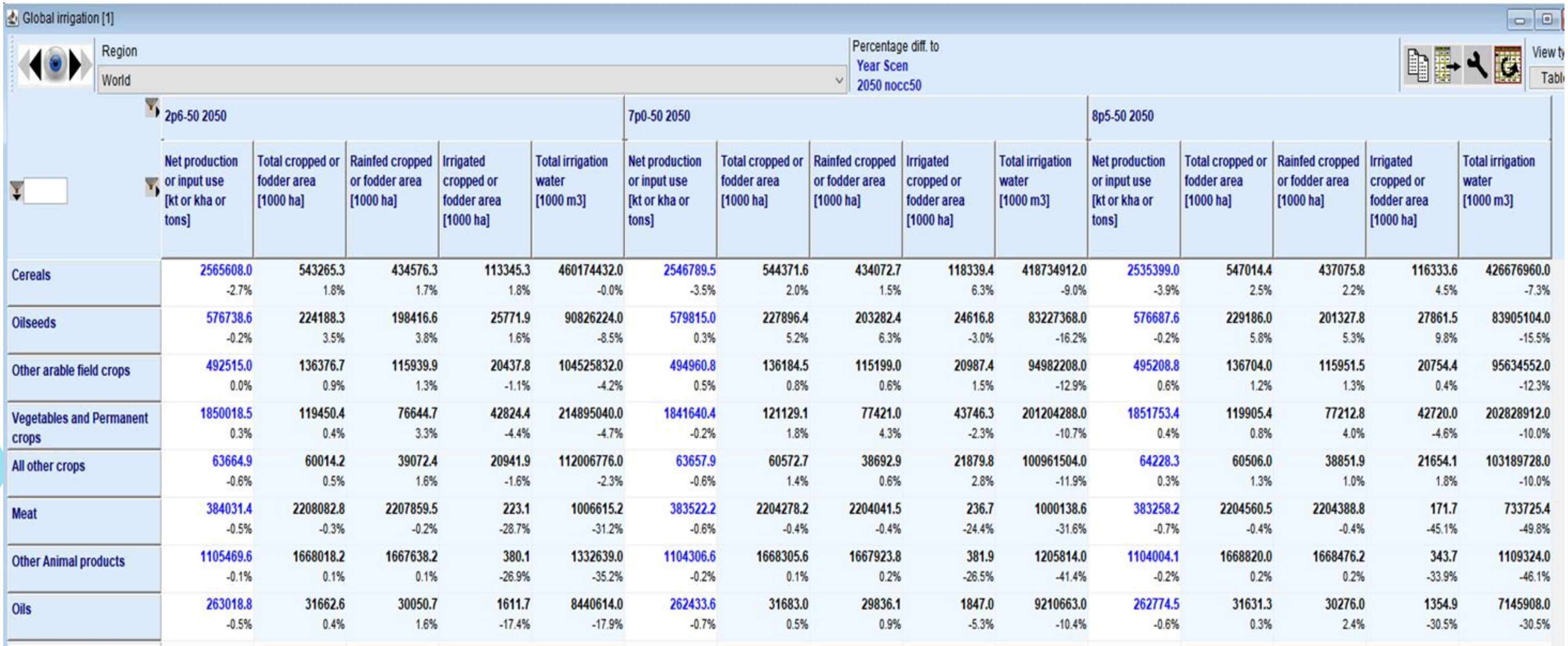
Table 5. Global producer prices result in 2050 under climate change (% change from no climate change in 2050)



	2p6-50 2050	7p0-50 2050	8p5-50 2050
Cereals	7.9%	9.5%	9.9%
Oilseeds	8.4%	9.7%	11.4%
Other arable field crops	1.3%	1.0%	0.4%
Vegetables and Permanent crops	-0.3%	2.3%	-0.0%
All other crops	0.5%	0.8%	-0.3%
Meat	3.5%	5.8%	5.6%
Other Animal products	2.8%	3.8%	3.7%

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 Table 6, total area of cereals and oilseeds increase under more climate change and compared to no climate change in 2050. However, total production decreases under more climate change even with price increase. 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 and crop water requirements, will have a bigger influence on food production patterns under climate change in 2050.

Table 6. Global production, area and total water for irrigation results under climate change in 2050 (value and % change from no climate change in 2050)



Region: World

Percentage diff. to: Year Scen 2050 nocc50

	2p6-50 2050					7p0-50 2050					8p5-50 2050				
	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]	Net production or input use [kt or kha or tons]	Total cropped or fodder area [1000 ha]	Rainfed cropped or fodder area [1000 ha]	Irrigated cropped or fodder area [1000 ha]	Total irrigation water [1000 m3]
Cereals	2565608.0 -2.7%	543265.3 1.8%	434576.3 1.7%	113345.3 1.8%	460174432.0 -0.0%	2546789.5 -3.5%	544371.6 2.0%	434072.7 1.5%	118339.4 6.3%	418734912.0 -9.0%	2535399.0 -3.9%	547014.4 2.5%	437075.8 2.2%	116333.6 4.5%	426676960.0 -7.3%
Oilseeds	576738.6 -0.2%	224188.3 3.5%	198416.6 3.8%	25771.9 1.6%	90826224.0 -8.5%	579815.0 0.3%	227896.4 5.2%	203282.4 6.3%	24616.8 -3.0%	83227368.0 -16.2%	576687.6 -0.2%	229186.0 5.8%	201327.8 5.3%	27861.5 9.8%	83905104.0 -15.5%
Other arable field crops	492515.0 0.0%	136376.7 0.9%	115939.9 1.3%	20437.8 -1.1%	104525832.0 -4.2%	494960.8 0.5%	136184.5 0.8%	115199.0 0.6%	20987.4 1.5%	94982208.0 -12.9%	495208.8 0.6%	136704.0 1.2%	115951.5 1.3%	20754.4 0.4%	95634552.0 -12.3%
Vegetables and Permanent crops	1850018.5 0.3%	119450.4 0.4%	76644.7 3.3%	42824.4 -4.4%	214895040.0 -4.7%	1841640.4 -0.2%	121129.1 1.8%	77421.0 4.3%	43746.3 -2.3%	201204288.0 -10.7%	1851753.4 0.4%	119905.4 0.8%	77212.8 4.0%	42720.0 -4.6%	202828912.0 -10.0%
All other crops	63664.9 -0.6%	60014.2 0.5%	39072.4 1.6%	20941.9 -1.6%	112006776.0 -2.3%	63657.9 -0.6%	60572.7 1.4%	38692.9 0.6%	21879.8 2.8%	100961504.0 -11.9%	64228.3 0.3%	60506.0 1.3%	38851.9 1.0%	21654.1 1.8%	103189728.0 -10.0%
Meat	384031.4 -0.5%	2208082.8 -0.3%	2207859.5 -0.2%	223.1 -28.7%	1006615.2 -31.2%	383522.2 -0.6%	2204278.2 -0.4%	2204041.5 -0.4%	236.7 -24.4%	1000138.6 -31.6%	383258.2 -0.7%	2204560.5 -0.4%	2204388.8 -0.4%	171.7 -45.1%	733725.4 -49.8%
Other Animal products	1105469.6 -0.1%	1668018.2 0.1%	1667638.2 0.1%	380.1 -26.9%	1332639.0 -35.2%	1104306.6 -0.2%	1668305.6 0.1%	1667923.8 0.2%	381.9 -26.5%	1205814.0 -41.4%	1104004.1 -0.2%	1668820.0 0.2%	1668476.2 0.2%	343.7 -33.9%	1109324.0 -46.1%
Oils	263018.8 -0.5%	31662.6 0.4%	30050.7 1.6%	1611.7 -17.4%	8440614.0 -17.9%	262433.6 -0.7%	31683.0 0.5%	29836.1 0.9%	1847.0 -5.3%	9210663.0 -10.4%	262774.5 -0.6%	31631.3 0.3%	30276.0 2.4%	1354.9 -30.5%	7145908.0 -30.5%

4.3 Energy/carbon emissions: PROMETHEUS

The PROMETHEUS energy system model delivers comprehensive projections of global energy demand, supply, power generation mix, energy-related carbon emissions, energy prices, and investments. It is a robust energy demand and supply simulation model designed for energy system analysis, energy price projections, power generation planning, and climate change mitigation policies. PROMETHEUS includes relations and exogenous variables for all key aspects relevant to general energy systems analysis.

At the global level, the following key results are presented:

Table 7. Global indicators simulated with PROMETHEUS

CATEGORY	SHORT DESCRIPTION
CAPITAL COST	Capital cost per technology type
CARBON CAPTURE	Carbon capture total and per technology
EMISSIONS	Emissions from demand sectors (industry, residential, transport) and energy production by energy type (electricity, liquids, gases), also process emissions from energy sectors and industrial processes.
FINAL ENERGY	Final energy consumption per energy type and sector, including energy consumption for non-energy processes in industry
PRIMARY ENERGY	Primary energy production by source: biomass, coal, other fossil, gas, geothermal, hydro, non-biomass renewables, nuclear, oil, solar, wind
GDP	at regional aggregate level
POPULATION	at regional aggregate level
CARBON PRICE	at regional aggregate level
SECONDARY ENERGY	Production of electricity by type: biomass, coal, other fossil, gas, hydro, non-biomass renewables, nuclear, oil, solar, wind

Note: 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).

Figure 12 illustrates the projected differences in global final energy consumption and primary energy mix, and CO_2 emissions under Current Policies (CurPol: SSP-RCP7.0) and Sustainable development (NetZero; SSP10RCP2.6) scenarios from 2020 to 2050, based on the PROMETHEUS model. Under the Current Policies scenario, final energy consumption remains heavily reliant on traditional fuels such as solids and liquids, with only a slight increase in the use of electricity, maintaining the persistence of fossil fuels in the absence of strong climate policies. In contrast, the Net Zero scenario shows a significant shift towards increased renewable-based electricity consumption and the introduction of green hydrogen, alongside a reduction in solids and liquids, reflecting a transition to cleaner energy sources and away from fossil fuels.

The primary energy mix under Current Policies scenario continues to be dominated by coal, oil, and gas, with a limited growth in renewables. However, the NetZero scenario indicates a substantial increase in the deployment of renewables, particularly solar and wind, with a corresponding decline in fossil fuel use.

Global CO_2 emissions under Current Policies scenario show only a slight downward trend from current levels, due to continued reliance on high-emission sectors and fuels. Conversely, the Net Zero scenario projects significant emissions reductions across all sectors (both energy demand and energy supply), underscoring the impact of stringent climate policies on achieving net-zero targets. This comparison underscores the critical role of policy interventions in driving the transition to a low-carbon economy and mitigating climate change impacts.

Similarly, the study presents a comparison between Current Policies and Net Zero scenarios for the European Union & UK (EU27 & UK) over the same period (Figure 13). Under Current Policies, the final energy consumption remains reliant on liquids and solids, with modest increases in electricity and minimal introduction of hydrogen. The primary energy mix is dominated by gas, oil, and nuclear, with modest growth in renewables (in particular solar and wind power). However, the NetZero scenario for the EU27&UK shows a considerable increase in the share of renewable energy, particularly solar, wind, and biomass, and a reduction in the use of fossil fuels. This shift results in significant CO_2 emissions reductions, particularly from power generation, transport, buildings, and industry sectors.

In conclusion, both the global and EU27 & UK scenarios under NetZero demonstrate the effectiveness of stringent climate policies in transforming energy consumption patterns and significantly reducing CO_2 emissions. The EU28 Net Zero scenario emphasizes a dramatic increase in solar, wind, and biomass, coupled with ambitious decarbonization efforts resulting in a more rapid decline in emissions. Notably, the EU28 scenario also projects negative emissions by 2050, benefitting from carbon capture technologies combined with biomass (BECCS), highlighting the EU's ambitious climate policy commitments aimed at achieving a net-negative carbon footprint. This underscores the critical role of stringent climate policies in transforming energy landscapes and achieving significant emissions reductions.

The summary visualisation of the results for other Global regions is available in the Annex.

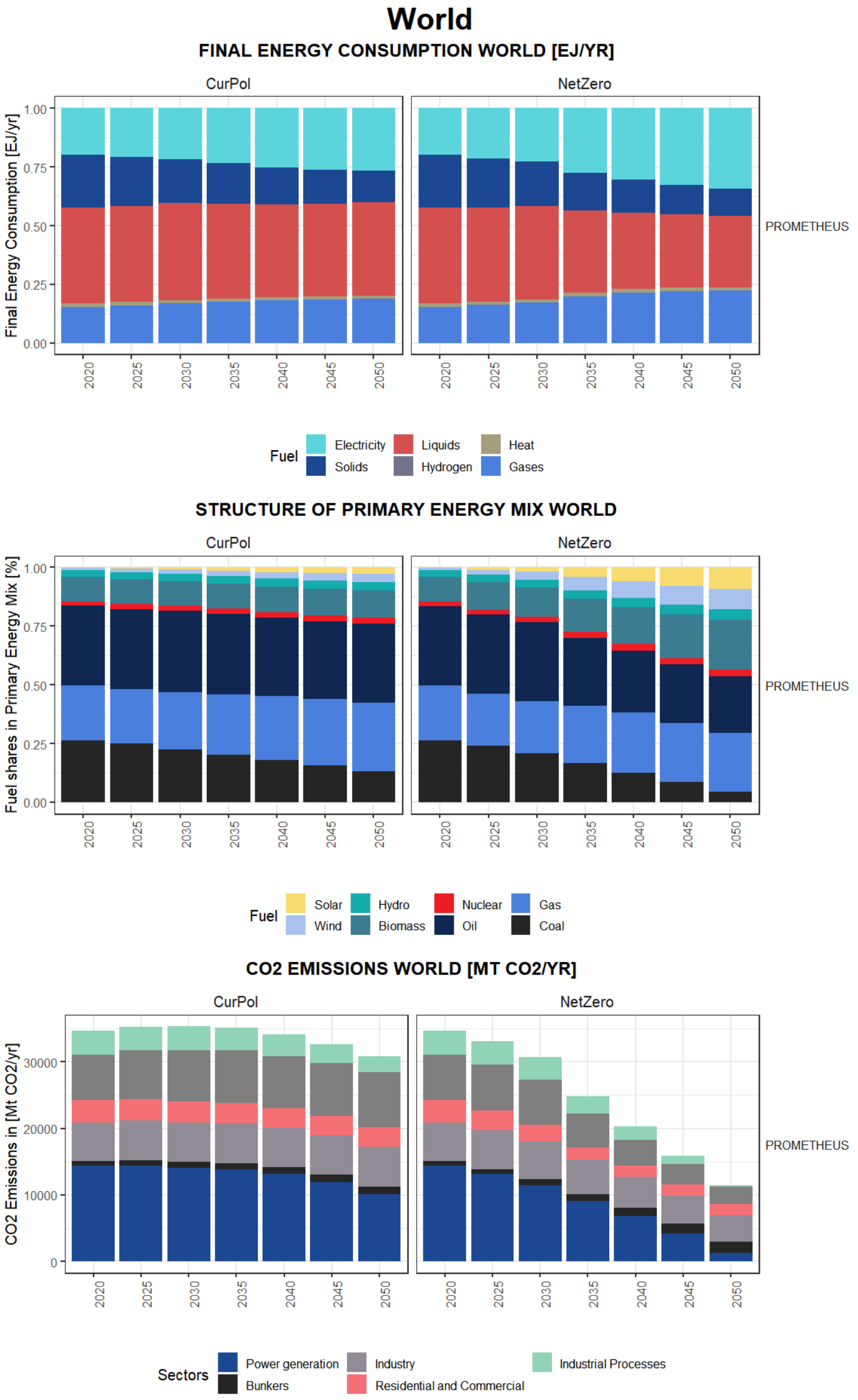


Figure 12 - PROMETHEUS baseline scenario results on final and primary energy consumption, CO_2 emissions, for Net Zero and Current policies scenarios World.

Note: In the Annex, the visualisation of the results is provided for the following 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).

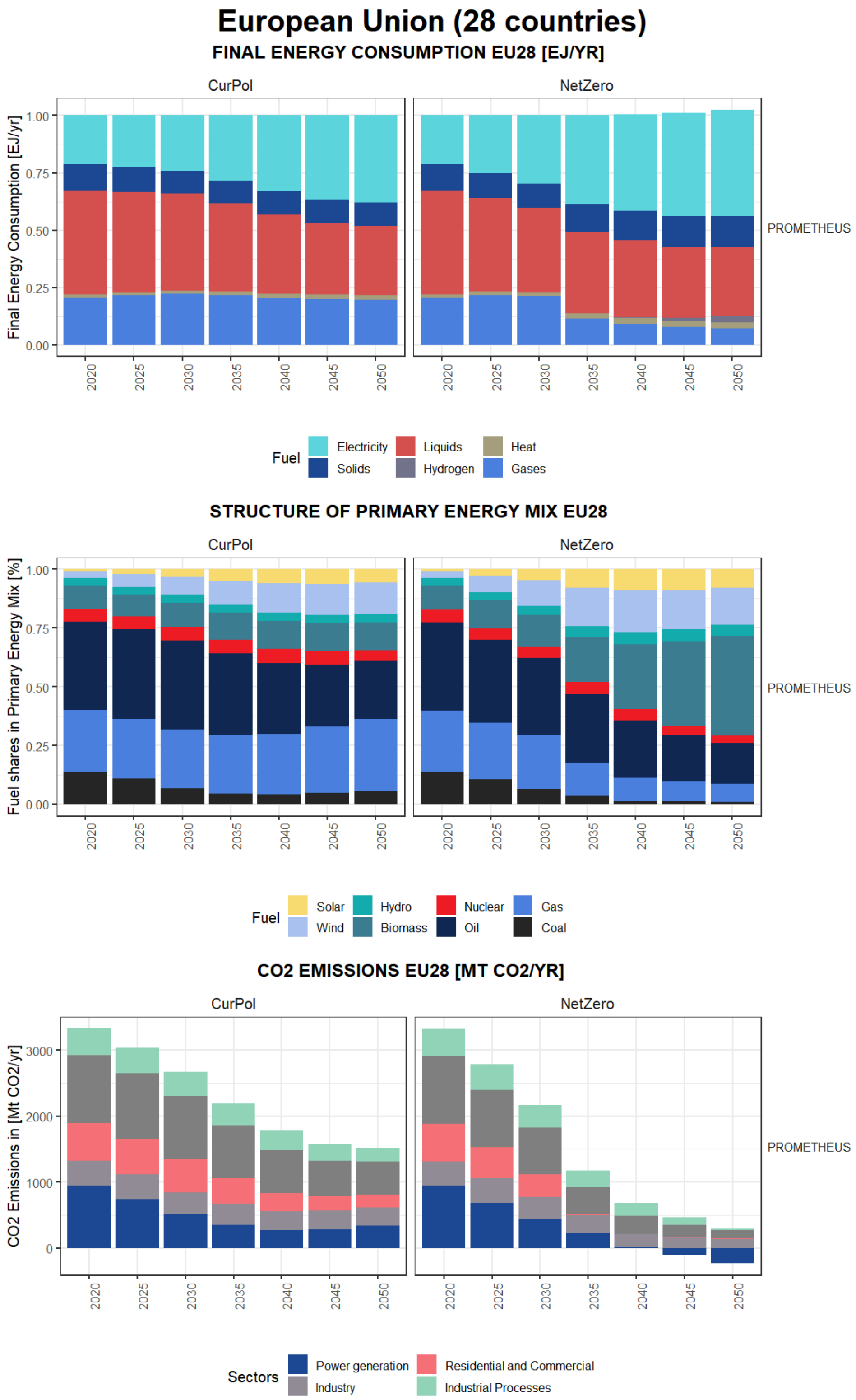


Figure 13. PROMETHEUS baseline scenario results on final and primary energy consumption, CO_2 emissions, for Net Zero and Current policies scenarios European Union (28).

Note: In the Annex, the visualisation of the results is provided for the following 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).

4.4 Ecosystems: GLOBIO

GLOBIO outputs include two indicators of biodiversity (the potentially lost range (PLR; %) of individual riverine fish species and the potentially affected fraction (PAF; %) of species, both quantified as a function of climate change (affecting river water temperature and streamflow) and the presence of dams (affecting habitat connectivity). Results are presented for four climate scenarios obtained under CMIP5 from the FutureStreams dataset (Bosmans et al., 2022). Tier 2 simulations will be done with the CMIP6 ISI-MIP3 forcing (Table 1).

The results for PLR reveal that impacts of climate change are highly variable: for some species, nearly the entire range is threatened by climate change, while for others it is a negligible proportion (Figure 14). In addition, there are clear increases in the proportions of range threatened from 2030 to 2050 and with increasing warming levels, with particularly large proportions of range threatened for the RCP8.5 warming scenario. Further, the presence of dams leads to a clear overall increase in the proportion of threatened range compared to the impact of climate change alone.

The results for PAF, which is an indicator of potential relative species loss in a given location (grid cell), confirm these trends, with PAF values increasing from 2030 to 2050 and with increasing levels of warming, in particular in the Amazon region (Figure 15). The presence of dams results in considerable increases in PAF compared to a situation where only climate change is considered, especially in Europe and south-east Asia (Figure 16).

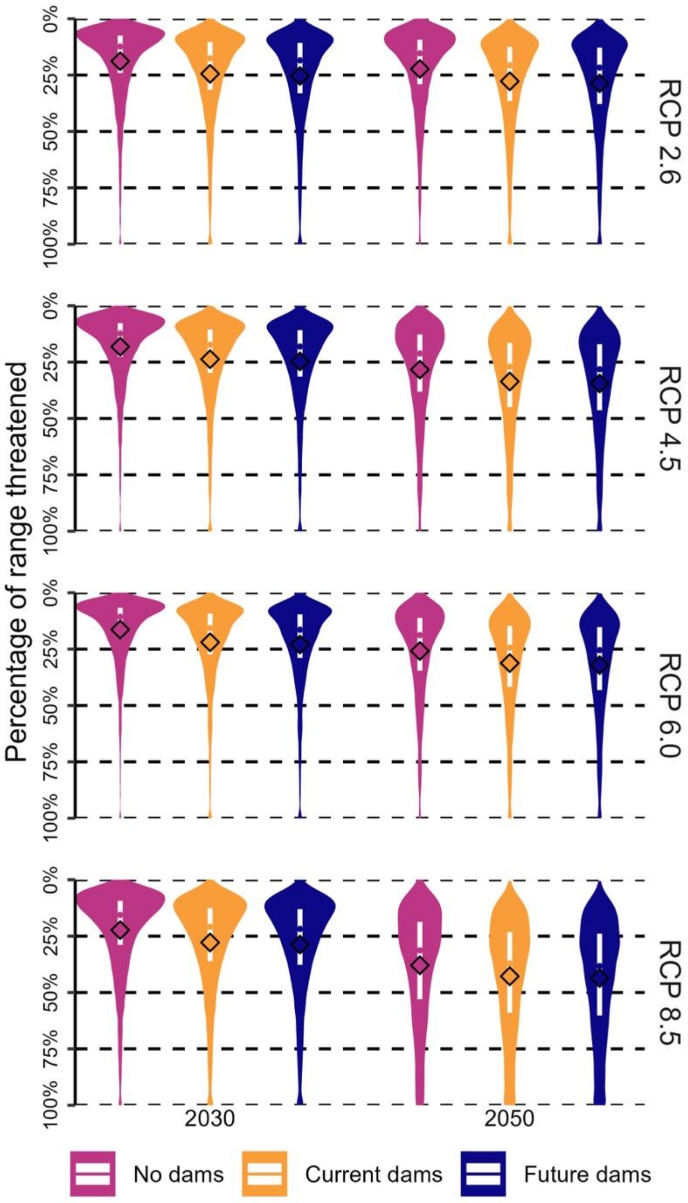


Figure 14: Potentially lost range (PLR; %) of riverine fish species projected for 2030 and 2050 according to four Tier 1 scenarios. The violin plots show the proportion of geographic range threatened by future climate extremes for 8,174 riverine fish species globally (of which 947 diadromous species and 7,227 non-diadromous species), different scenario years and three dams situations. Within each violin, the white boxes show the interquartile range as well as the median, while diamonds represent the mean across the species. Climate data were obtained from the FutureStreams dataset (which contains weekly streamflow and water temperature values from PCR-GLOBWB; Bosmans et al. 2020); current dams were obtained from the GRaND and GOODD databases (Lehner et al. 2011; McMulligan et al. 2020) and future dams were added based on planned dams available in the FHReD database (Zarfl et al. 2015). For each species and scenario, PLR was calculated as a mean value based on climate change projections resulting from five GCMs.

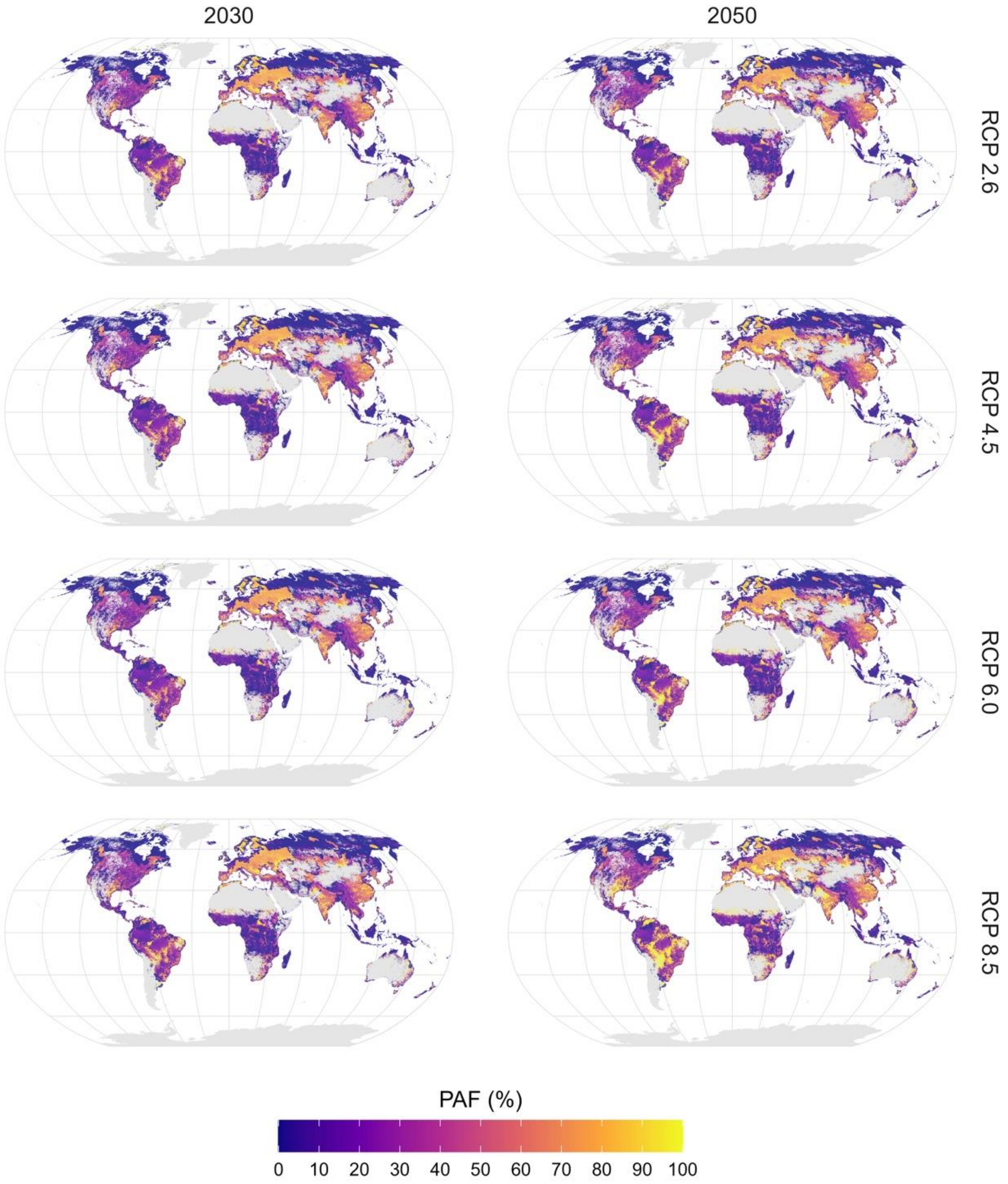


Figure 15: Potentially affected fraction (PAF; %) of riverine fish species due to future climate change and dams for 2030 (left) and 2050 (right) for Tier 1 scenarios. Climate change impacts are shown for different RCPs (rows), based on the median PAF across the GCMs at a five arc-minute resolution (~10 km). Dams represent current and planned dams combined according to the databases GRaND, GOODD and FHReD (Lehner et al. 2011; McMulligan et al. 2020; Zarfl et al. 2015). Gray denotes no data (no species occurring or no data available).

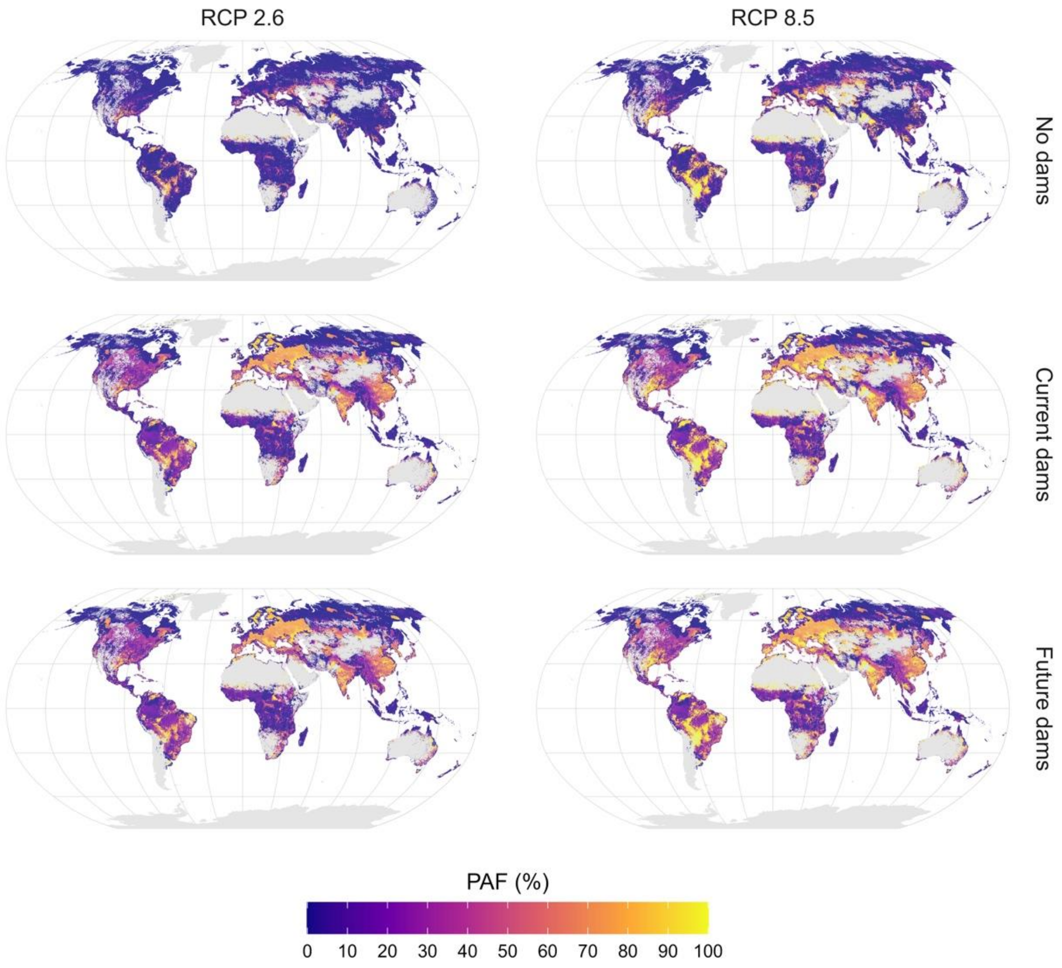


Figure 16: Potentially affected fraction (PAF) of riverine fish species estimated for 2050 for RCP2.6 (left) and RCP8.5 (right) for three dams situations: no dams (for comparison; top) current dams (based on the GRaND and GOODD databases (Lehner et al. 2011; McMulligan et al. 2020); middle) and current and planned dams combined (planned dams from the FHReD database (Zarfl et al. 2015); bottom). Results are for Tier 1 scenarios.

4.5 Economy: GEM-E3

The GEM-E3 model is a comprehensive tool used to analyse the macro-economy, its interaction with the environment, and the energy system. It is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model. The model facilitates consistent comparative analysis of policy scenarios, it integrates micro-economic mechanisms and institutional features within a macroeconomic framework, avoiding simplified behavioural representations.

GEM-E3 is particularly valuable for understanding the distributional impacts of long-term structural changes driven by the energy and climate policies globally and at regional level. For the current deliverable, the presented results focus on the GDP, total household expenditures and expenditure on food. Quantified results are given for two baseline scenarios without the impact of climate change: Current Policies and Net Zero scenarios (see Figure 17).

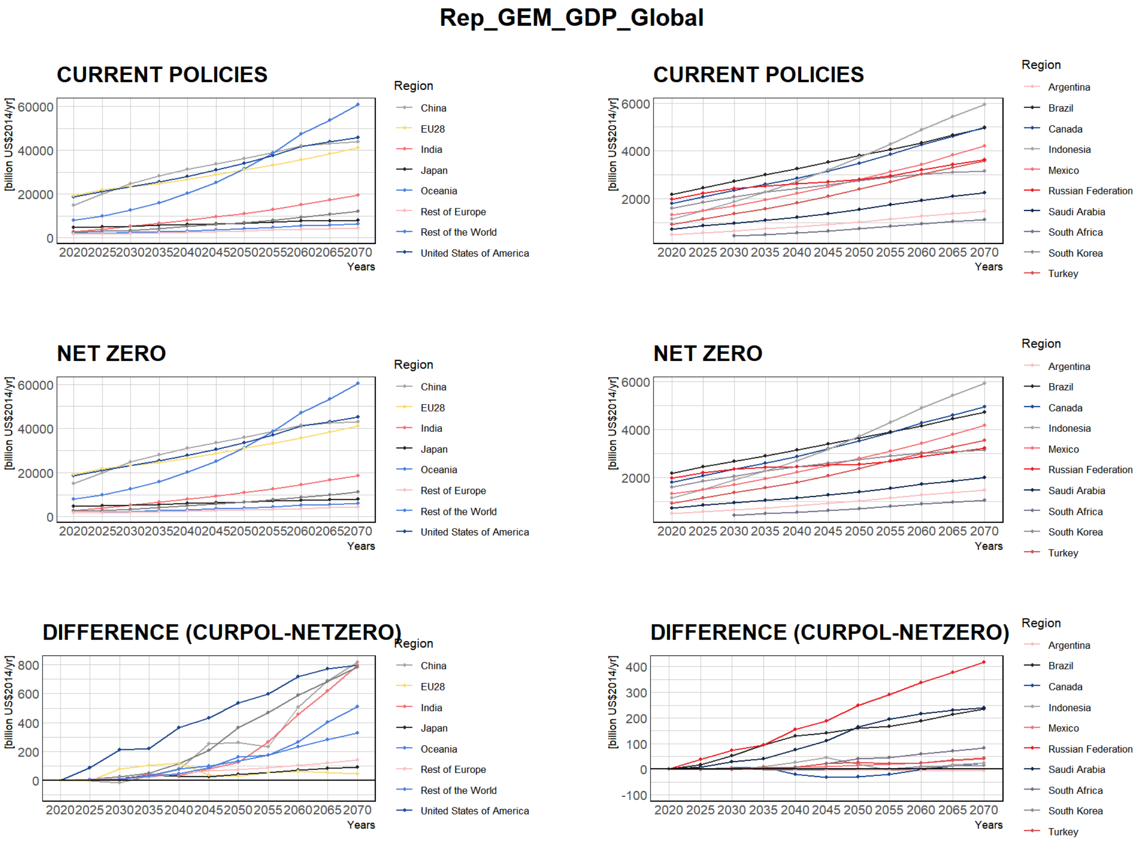


Figure 17. GEM-E3 baseline scenario results on GDP, for Net Zero and Current policies scenarios.

The Net Zero scenario, with high climate policy ambitions, result in lower GDP levels compared to Current Policies scenario (Figure 17). This finding is in line with the scientific literature, emphasizing that developing the necessary infrastructure for renewable energy, such as wind and solar power plants, requires significant upfront investments. Similarly, the decarbonization of all sectors of the economy, including industry, buildings and transportation is a capital and technology-intensive process that leads to lower operational costs but, depending on the availability of funds, can result in economic challenges. These costs can strain public and private budgets, leading to reduced expenditure in other sectors. Industries such as steel, cement, and chemicals, face substantial cost increases under stringent climate policies, explained by high energy consumption and high emissions intensity (see e.g. scenarios presented in IEA, 2020). Carbon pricing mechanisms such as carbon taxes and introduction of the emissions trading system, can significantly raise operational costs for industries. These policies internalize the environmental cost of carbon emissions, compelling industries to adopt cleaner but often more expensive technologies. The immediate impact on GDP can be negative as economies adjust. Increased production costs are often passed on to consumers in the form of higher prices. This can reduce overall demand and consumer spending, which are critical components of GDP (IMF 2019). The magnitude of effects depends on a number of factors, namely the carbon intensity of the economy, the potential crowding-out of other types of investments, the skill shortages associated with the transition, the manufacturing potential of each region for clean energy equipment and production of renewable energy. However, comparing GDP between the Current policies and net Zero scenarios, does not provide us with an indication on the economic benefits of mitigation action from avoided damages from climate change (see the report IPCC, 2022). Despite the high upfront costs, long-term benefits from advanced climate policies as in the Net Zero scenario include improved energy efficiency and enhanced energy security accompanied by large-scale investments in green technologies. While initial investments in green technology are high, they can lead to cost reductions over time through technological advancements, knowledge spillovers and economies of scale that are not considered in these scenarios.

Despite the different projected levels of the GDP, share of household expenditure on food to total expenditure remains (see Figure 18). An increase in the unit cost of production of goods and services brings lower levels of household consumption. Despite the overall lower levels, the share of consumption on food is marginally higher in the NetZero scenario as food prices increase and the consumption of food is fundamental to the welfare of households, thus not substituted by other consumption categories.

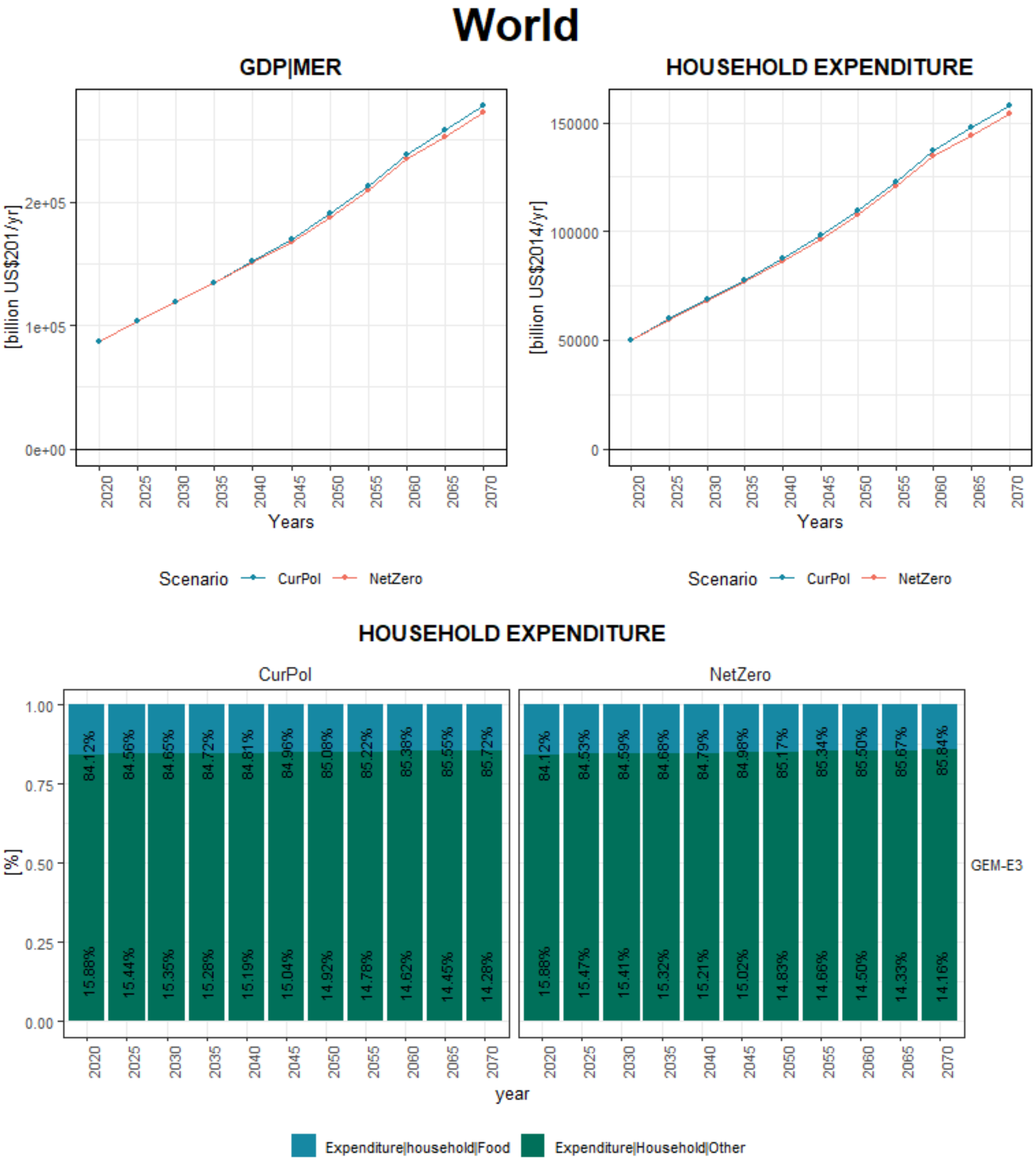


Figure 18. GEM-E3 baseline scenario results on GDP, expenditure of households (total and food) for Net Zero and Current policies scenarios.

Note: In the Annex, the visualisation of the results is provided for the following countries and global regions: United States of America, Japan, Canada, Brazil, China, India, South Korea, Indonesia, Mexico, Argentina, Turkey, Saudi Arabia, Oceania, Russian Federation, Rest of Energy Producing Countries, South Africa, Rest of Europe, Rest of the World, European Union (28 countries), World.

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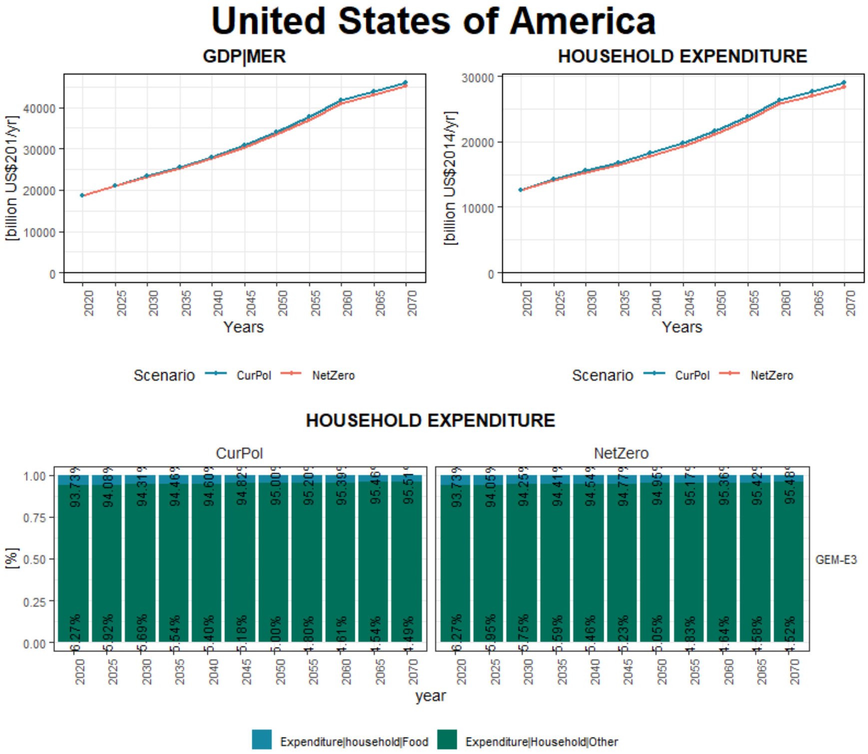
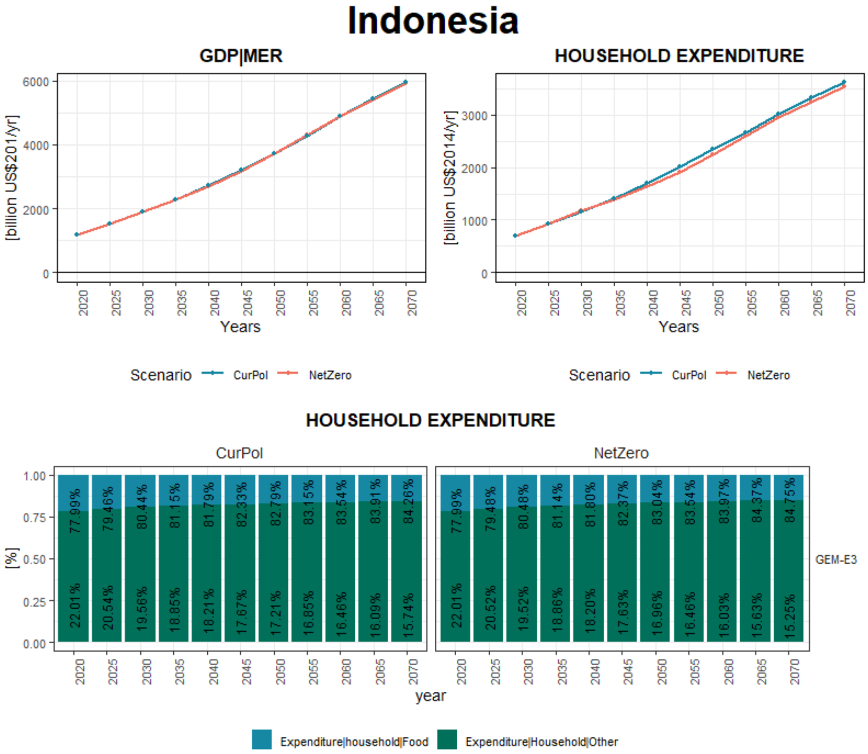
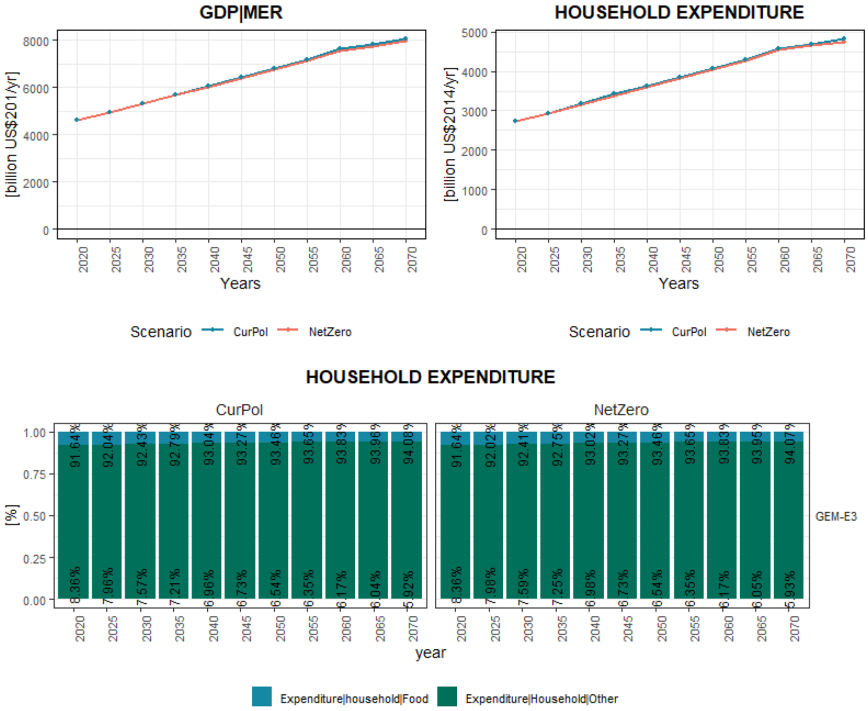
Annex

A1. Regional results GEM-E3



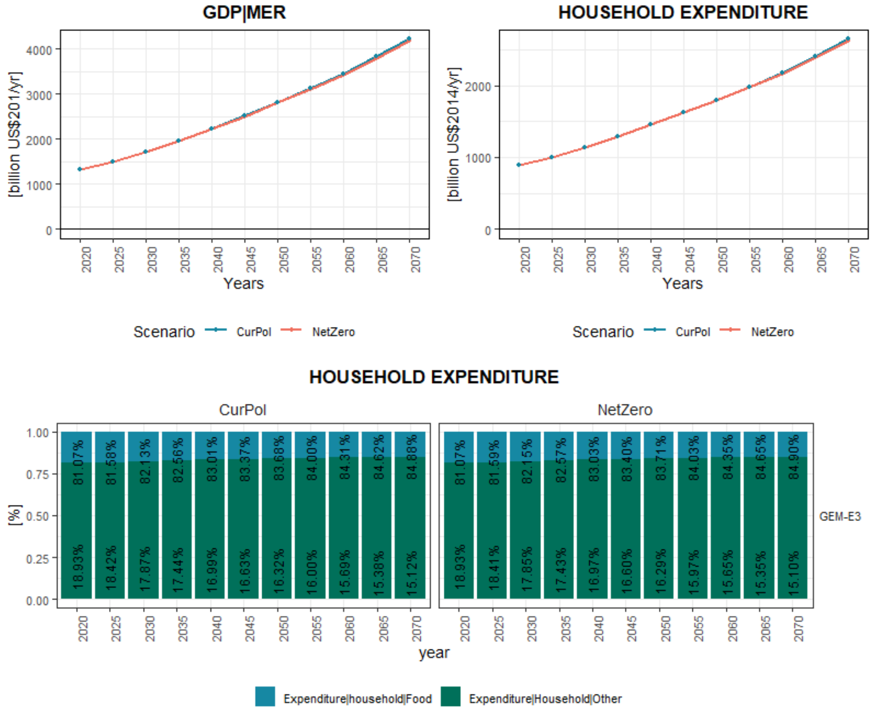


Japan

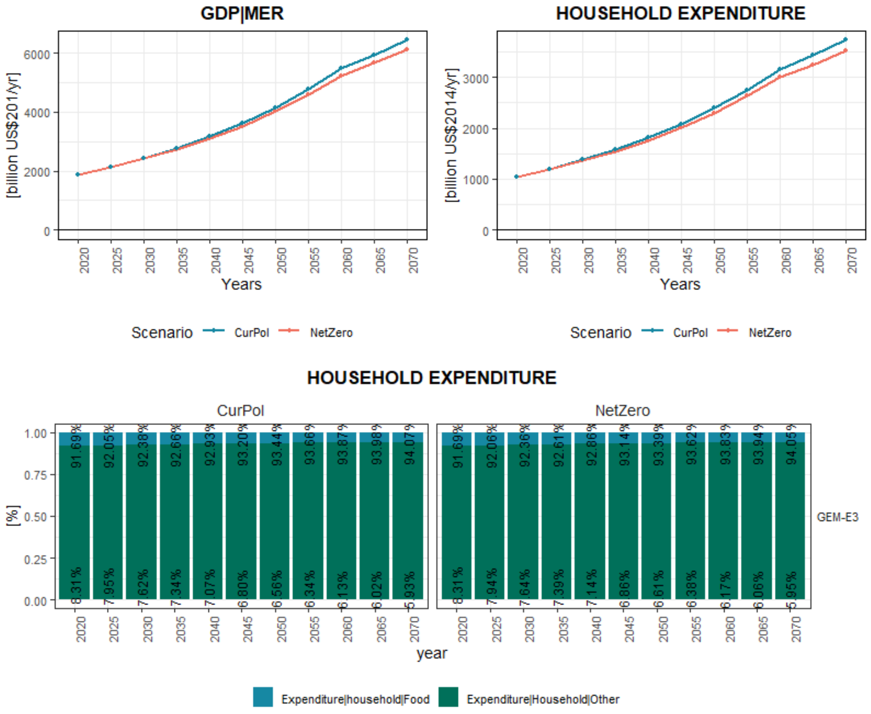


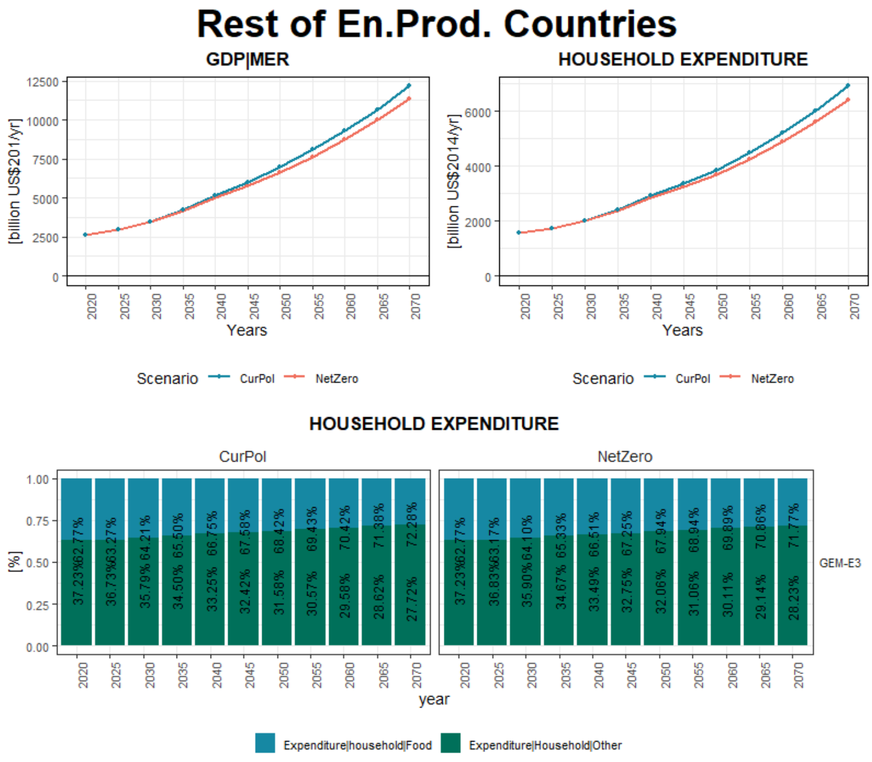
South Korea

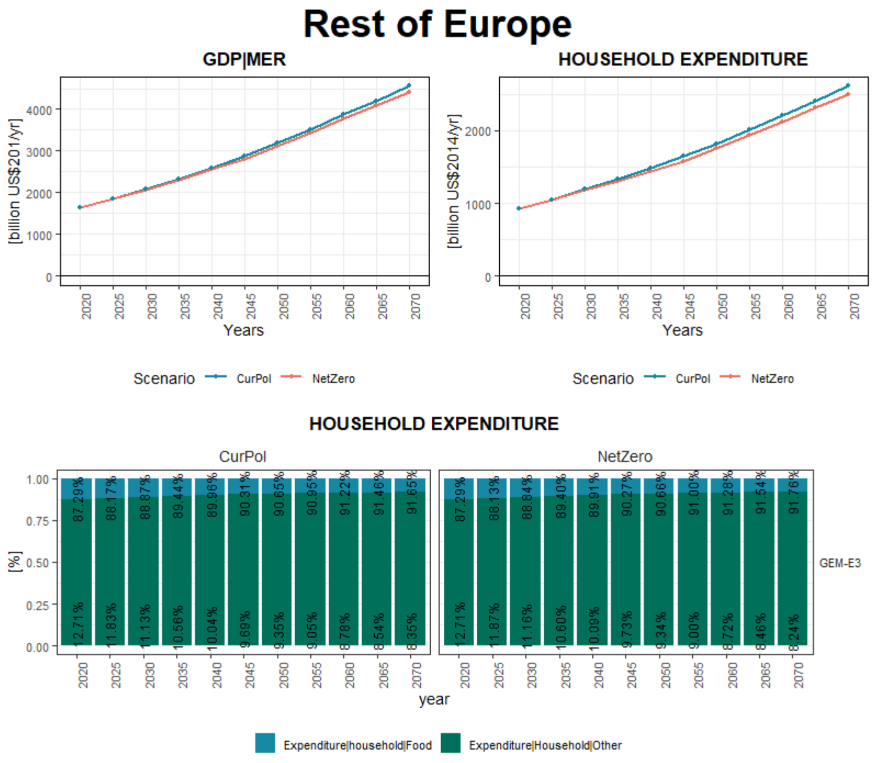
Mexico

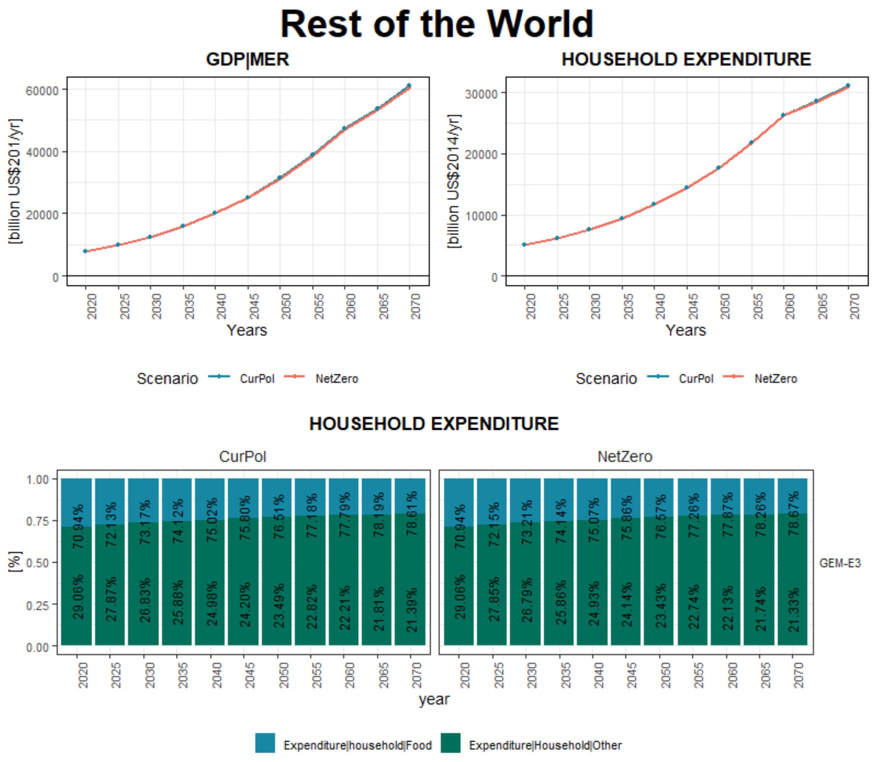


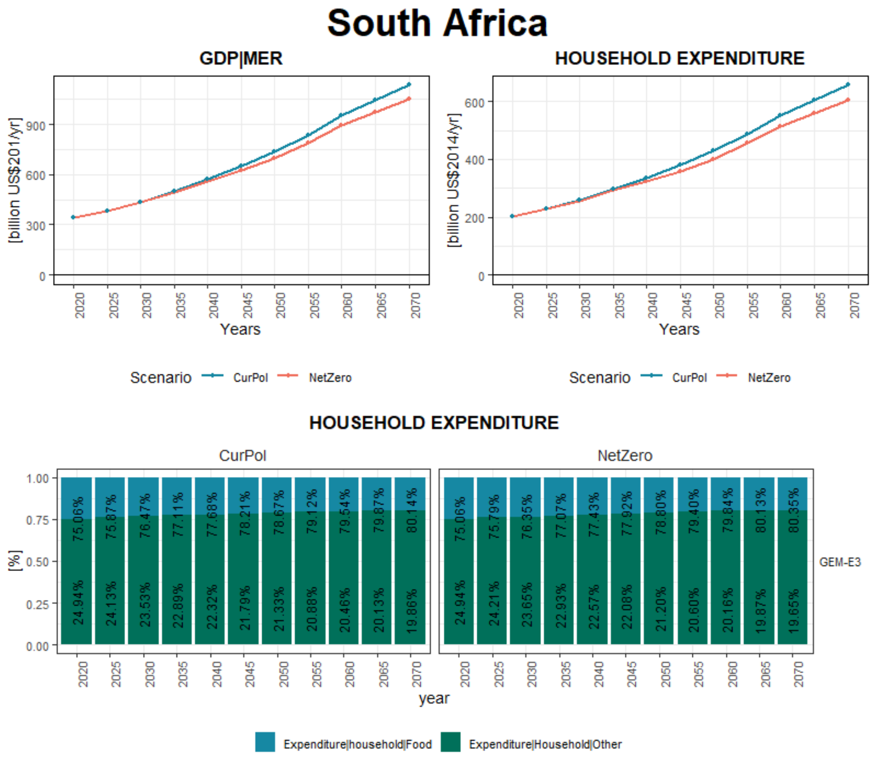
Oceania



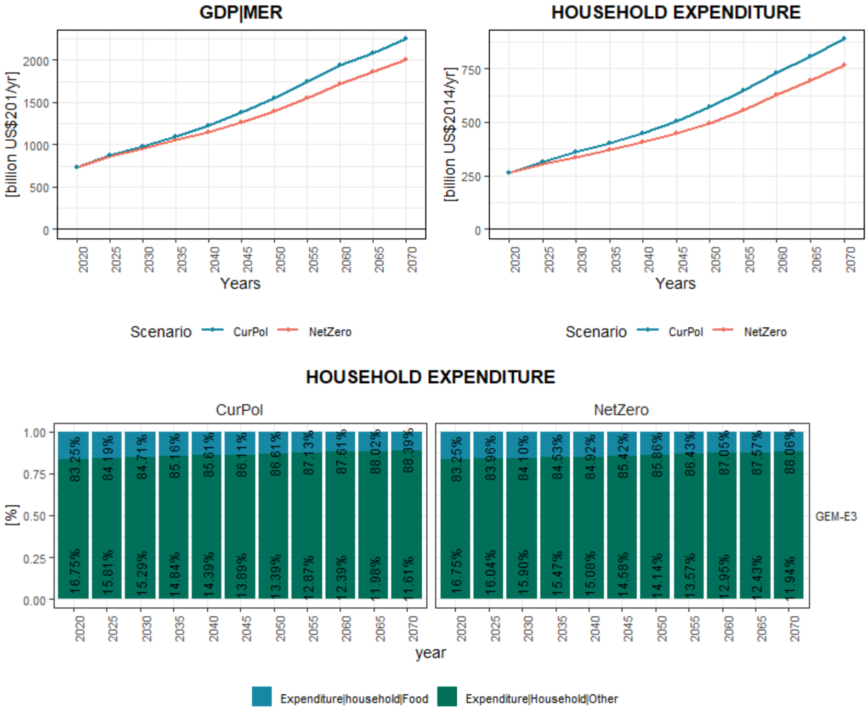

Rest of En.Prod. Countries
GDP|MER
HOUSEHOLD EXPENDITURE
[billion US$201/yr]
12500
10000
7500
5000
2500
0
[billion US$2014/yr]
6000
4000
2000
0
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Years
Scenario
CurPol
NetZero
HOUSEHOLD EXPENDITURE
CurPol
NetZero
[%]
1.00
0.75
0.50
0.25
0.00
37.23%62.77%
36.73%63.27%
35.79%64.21%
34.50% 65.50%
33.25% 66.75%
32.42% 67.58%
31.58% 68.42%
30.57% 69.43%
29.58% 70.42%
28.62% 71.38%
27.72% 72.28%
37.23%62.77%
36.83%63.17%
35.90%64.10%
34.67% 65.33%
33.49% 66.51%
32.75% 67.25%
32.06% 67.94%
31.06% 68.94%
30.11% 69.89%
29.14% 70.86%
28.23% 71.77%
GEM-E3
year
Expenditure|household|Food
Expenditure|Household|Other


Rest of Europe
GDP|MER
HOUSEHOLD EXPENDITURE
[billion US$201/yr]
4000
3000
2000
1000
0
[billion US$2014/yr]
2000
1000
0
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Years
Scenario
CurPol
NetZero
HOUSEHOLD EXPENDITURE
CurPol
NetZero
[%]
1.00
0.75
0.50
0.25
0.00
12.71% 87.29%
11.83% 88.17%
11.13% 88.87%
10.56% 89.44%
10.04% 89.96%
9.69% 90.31%
9.35% 90.65%
9.05% 90.95%
8.78% 91.22%
8.54% 91.46%
8.35% 91.65%
12.71% 87.29%
11.87% 88.13%
11.16% 88.84%
10.60% 89.40%
10.09% 89.91%
9.73% 90.27%
9.34% 90.66%
9.00% 91.00%
8.72% 91.28%
8.46% 91.54%
8.24% 91.76%
GEM-E3
year
Expenditure|household|Food
Expenditure|Household|Other


Rest of the World
GDP|MER
[billion US$201/yr]
0
20000
40000
60000
HOUSEHOLD EXPENDITURE
[billion US$2014/yr]
0
10000
20000
30000
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Years
Scenario
CurPol
NetZero
HOUSEHOLD EXPENDITURE
CurPol
NetZero
[%]
0.00
0.25
0.50
0.75
1.00
70.94%
29.06%
72.13%
27.87%
73.17%
26.83%
74.12%
25.88%
75.02%
24.98%
75.80%
24.20%
76.51%
23.49%
77.18%
22.82%
77.79%
22.21%
78.19%
21.81%
78.61%
21.39%
70.94%
29.06%
72.15%
27.85%
73.21%
26.79%
74.14%
25.86%
75.07%
24.93%
75.86%
24.14%
76.57%
23.43%
77.26%
22.74%
77.87%
22.13%
78.26%
21.74%
78.67%
21.33%
GEM-E3
year
Expenditure|household|Food
Expenditure|Household|Other

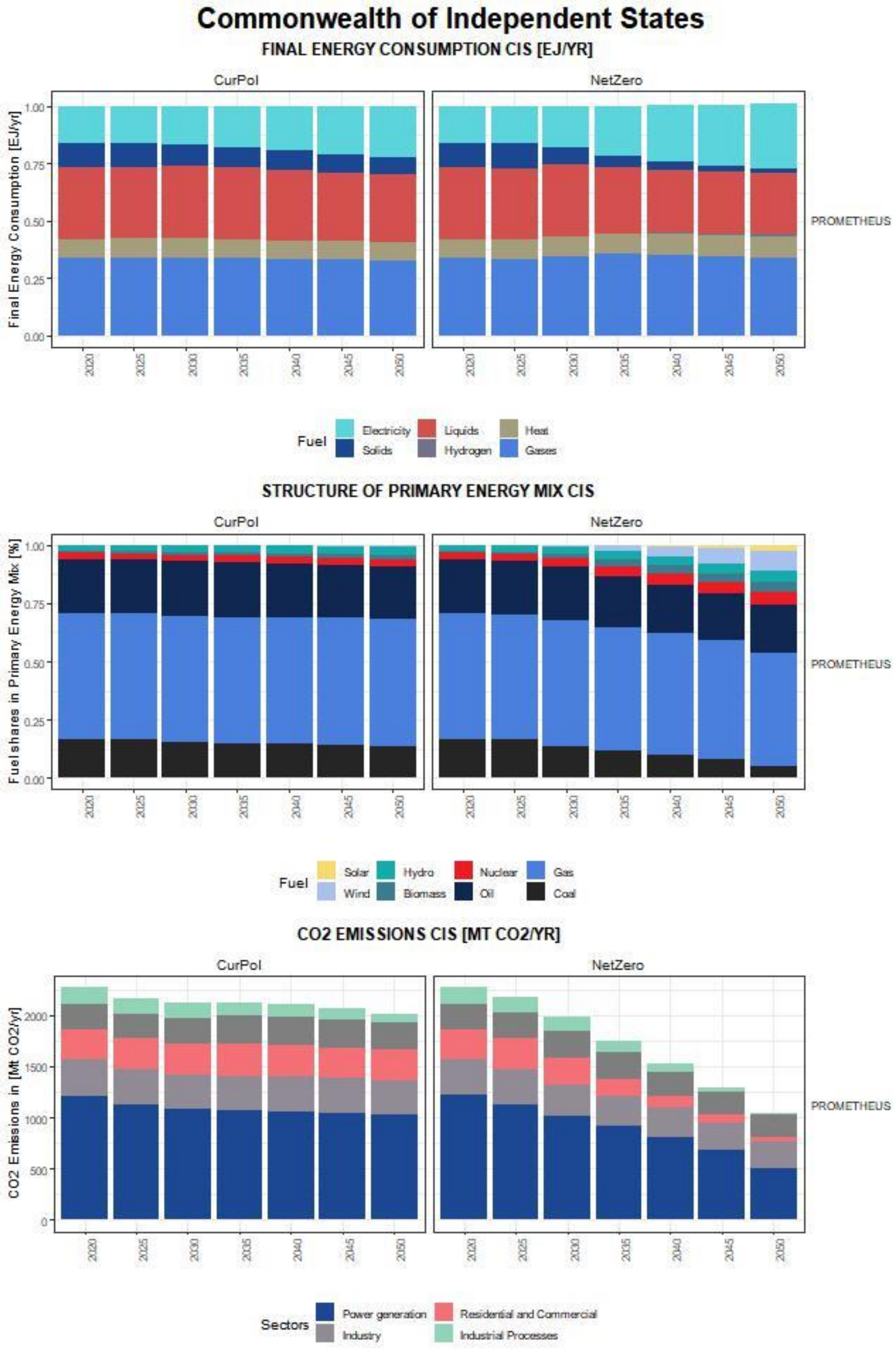

South Africa
GDP|MER
[billion US$201/yr]
0
300
600
900
HOUSEHOLD EXPENDITURE
[billion US$2014/yr]
0
200
400
600
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Years
Scenario
CurPol
NetZero
HOUSEHOLD EXPENDITURE
CurPol
NetZero
[%]
0.00
0.25
0.50
0.75
1.00
75.06%
24.94%
75.87%
24.13%
76.47%
23.53%
77.11%
22.89%
77.68%
22.32%
78.21%
21.79%
78.67%
21.33%
79.12%
20.88%
79.54%
20.46%
79.87%
20.13%
80.14%
19.86%
75.06%
24.94%
75.79%
24.21%
76.35%
23.65%
77.07%
22.93%
77.43%
22.57%
77.92%
22.08%
78.80%
21.20%
79.40%
20.60%
79.84%
20.16%
80.13%
19.87%
80.35%
19.65%
GEM-E3
year
Expenditure|household|Food
Expenditure|Household|Other

Saudi Arabia

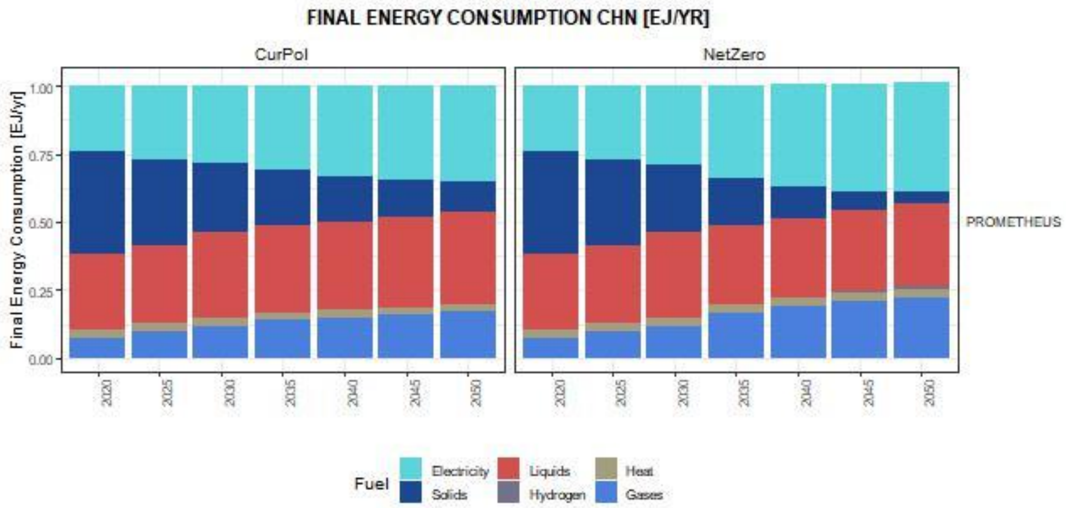


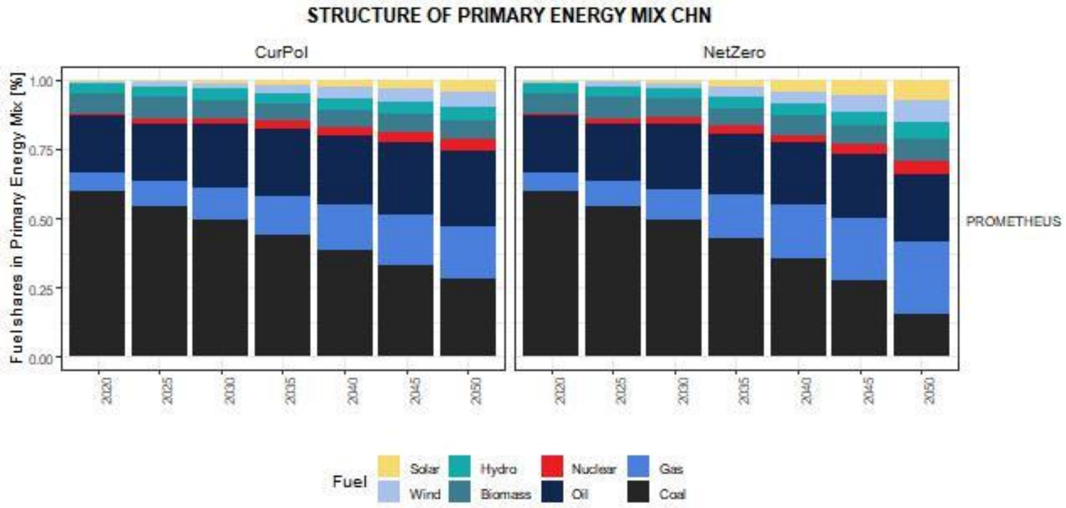
Turkey

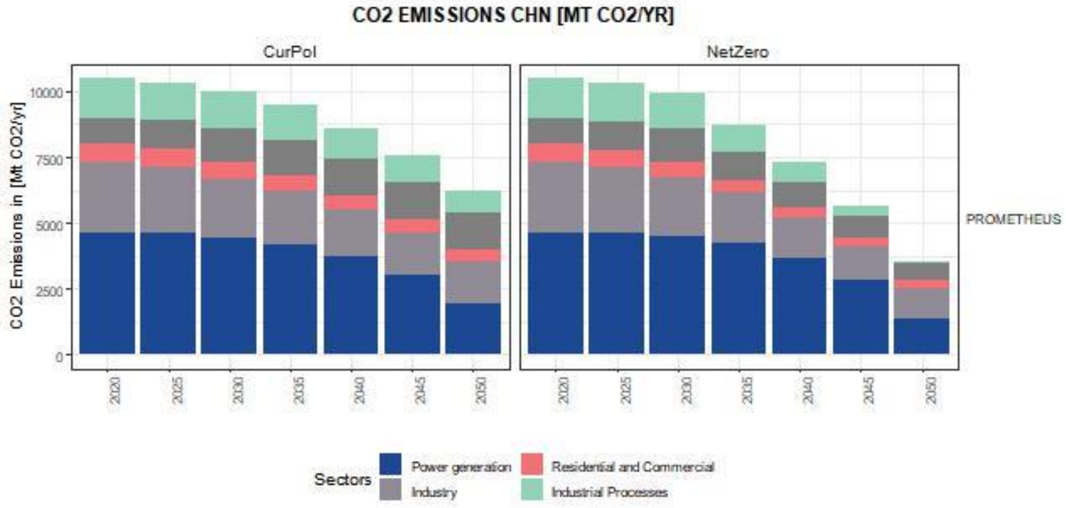
A2. Regional results PROMETHEUS



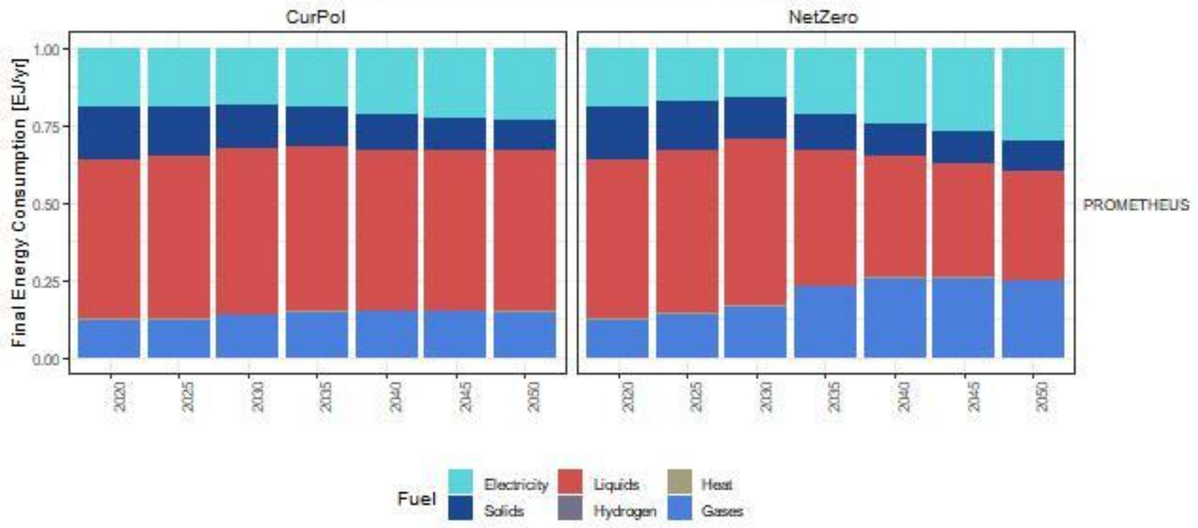
China

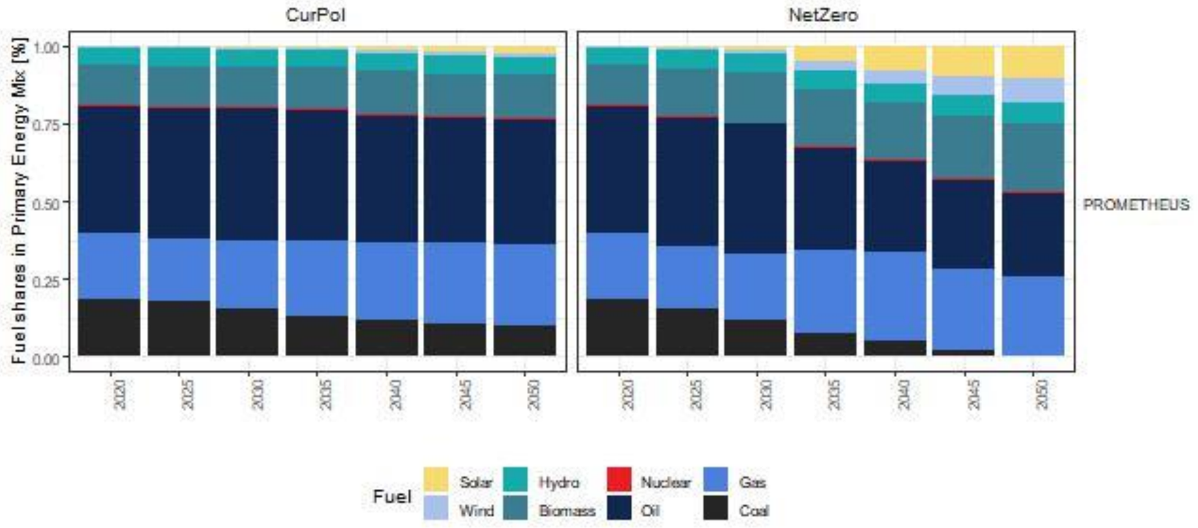

FINAL ENERGY CONSUMPTION CHN [EJ/YR]
CurPol
NetZero
Final Energy Consumption [EJ/yr]
0.00
0.25
0.50
0.75
1.00
2020
2025
2030
2035
2040
2045
2050
PROMETHEUS
Fuel
Electricity
Solids
Liquids
Hydrogen
Heat
Gases

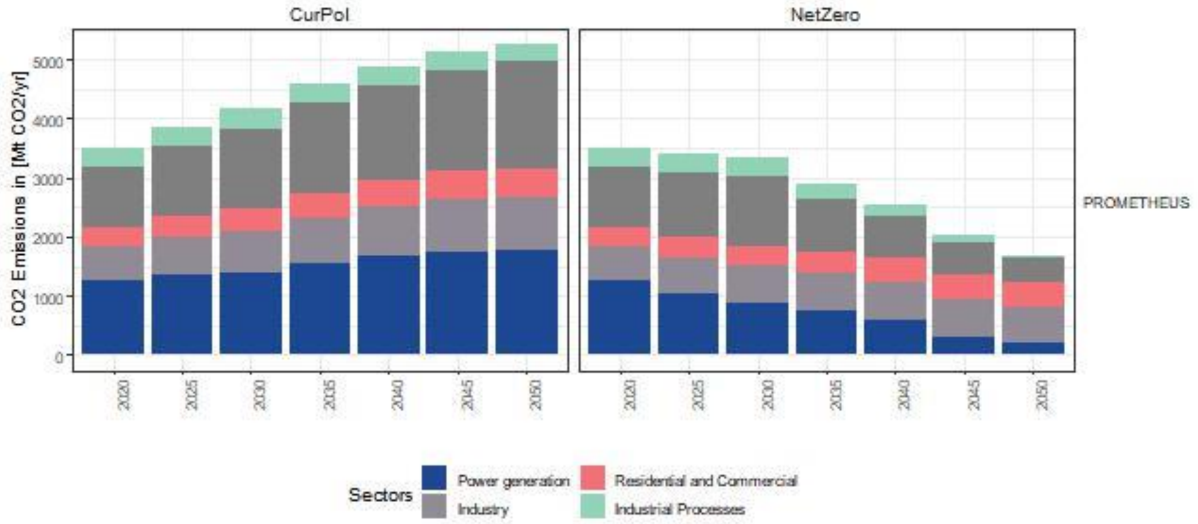

STRUCTURE OF PRIMARY ENERGY MIX CHN
CurPol
NetZero
Fuelshares in Primary Energy Mix [%]
0.00
0.25
0.50
0.75
1.00
2020
2025
2030
2035
2040
2045
2050
PROMETHEUS
Fuel
Solar
Wind
Hydro
Biomass
Nuclear
Oil
Gas
Coal


CO2 EMISSIONS CHN [MT CO2/YR]
CurPol
NetZero
CO2 Emissions in [Mt CO2/yr]
0
2500
5000
7500
10000
2020
2025
2030
2035
2040
2045
2050
PROMETHEUS
Sectors
Power generation
Industry
Residential and Commercial
Industrial Processes

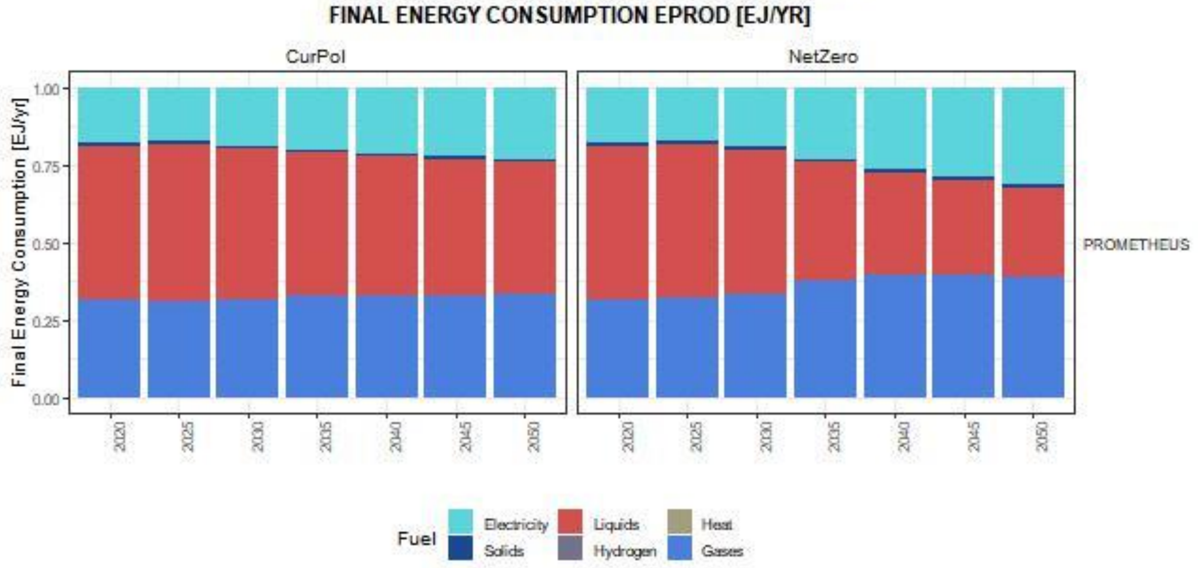
Emerging Economies

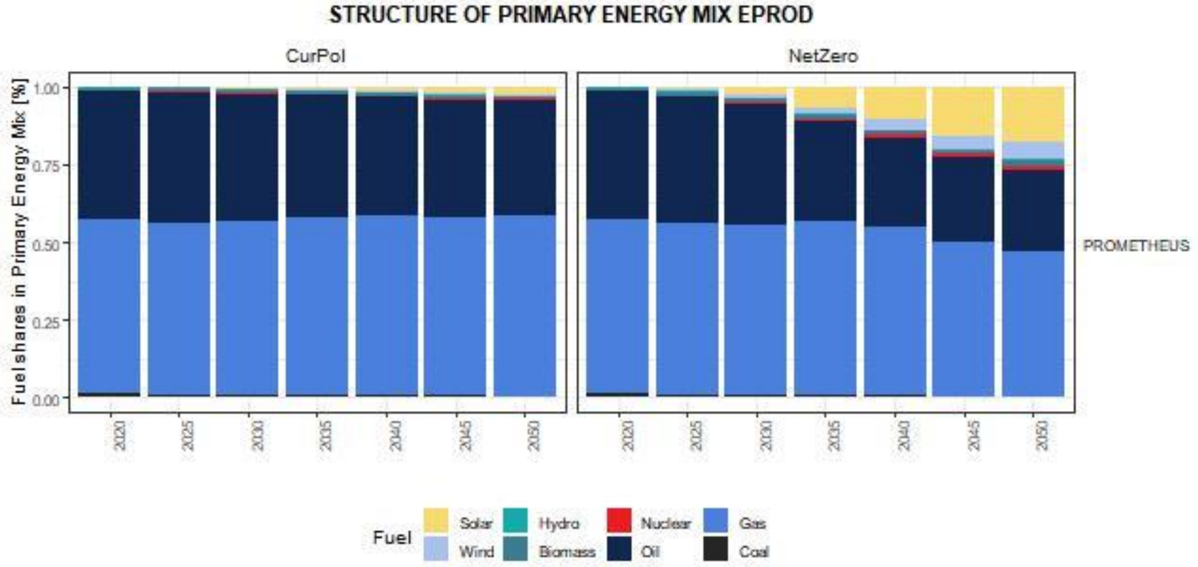

FINAL ENERGY CONSUMPTION EMRG [EJ/YR]

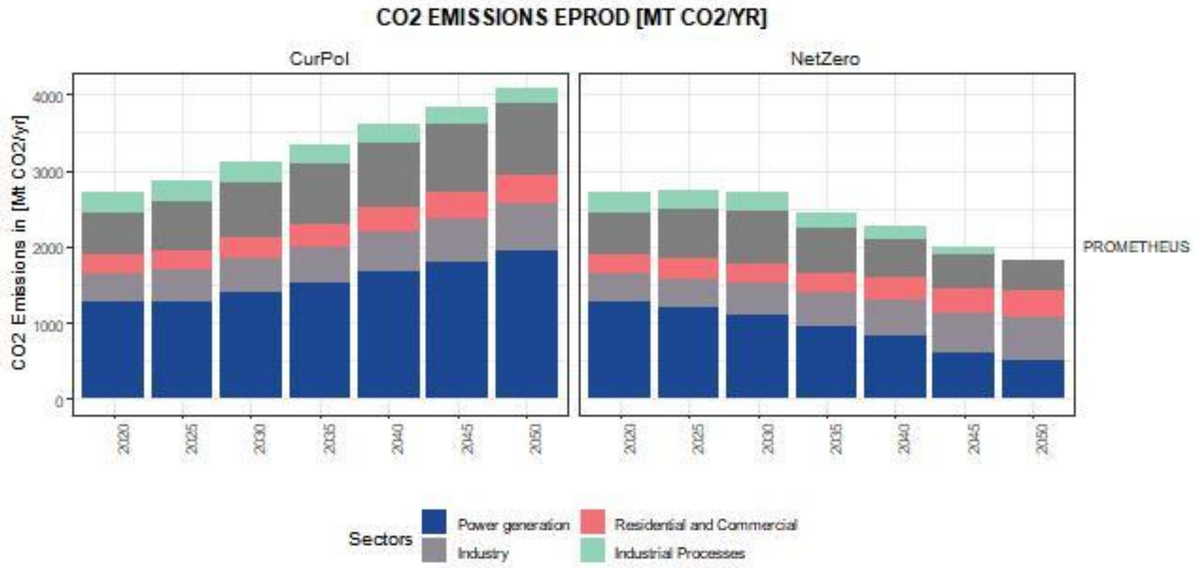

STRUCTURE OF PRIMARY ENERGY MIX EMRG


CO2 EMISSIONS EMRG [MT CO2/YR]

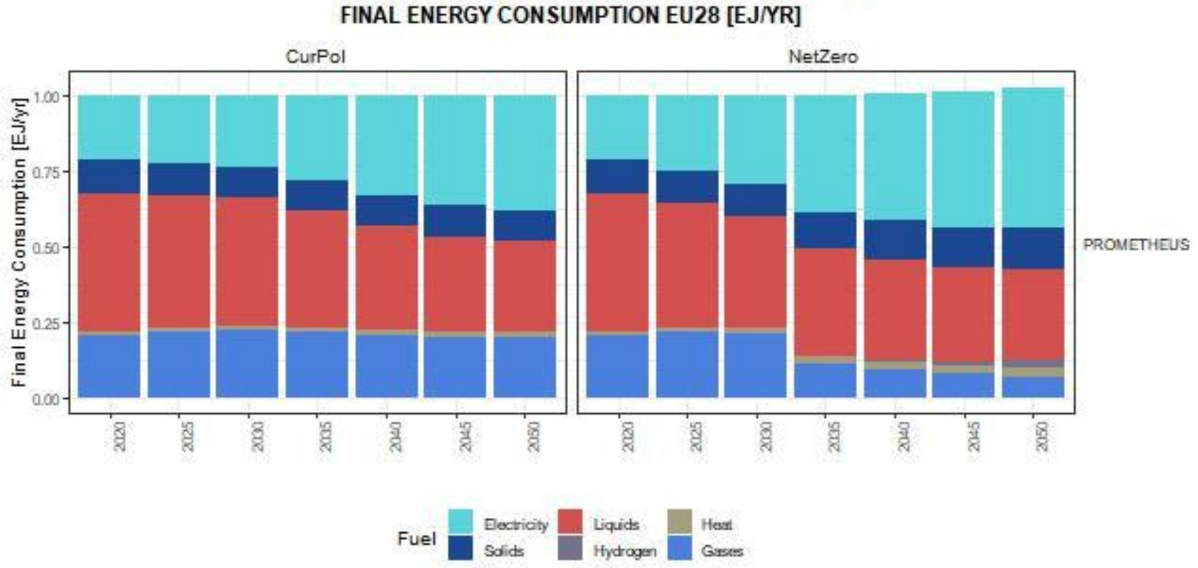
Europe and Other Economies

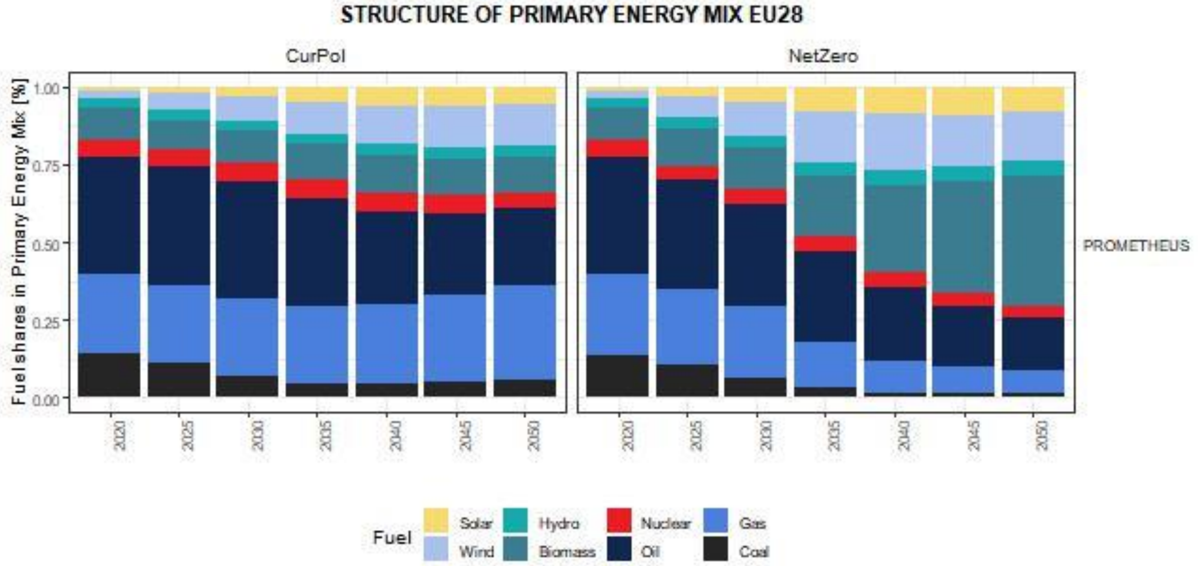


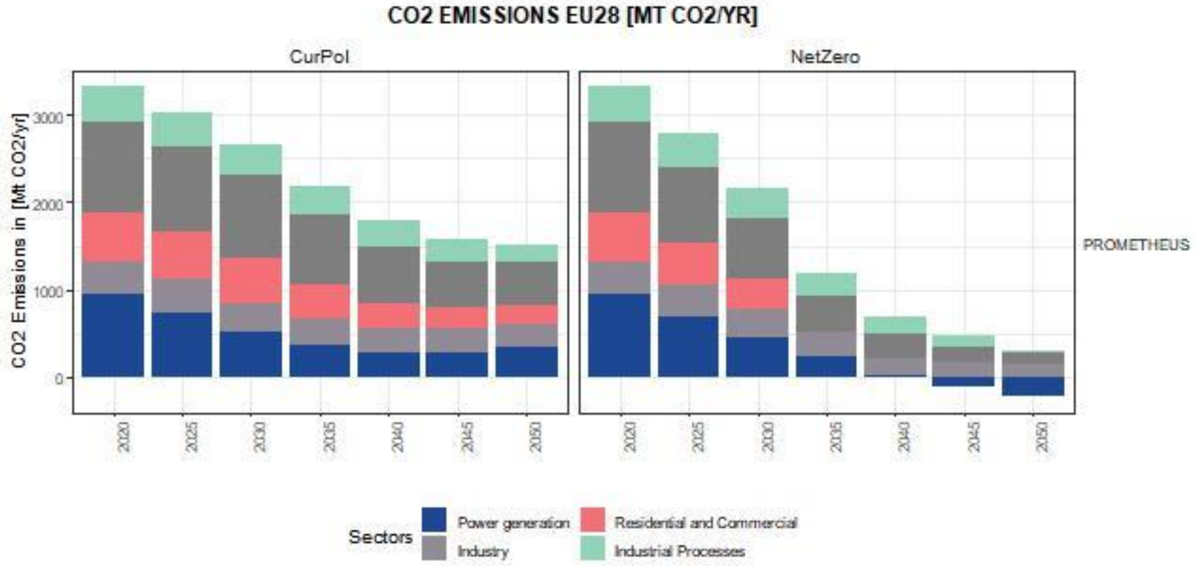




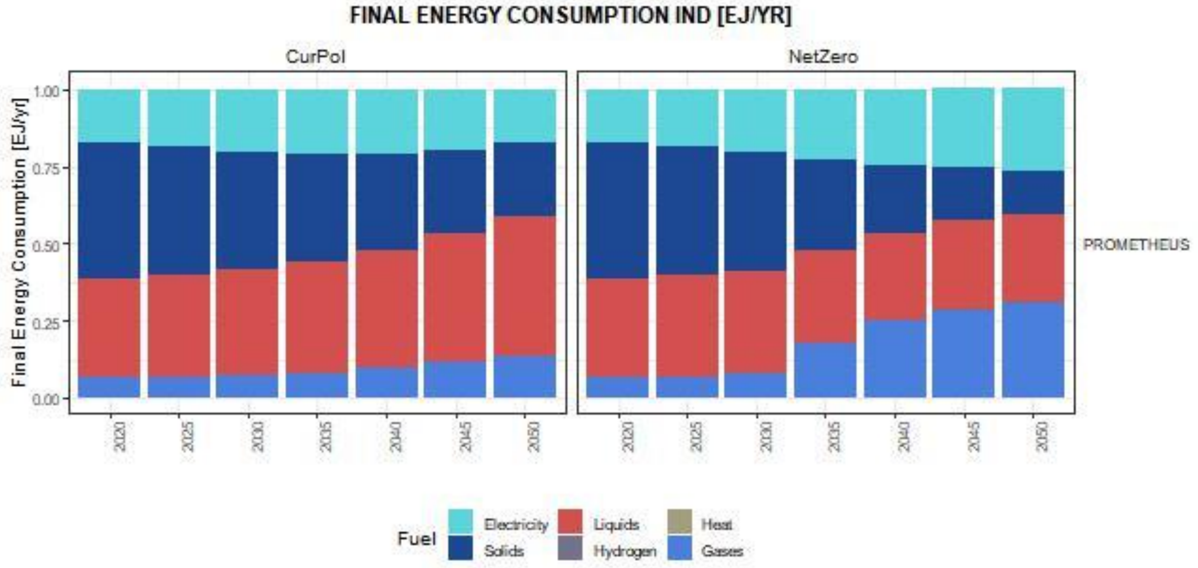
European Union (28 countries)

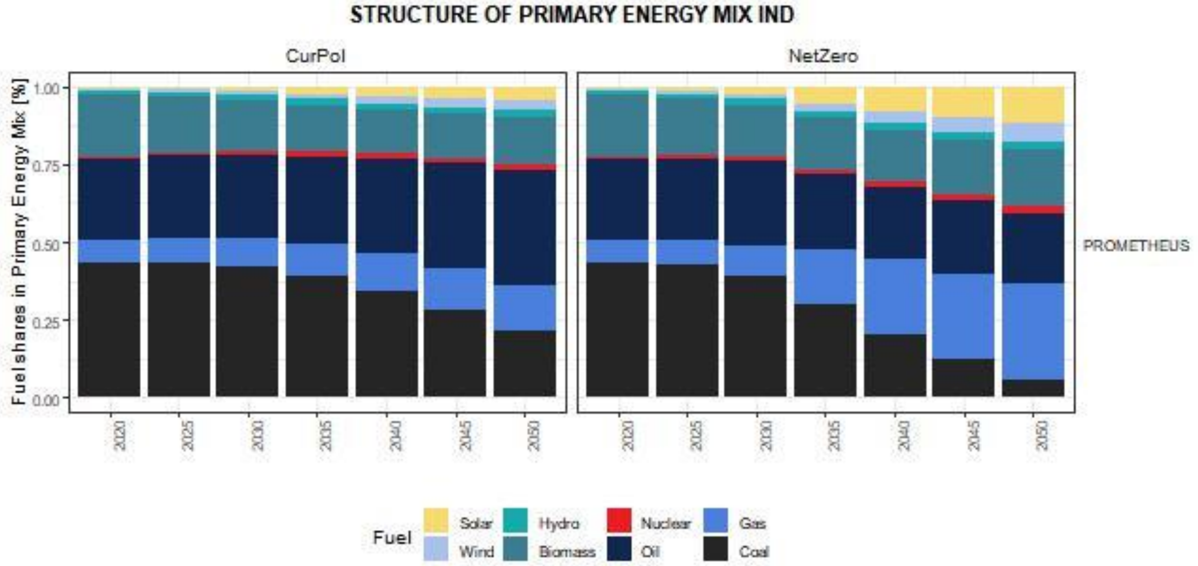


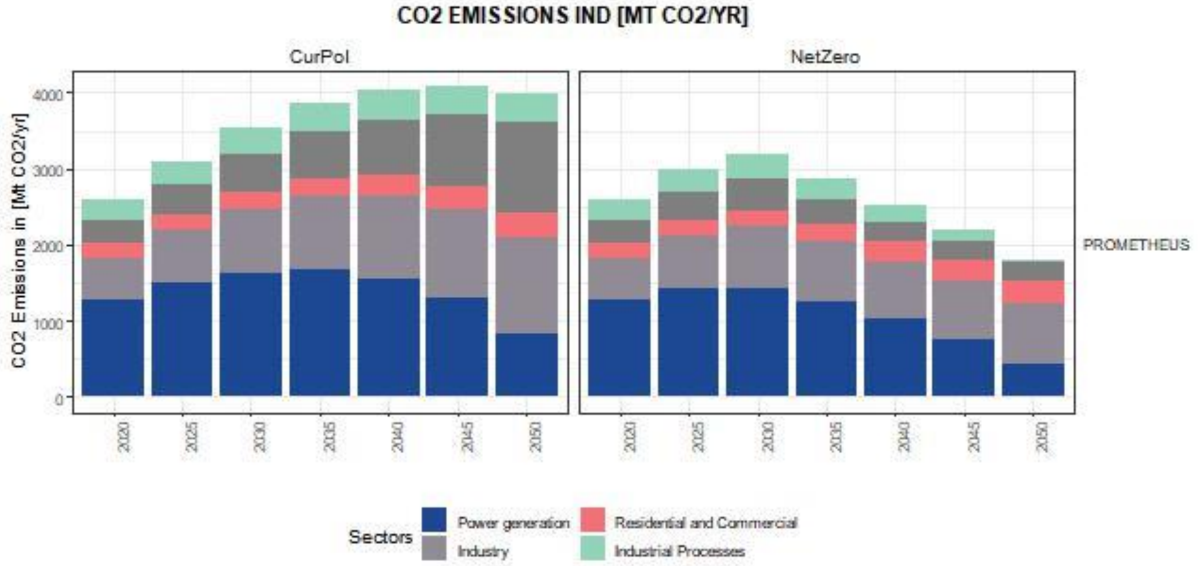




India

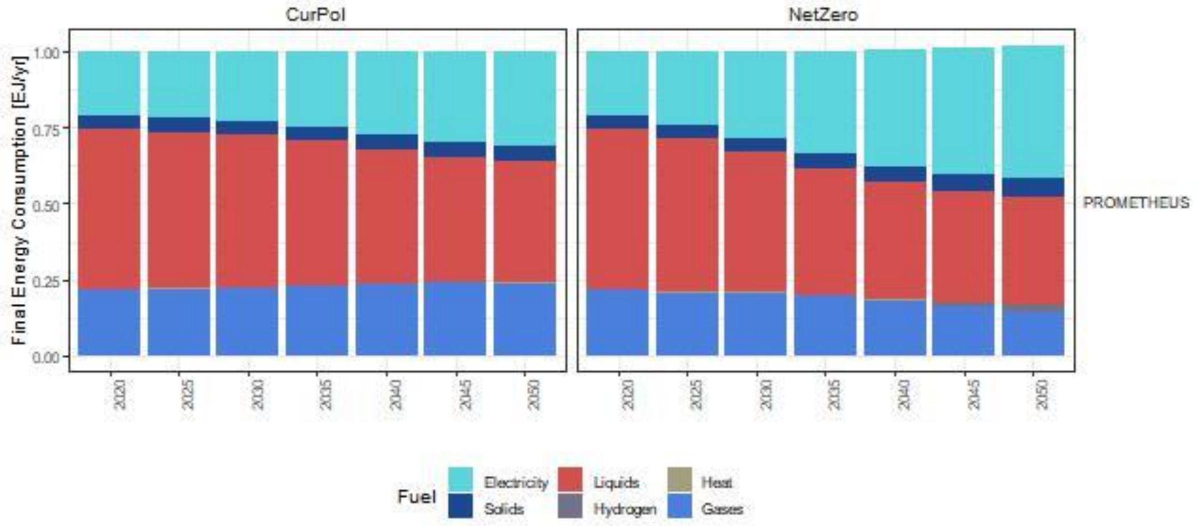

FINAL ENERGY CONSUMPTION IND [EJ/YR]


STRUCTURE OF PRIMARY ENERGY MIX IND

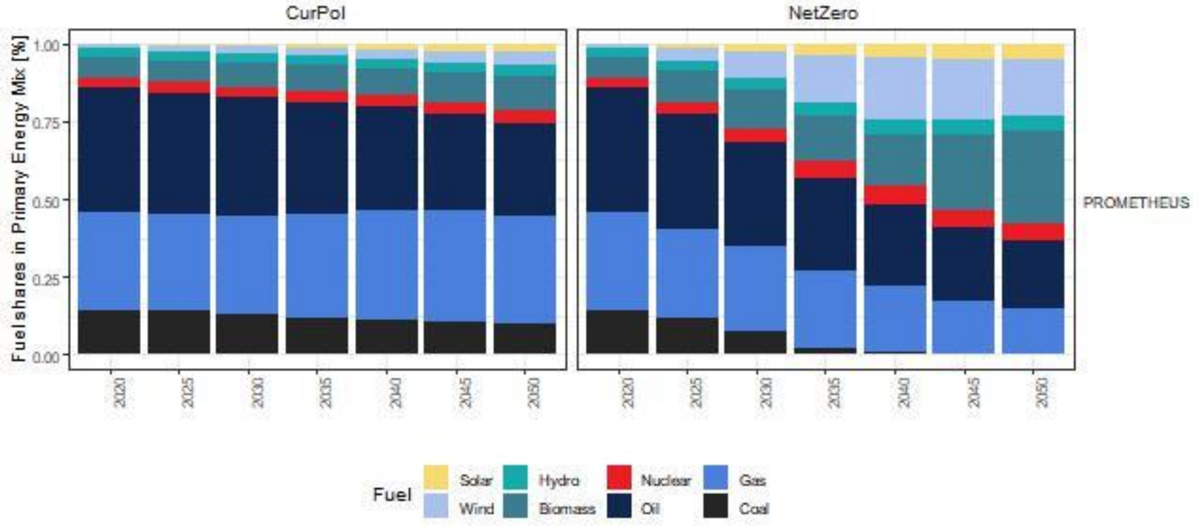

CO2 EMISSIONS IND [MT CO2/YR]

North America

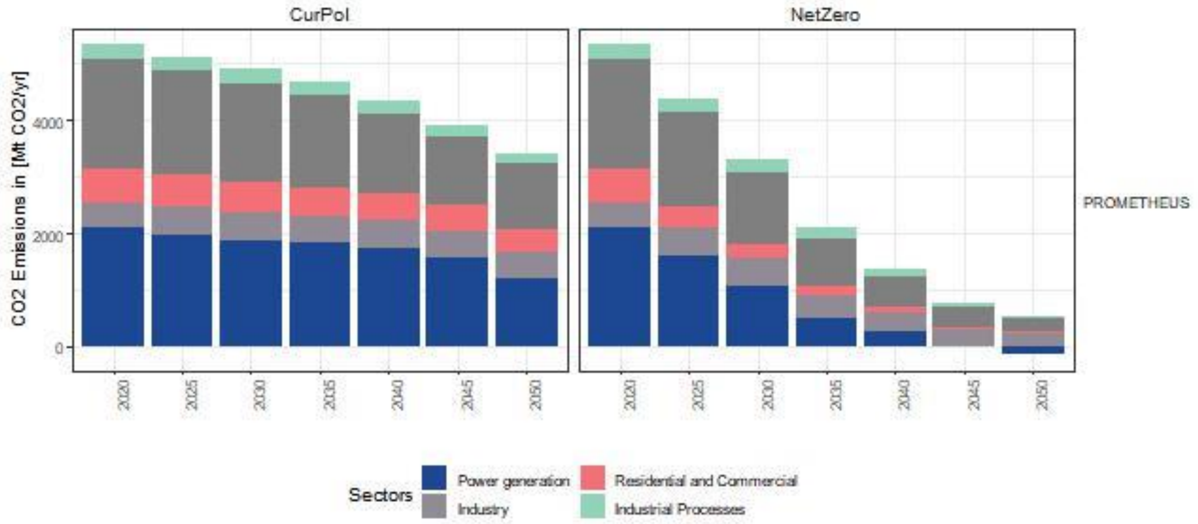
FINAL ENERGY CONSUMPTION NOAM [EJ/YR]



STRUCTURE OF PRIMARY ENERGY MIX NOAM

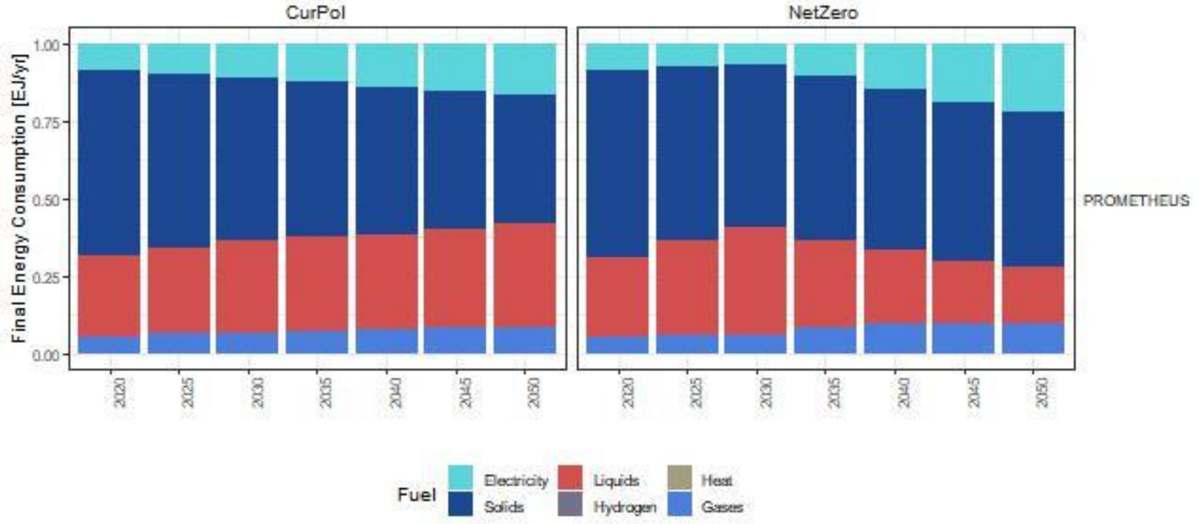


CO2 EMISSIONS NOAM [MT CO2/YR]

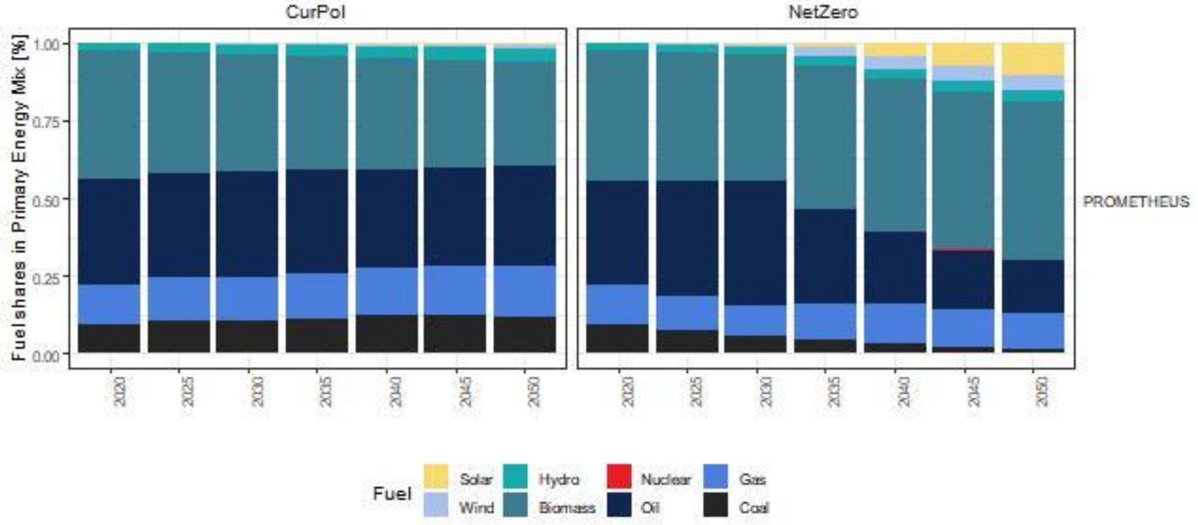


Rest of the World

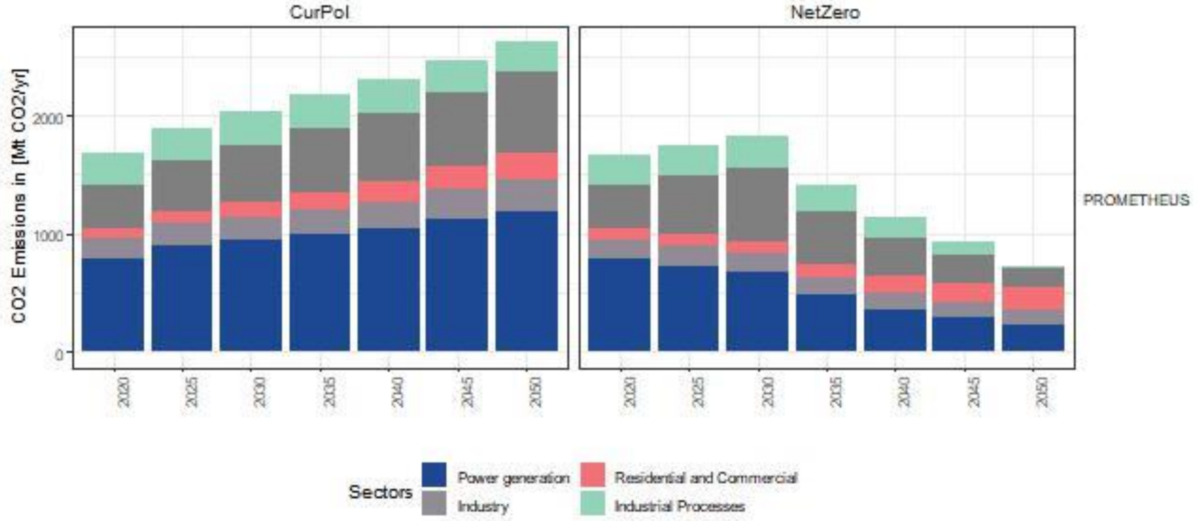
FINAL ENERGY CONSUMPTION RESTW [EJ/YR]



STRUCTURE OF PRIMARY ENERGY MIX RESTW

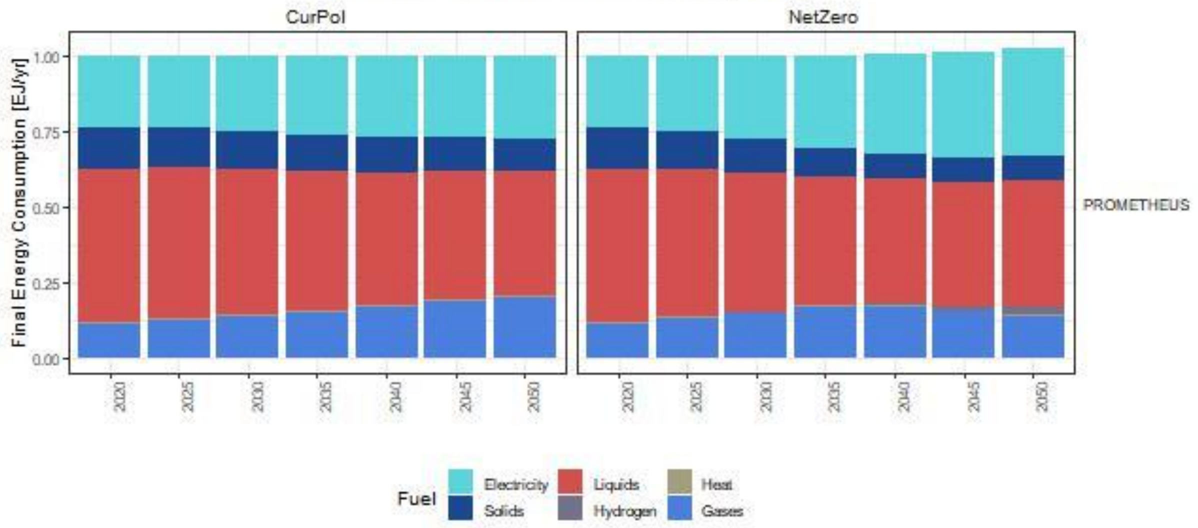


CO2 EMISSIONS RESTW [MT CO2/YR]

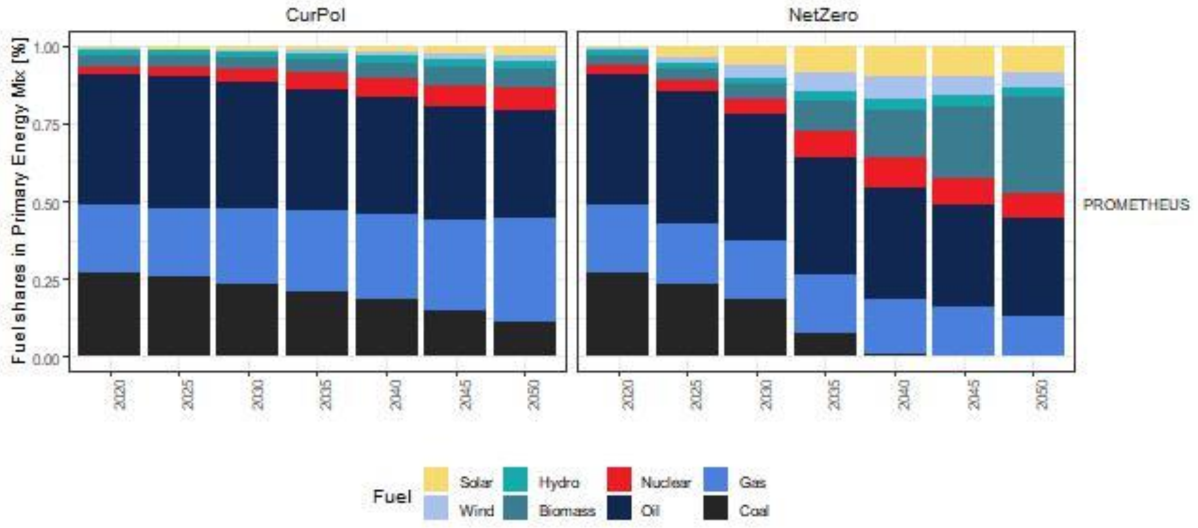


Western Pacific

FINAL ENERGY CONSUMPTION WPAC [EJ/YR]



STRUCTURE OF PRIMARY ENERGY MIX WPAC



CO2 EMISSIONS WPAC [MT CO2/YR]