Synthesis of the model, selected results, and scenario assessment

WP9, Task 9.2, D.9.3

31 August 2023

LOW-CARBON SOCIETY: AN ENHANCED MODELLING TOOL FOR THE TRANSITION TO SUSTAINABILITY (LOCOMOTION)

H2020-LC-CLA-2018-2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821105.

DOCUMENT HISTORY

Project Acronym	LOCOMOTION	
Project title	Low-carbon society: an enhanced modelling tool for the transition to sustainability	
Project coordination	Universidad de Valladolid (Spain)	
Project duration	1st June 2019 – 30th November 2023	
Deliverable No.	D9.3. Synthesis of the model, selected results and scenario assessment	
Dissemination level	Confidential (CO) / Public (PU)	
Status		In progress
		To be verified by other WPs
	*	Final
Due date of deliverable	31st of August 2023	
Delivery date	31st of August 2023	
Version	v.1.7	
Work package	WP9 - Technical coordination and quality assurance	
Lead beneficiary	UVa	
Author (s)	Mohamed Lifi (UVa), Ignacio de Blas (UVa), Iñigo Capellán-Pérez (UVa), Margarita Mediavilla (UVa), Luis Javier Miguel (UVa), Gonzalo Parrado-Hernado (UVa), Luis LLases (UVa), David Álvarez Antelo (UVa), Marta Calleja (UVa), Nathalie Wergles (UVa), Noelia Ferreras (CARTIF), Iván Ramos (CARTIF), Iñaki Arto (BC3), Tomás Calheiros (FC.ID), Tiago Capela Lourenço (FC.ID), Guilherme Spinato Morlin (UNIPI), Simone D'Alessandro (UNIPI), Ole van Allen (INN), Lukas Eggler (AEA), Stavroula Papagianni (CRES), Robert Oakes (UNU).	

Date	Ver.	Contributors	Comment
26/06/2023	0.1	Mohamed Lifi (UVa), Ignacio de Blas (UVa), Luis Javier Miguel (UVa), Nathalie Wergles (UVa).	Table of contents
27/06/2023	0.2	Mohamed Lifi (UVa) & Ignacio de Blas (UVa)	First draft
03/07/2023	0.3	Iñigo Capellán-Pérez (UVa) & Mohamed Lifi (UVa)	The overview and structure of WILIAM model are added
03/07/2023	0.4	Margarita Mediavilla (UVa) & Mohamed Lifi (UVa)	The description and selected results sections of Land and Water Module are added

14/07/2023	0.5	Gonzalo Parrado-Hernado (UVa) & Mohamed Lifi (UVa)	The description and selected results sections of Demography Module are added
18/07/2023	0.6	Luis LLases (UVa) & Mohamed Lifi (UVa)	The description and selected results sections of Finance Module are added
24/07/2023	0.7	Marta Calleja (UVa) & Mohamed Lifi (UVa)	The description and selected results sections of Society Module are added
27/07/2023	0.8	Noelia Ferreras (CARTIF) & Mohamed Lifi (UVa)	The description section of Climate Module is added
01/08/2023	0.9	Iñaki Arto (BC3) & Mohamed Lifi (UVa)	The description section of Economy Module is added
03/08/2023	1.0	Tomás Calheiros (FC.ID), Tiago Capela Lourenço (FC.ID) & Mohamed Lifi (UVa)	The Water model results are added to “Selection of preliminary results” section of Land and Water module.
04/08/2023	1.1	Guilherme Spinato Morlin (UNIPI), Iñaki Arto (BC3), Simone D'Alessandro (UNIPI) & Mohamed Lifi (UVa)	The Economy module results are added to “Selection of preliminary results” section of Economy module.
09/08/2023	1.2	Noelia Ferreras (CARTIF) & Mohamed Lifi (UVa)	The Climate module results are added to “Selection of preliminary results” section of Climate module.
11/08/2023	1.3	Iñigo Capellán-Pérez (UVa)	Model validation section is added
12/08/2023	1.4	Iñigo Capellán-Pérez (UVa) & Mohamed Lifi (UVa)	“Assessment of critical features missing from WILIAM” section is added
16/08/2023	1.5	Iñigo Capellán-Pérez (UVa), Mohamed Lifi (UVa), Gonzalo Parrado-Hernado (UVa), Ole van Allen (INN)	Critical features missing of Energy, Land and Water, Demography, Society, Economy, Finance, and Materials modules are added to Assessment of critical features missing from WILIAM” section.
22/08/2023	1.6	Ole van Allen (INN), Iñigo Capellán-Pérez (UVa), Mohamed Lifi (UVa)	The description and selection of preliminary results sections of Materials module are added.
24/08/2023	1.7	Lukas Eggler (AEA), Iñigo Capellán-Pérez (UVa), Mohamed Lifi (UVa)	The description and selection of preliminary results sections of Energy module are added.

COPYRIGHT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

Acronym	Description
AMOC	Atlantic Meridional Overturning Circulation
BI	Basic Income
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power plants
CSP	Concentrated solar power
CGE	Computable General Equilibrium
DSM	Demand Side Management
EOL	End-Of-Life
EROI	Energy Return on Energy Investment
EROIst	Standard EROI
ESOI	Energy Stored on Energy Investment
EU	European Union
EV	Electrical Vehicles
GDPpc	Gross Domestic Product per capita
GFCF	Gross Fixed Capital Formation
GHG	Greenhouse Gas
HDI	Human Development Index
IAM	Integrated Assessment Model
IO	input-output
LCOE	Life Cycle Cost of Electricity
LUC	Land Use Change
LULUCF	Land Use, Land Use Change, Forests
Mbd	million barrels per day
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operation Expenditures
ppm	parts per million
PV	Photovoltaics
RURR	Remaining Ultimately Recoverable Resources
RES	Renewable Energy Sources
SC	Spare Capacity

SDI	Sustainable Development Index
WPs	Work Packages

EXECUTIVE SUMMARY

This deliverable represents the third deliverable of WP9 within the LOCOMOTION project. This deliverable serves as a comprehensive report of the work of WILIAM model development accomplished within WP9.

The WILIAM model has been developed in a collaborative distributed (Gitlab) and sequential way, from modules to full model, and from simpler to more complex structures. It is structured in eight modules (Demography, Society, Economy, Finance, Energy, Materials, Land and Water and Climate), to allow for flexibly testing, improving, and expanding each module without impairing the robustness of the model.

Gitlab platform has allowed a significant number of modellers to work in parallel in a decentralized and coordinated way. The modelling rules elaborated in D9.1 have been updated 3 times since the original publication in May 2020 in order to keep pace with new issues arisen during model development.

Due to the difficulties to achieve all the challenges and ambitions initially proposed in the project in the planned time, the European Commission requested to limit the expectations and scope that the WILIAM model to a level that can be realistically achieve by the end of this project. That's why, at the time of writing this deliverable, WILIAM is not a fully functional model yet. Hence, these deliverable reports preliminary results from the most updated version of WILIAM (v1.1) including those validated functionalities.

This deliverable is organized in three main parts. The first one consists of a description of the WILIAM model, including a general description of each of its eight modules. The second part of the deliverable shows preliminary results in order to show its potentiality, with the objectives to showcase (1) the capabilities and functionalities of each module and (2) the interactions between modules. The third part is dedicated to the assessment of the critical features missing, including its status, in order to guide model development until the end of the project.

DELIVERABLE CONTENTS

1. INTRODUCTION

This deliverable is the second public report encompassing Task 9.2, which involves the description of the WILIAM model modules and preliminary results to showcase the WILIAM model's potentialities. It stands as a more updated and concise version of the previously published D9.2 (de Blas Sanz et al., 2022a) that focuses on providing a detailed description of each module within the WILIAM model. Moreover, this deliverable is associated with the WILIAM model, the main outcome of WP9, and is delivered collaboratively.

The WILIAM model is structured in eight modules (Demography, Society, Economy, Finance, Energy, Materials, Land and Water and Climate). It has been developed in a collaborative distributed way (Gitlab) and sequential way, from modules to full model, and from simpler to more complex structures, to allow for flexibly testing, improving, and expanding each module without impairing the robustness of the model. Its final objective extends beyond the analysis of climate policies, encompassing the design of energy transition pathways, with a particular emphasis on considering physical limitations.

Gitlab platform has allowed a significant number of modellers to work in parallel in a decentralized and coordinated way. The modelling rules elaborated in D9.1 have been updated 3 times (November 2020, October 2021, and January 2023) since the original publication in May 2020 in order to keep pace with new issues arisen during model development.

Between the two deliverables 9.2 and 9.3, significant progress has been accomplished across all modules. On the one hand, new functionalities have been developed, for example a forest and grasslands submodules in Land and Water module, new modelling of migrations between regions in Demography module, new indicators as HDI, SDI or GINI in Society module, the variability of renewables in Energy module, changes in investment submodule in Economy module, a full accounting of GHG emissions in Climate module, or the inclusion of the maximum resources/reserves' availability in Materials module. On the other hand, all modules have been reviewed, updated, validated, and documented (cf. also D11.2 (Samsó et al., 2023)).

However, the most important progress that has been made since the submission of deliverable 9.2 has been the development of the links and feedbacks between the different modules. The current version of the WILIAM model incorporates several inter-module feedbacks, and among them, we can cite the following examples:

- Oil price feedback that affects Economy, Energy, and Materials modules.
- Availability of land for solar and bioenergy feedback between Land and Water and Energy modules.
- Climate change impacts feedbacks for example affecting land use in Land and Water module.
- Feedback on passenger transportation between Economy and Energy modules.

Still, at the time of writing this deliverable, WILIAM is not a fully functional model yet. Hence, these deliverable reports preliminary results from the most updated version of WILIAM (v1.1). Other non-validated features under work have not been considered here.

Furthermore, working together with WP11, these advancements have been successfully prepared for integration into WILIAM user interfaces: Explorer, Analyzer, and Simplified Analyzer applications. Also, in coordination with WP8 a portfolio of conventional and heterodox policies such as basic income, behavioural changes or working time reduction have been modelled in WILIAM model.

Section 2 of the deliverable provides a description of the WILIAM model. It starts with an overview of the model and how it is structured. Following that, a general description of each WILIAM module (Demography, Society, Economy, Finance, Energy, Materials, Land and Water, and Climate) is presented. This section aims to give a clear understanding of how the WILIAM model is designed and functions.

Section 3 outlines the model validation process, which was conducted using various standard validation procedures commonly employed in system dynamics modelling.

In Section 4, some preliminary results from each WILIAM module are presented to highlight the potential of the model. For each module, different policy scenarios are tested to observe how they are affected when switching from one scenario to another. For obtaining these preliminary results inputs from WP8 with relation to policies and scenarios have been used (cf. D8.2 and D8.3 for a thorough reporting of scenarios and policies).

Section 5 presents the assessment of critical features missing from WILIAM model, and Section 6 concludes.

2. DESCRIPTION OF WILIAM MODEL

2.1. OVERVIEW OF THE WILIAM MODEL

WILIAM is a system dynamics policy-simulation model, descendent from MEDEAS (Capellán-Pérez et al., 2020) which has been designed to explore long-term decarbonization pathways within planetary boundaries by addressing a series of limitations of existing IAMs. In fact, despite the high number of IAMs, many share several relevant and disputable hypotheses/characteristics. The main shortcomings aimed to be addressed with WILIAM are: lack of plurality/simplified representation of economic processes typically based on optimization, equilibrium dynamics, aggregate production functions and representative agents (Hardt & O'Neill, 2017; Scrieciu et al., 2013), future energy transitions modelled as demand-driven transformations (assumption of future high energy availability at affordable cost, both for renewables and non-renewables), the neglect of implications of future energy investments required to achieve the transition to renewables for the entire system (Energy Return on Energy Investment of the full system (Capellán-Pérez et al., 2019a), difficulties to reach 100% renewable systems, underestimation of the damages caused by climate change, the absence of the material dimension and key sustainability dimensions other than climate change.

WILIAM focuses on the detailed representation of the economic processes following a Dynamic Econometric Input-Output approach and consistently linking the economic and biophysical spheres according to the principles of Ecological Macroeconomics. WILIAM follows a complex system approach, in which the interactions between dimensions are more relevant than the complexity within each module. System dynamics allows to capture complex feedback loops and nonlinear relationships among social, economic, and environmental variables.

WILIAM model comprises 8 integrated modules of earth and human systems: (1) demography, (2) society, (3) economy, (4) finance, (5) energy, (6) materials, (7) land and water and (8) climate. Figure 1 shows the structure overview of the last updated version (v1.1) with the main validated linkages between modules. Different modules reach different levels of detail and complexity. WILIAM starts to run in 2005 and typically runs until 2060, although the simulation horizon may be extended to 2100. WILIAM is a multiregional model which blends top-down and bottom-up (end-use) modelling approaches and integrates knowledge and methods from different disciplines aiming to capture the main dynamics between human and natural systems and taking into account socioeconomic constraints and biophysical limits. This comprehensive integration is particularly relevant when modelling disruptive scenarios involving significant shifts in economic structure, social values, norms, and individual behaviour. Indeed, the ultimate goal of WILIAM is to explore the social, economic, and environmental implications at the global and regional levels of long-term socio-ecological transition pathways', considering biophysical planetary limits as well as socio-economic constraints.

More information about the main characteristics of WILIAM model can be found in Deliverable 11.2 (Samsó et al., 2023).

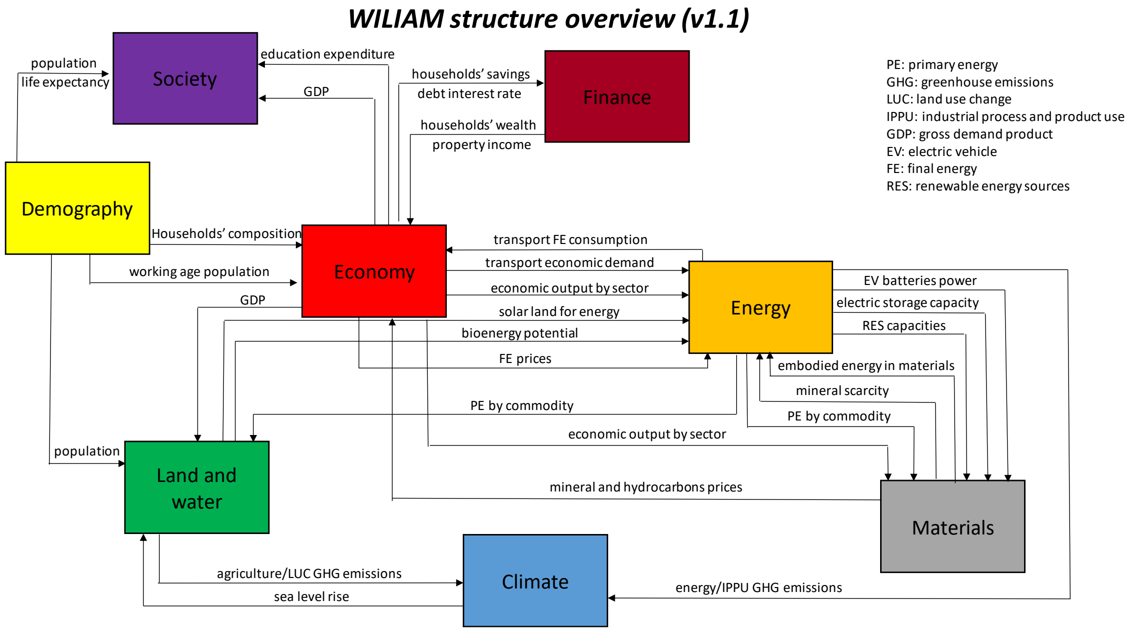

Figure 1: WILIAM simplified structure overview of the last updated version of the model (v1.1). Main linkages between modules.

2.2. DESCRIPTION OF DEMOGRAPHY MODULE

Humans trigger economy, energy, services, food, etc., assets derived from the social relationships and human needs. Here, the physical dimension of human beings is explained, i.e., mathematical representation of the number of people by sex (male and female) and age (5-year aggregations until 80) by 35 regions.

The general overview of demography module is shown in Figure 2. Births, deaths, migration flows, life expectancy at birth and mortality rates are endogenous variables. On the other hand, exogenous data complete the bounds of the system in the historical time. Historical data used to implement realistic scenario hypothesis for the future in this module:

- Women are the principal driver in reproduction. They are affected with different fertility rates by age group, while gender ratios estimate the sex of births in the model.
- Given a specific region and age, all the mortality rates (by region, sex, and age group) are endogenized by one life expectancy at birth (by sex and region) through exponential equations,

i.e., one by age group. The analytic formulas are reproduced in the model with the same constant assumptions.

- There is not a comprehensive method to represent the causes and effects on demographic changes across regions (migration flows). Therefore, exogenous assumptions are assumed, adjustable values for the user that can customize to test specific scenarios. The emigration rates are multiplied by a constant profile (sex and age) and the number of people in a region to calculate the emigration flow in the year. Then, a matrix of shares distributes such migrants across the world regions in WILIAM model, with net balance equal zero.
- From the literature, three relationships of climate impacts to the life expectancy at birth were considered. The parameters introduced are assumed as constant hypothesis.
- Switches is a powerful feature of WILIAM model, they are able to de/activate parts of the model to study an aspect in isolation. Two switches are applied within the demography module, the first one to enable migration flows, and the other one to activate the three feedbacks to the life expectancy at birth.

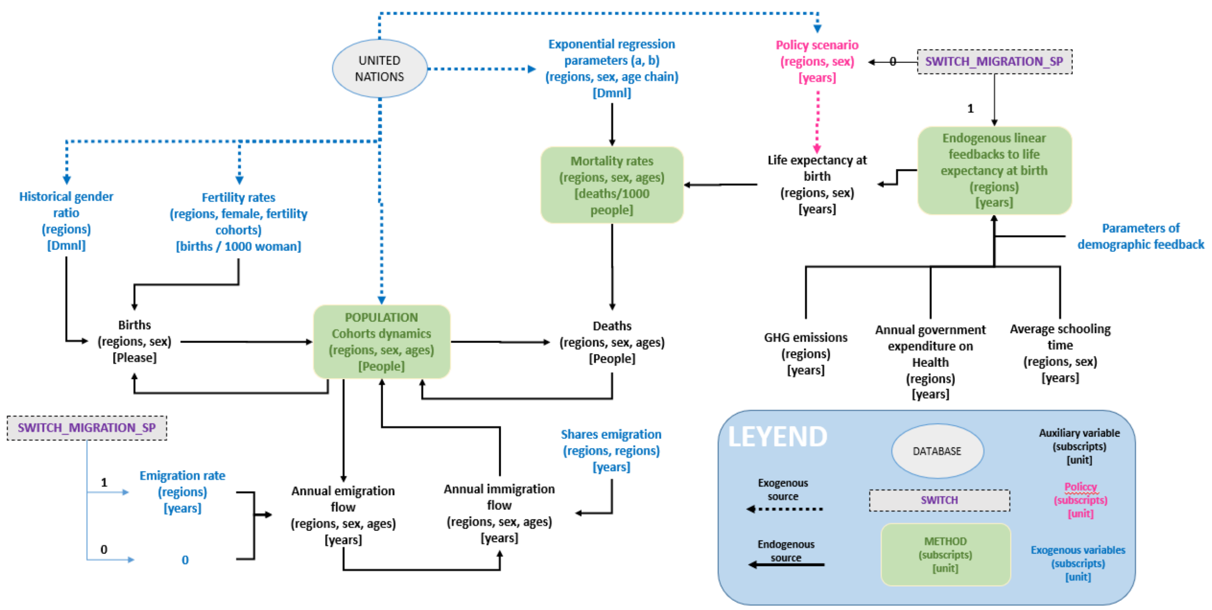

Figure 2: Demography module overview

2.3. DESCRIPTION OF SOCIETY MODULE

The Society module is a regional model (9 global regions), but it also allows the disaggregation of the European region by country, so that a total of up to 35 regions can be analysed separately. As shown in in Figure 3, there is no feedback from Society module to other WILIAM modules, however there are several links, that allow to calculate certain social indicators. Several data are sent from the Demography module to represent the composition of households, which materializes for most of the countries comprising the European Union. In turn, this serves as an input to subsequently estimate the consumption of patterns. On the other hand, through the accumulated public expenditure on education per capita and the classification of the population by levels of educational attainment, the labour force is calculated based on the level of education attained. What is interesting here is that there is a gender parity index that allows us to calculate the relative access of men and women to education, therefore we can have the latter output disaggregated by sex. Finally, this module allows to calculate two social welfare indicators, the first one is the GINI coefficient that is designed to measure income inequality within a country, and the second one is the Human Development Index (HDI), which is used to classify countries according to their degree of development in three different dimensions: education, life expectancy, and living conditions.

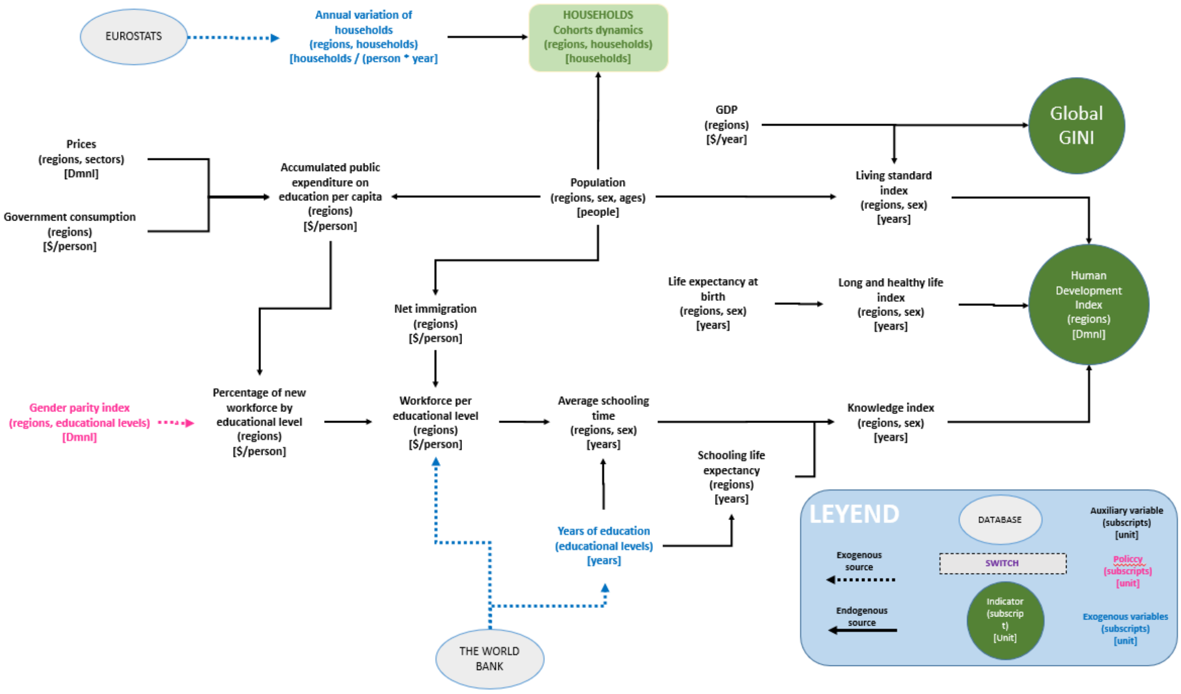

Figure 3: Society module overview

2.4. DESCRIPTION OF ECONOMY MODULE

The foundational element of WILIAM's Economy module is a hybrid input-output (IO) model. This model has been expanded to include endogenous final demand (as in a type ii IO model) and incorporates reciprocal interactions between quantities and prices (as in a Computable General Equilibrium (CGE) model) (Figure 4). In contrast to CGE models, the IO model in WILIAM has New Keynesian features, as markets are not generally cleared by the price mechanism, but effective demand under supply constraints determines the outcome for the different industries. The macroeconomic IO model in WILIAM is especially designed for incorporating feedbacks between the economy and nature. That comprises primary energy supply, land use and water supply as well as the feedbacks of climate change to the economy. The WILIAM Economy module is composed of seven submodules, namely households, government, firms/production, investment/capital, labour, international trade, and prices. More detailed explanations of these submodules and the key equations they utilize can be located in Deliverable 11.2 (Samsó et al., 2023).

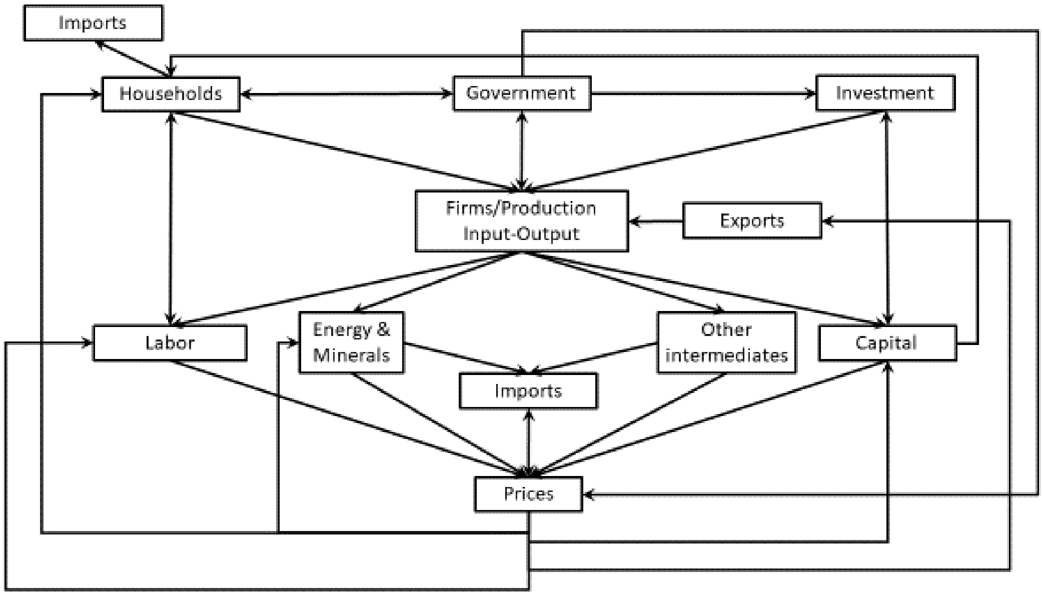

Figure 4: Main components and relations of the economy module.

2.5. DESCRIPTION OF FINANCE MODULE

The financial module of the WILIAM model tries to replicate the progression of household wealth over time. By doing so, it impacts their spending choices and imposes financial limitations on the acquisition of vehicles. This segment has the capability to simulate various scenarios across all 35 WILIAM regions. In the majority of European countries, the model is broken down into 60 different household types (as explained in the economy module section). In cases where data was unavailable, a single representative household was utilized.

The three primary inputs for the financial module are derived from the economic module. These inputs consist of households' gross savings, the government debt interest rate specific to each region (which serves as the base interest rate), and the price of gross fixed capital formation in the real estate sector. Starting with initial data on households' capital stock, financial assets, and financial liabilities, the net savings of households are accumulated, leading to modifications in these three variables. Depending on the cumulative assets and liabilities, the income from property that households either receive or pay is calculated. This property income, in turn, aids in determining households' disposable income, which is then used to calculate gross savings. These changes in gross savings impact households' assets and liabilities, effectively closing the feedback loop between the financial and economic modules. On the other hand, household net wealth and disposable income affect household vehicle purchases.

The representation of the relationships of the financial module with other modules is shown in Figure 5.

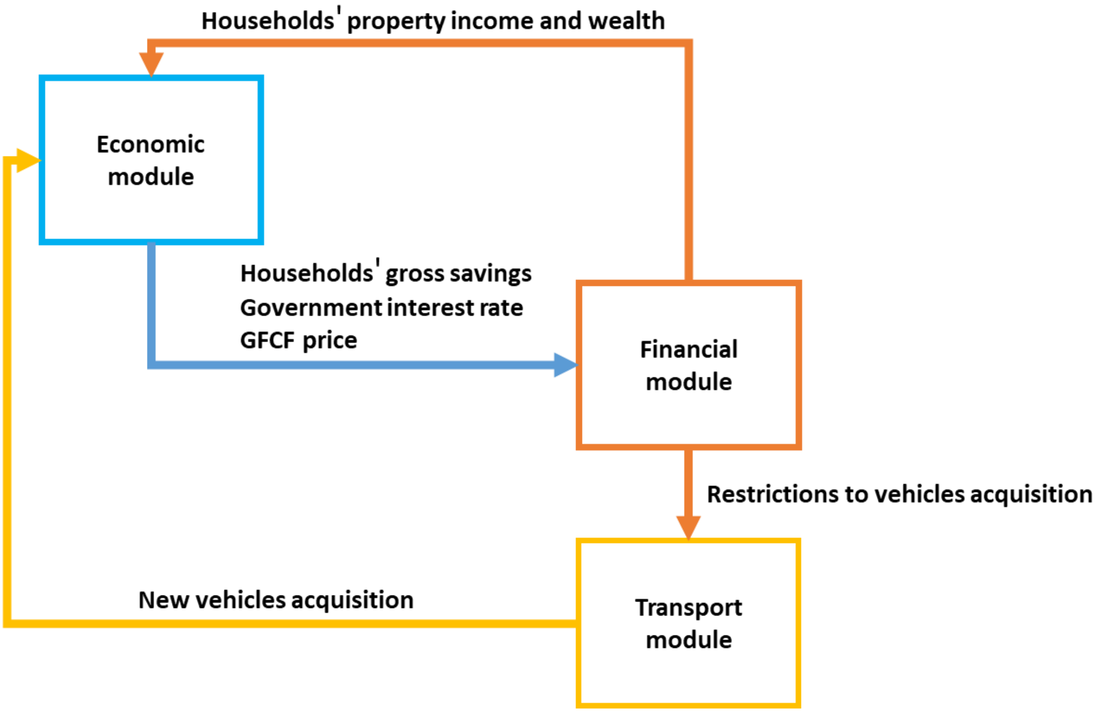

Figure 5: Financial module relationships with other modules

2.6. DESCRIPTION OF ENERGY MODULE

The WILIAM Energy module (Figure 6) encapsulates the entire transformation process from primary to final energy necessary to fulfil societal economic demands. This module is parameterized across nine geographical regions and integrates seven final energy commodities, 12 primary energy commodities, and 35 energy transformation technologies for electricity and heat. The outcomes of the energy module are primarily driven by the economic demand simulated by the Economy module taking into account restrictions from other parts of WILIAM (e.g., land-use). The Energy module consists of seven closely connected submodules: End-Use, Energy Transformation, Energy Capacity, RES Potentials, Variability Management, EROI / ESOI, and GHG Emissions. Further information about the description of submodules within the Energy module and the main equations employed in this module can be found in Deliverable 11.2 (Samsó et al., 2023).

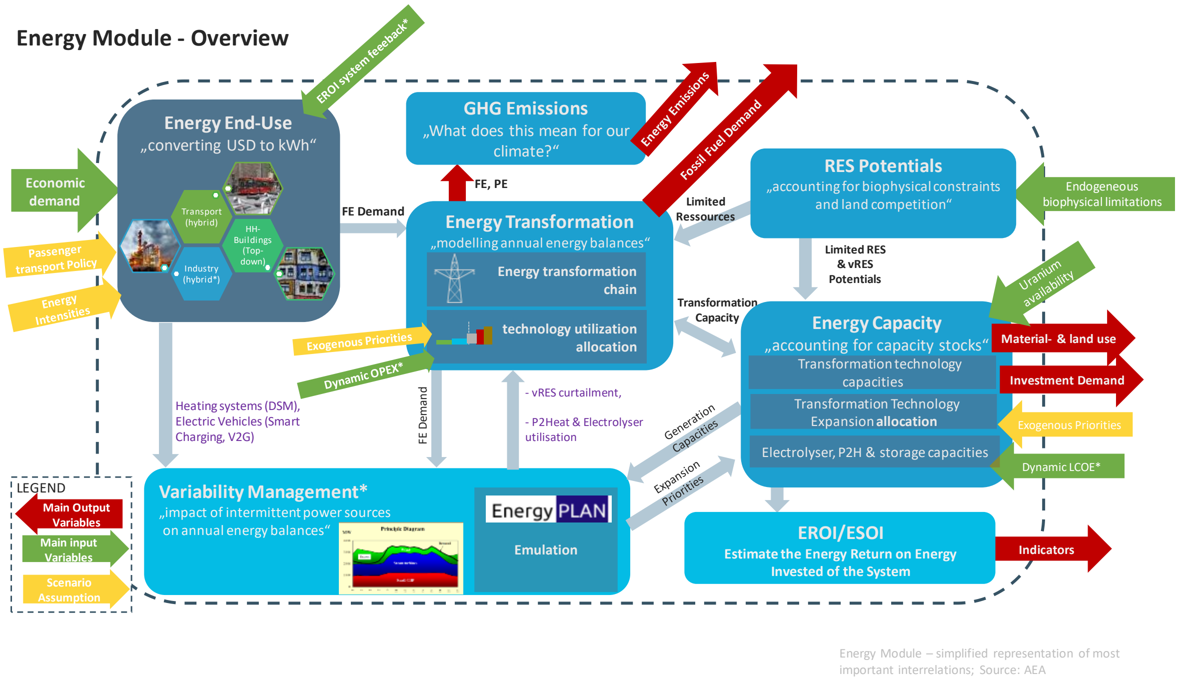

Figure 6: Energy Module – Overview.

2.7. DESCRIPTION OF MATERIALS MODULE

The Materials module constitutes one of the eight modules within the WILIAM model. The main purpose of this module is to model the extraction, and availability of resources and their prices (where the price signal is than delivered to the Economy module). And it is organized into four distinct sub-modules: (1) Metals, encompassing elements like Fe, Cu, Ni, and Al; (2) Fossil Fuels, covering resources such as natural gas, crude oil, and coal; (3) Uranium; and (4) Material Requirements of Green Energy Technologies, catering to solar PV, onshore wind, offshore wind, and electric batteries. In Figure 7, there's a simple illustration that shows the Materials module, its sub-modules, and how they connect with the rest of the WILIAM model. For more details regarding the description of each sub-module within the Materials module and the equations utilized in each of them, please refer to deliverable 11.2 (Samsó et al., 2023).

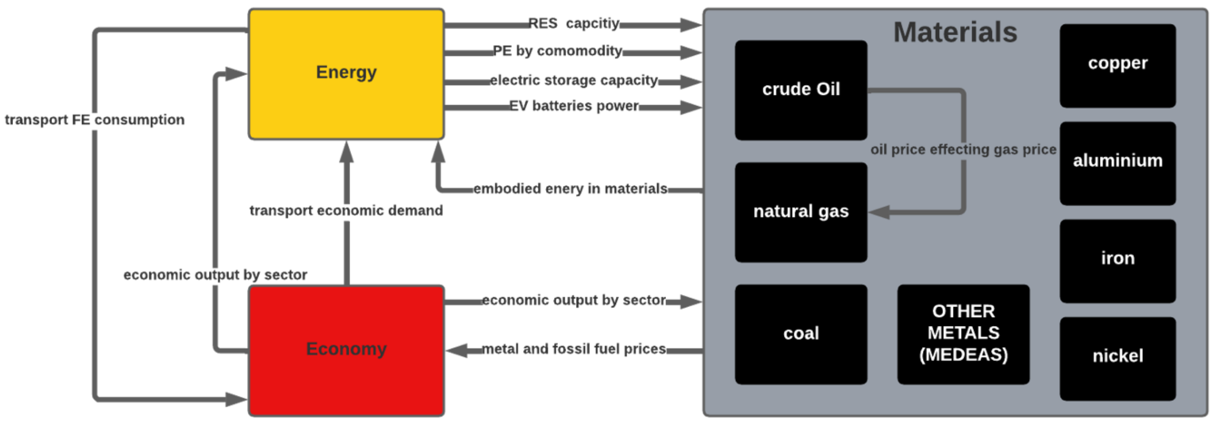

Figure 7: Overview of the Materials Submodules with linkages to other modules of WILIAM.

2.8. DESCRIPTION OF LAND AND WATER MODULE

The Land and Water module is working in 9 global regions: EU27, UK, CHINA, EASOC, INDIA, LATAM, RUSSIA, USMCA, and LROW (de Blas Sanz et al., 2022a). The interactions of the Land and Water Module with the rest of the model are reported in Figure 8. As shown in Figure 8 from the Economy Module the Gross Domestic Product per capita (*GDPpc*) is received as input to calculate the demand of food; Also, the Land and Water Module receives the production of the sectors (*real output*) to calculate the demand of wood for industry; From the Society and Demographics Modules it receives the values for population and demand of land for urbanization, then the shortage of food and some nutritional indicators that measure the average quality of the diet are calculated; and finally the Energy Module provides the values for primary energy by commodity, the emissions from energy and material use, and the land demand for solar energy, while receiving from Land Module signals of shortage of land products and land for solar energy. The division of the Land and Water Module into various sub-modules has led to the inclusion of Land Uses, Croplands and Yields, Diets and Land Product Demand, Availability of Land Products, Forests, Grasslands, and Water. Further information on their descriptions and the equations used can be found in deliverable 11.2 (Samsó et al., 2023).

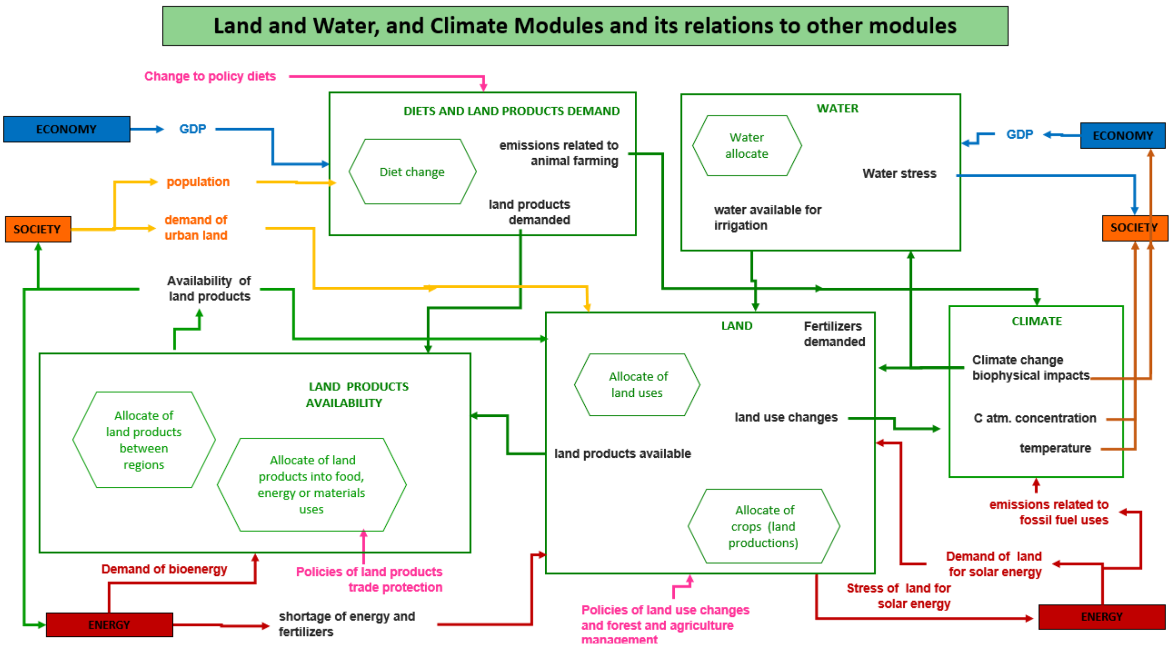

Figure 8: Interaction of Land and Water Module with the rest of the WILIAM model

2.9. DESCRIPTION OF CLIMATE MODULE

The Climate module of WILIAM model is a global and regional model that is working in 9 LOCOMOTION regions (de Blas Sanz et al., 2022a). The interactions between the Climate module and the rest of WILIAM modules are presented in Figure 9. As shown in Figure 9, from Energy module, the GHGs emissions related to fossil fuel uses (transport, energy consumption, etc.) are sent to the Climate module to calculate the concentrations of these gases through their respective cycles; The emissions related to agriculture, land use change, and forestry emissions are calculated in the Land and Water module and then are sent also to the Climate module to the CO_2, CH_4 and N_2O cycles. The Climate module provides the global and regional mean temperature changes that allow to estimate some climate change impacts in several modules through damage functions such as: the capital stock and labor productivity losses in Economy module, and the sea level rise, ocean acidification and crop yield in Land and Water module. Also, it provides the annual variation of CO_2 emissions to estimate the impact on life expectancy at births in

Demography module. In addition, five tipping points are also assessed in the Climate Module, with increasing probabilities depending on the temperature increase in future climate. Specifically, the Atlantic Meridional Overturning Circulation (AMOC) weakening is a tipping point that can be activated and has impacts in regional temperature changes in the northern hemisphere, with low probability. The other modelled tipping points are the Melt of the Greenland Ice Sheet, the Disintegration of the West Antarctic Ice Sheet, the Dieback of the Amazon Rainforest and the Shift to a more persistent El Niño Southern Oscillation. On the other hand, the permafrost tipping points whose effects will feed directly into the carbon and methane cycles is by default deactivated due to its uncertainty.

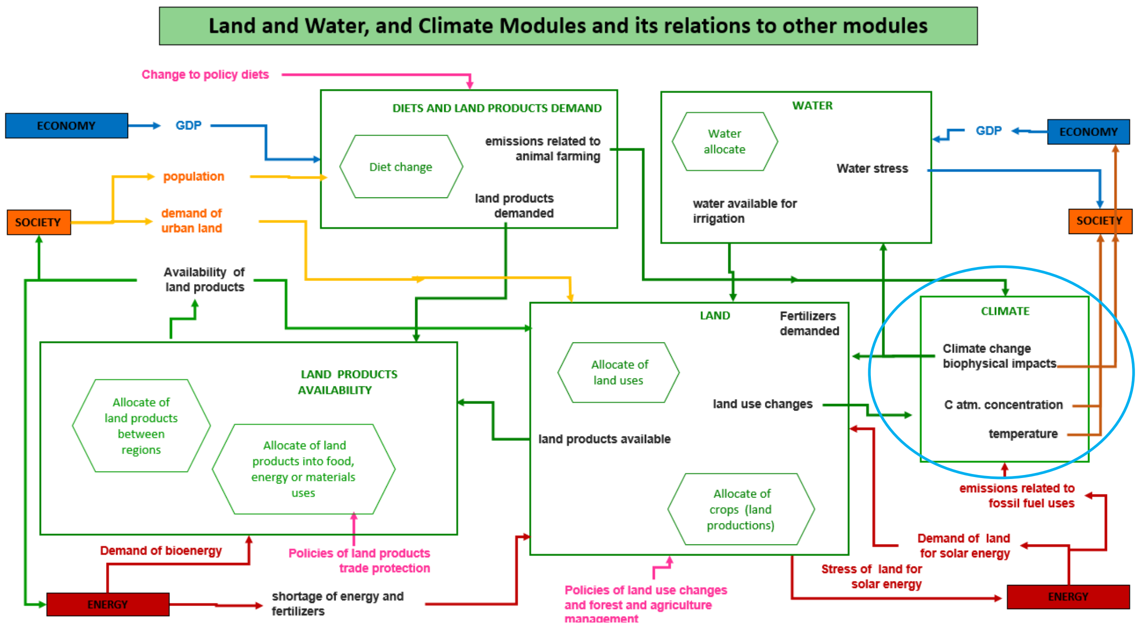

Figure 9: Interaction of Climate Module with the rest of the WILIAM model

3. MODEL VALIDATION

The WILIAM model has been developed in a sequential way, from modules to full model (i.e. including interlinkages), and from simpler to more complex structures, to allow for flexibly testing, improving, and expanding each module without impairing the robustness of the model.

The validation of the model has been carried out following several of the usual validation procedures of models in system dynamics (Barlas, 1996; Sterman, 2000). The historical data has also been used for a first validation, and the obtained results have been compared with other models and assessments. Among the methods applied to test and validate the model: structure-confirmation tests, parameter-confirmation tests, extreme condition tests (robustness analyses), behaviour sensitivity tests, sensitivity analyses, etc. These methods have been applied both by modellers as well as by module and general coordinators within WP9, setting up a back-and-forth process with module leaders.

Templates have been built to automatize the analysis of results outside of VENSIM, which have significantly speed up time to detect eventual errors and inconsistencies (both ours as in the original datasets used).

In particular, sensitivity analysis has been performed in collaboration with WP8 during the development of the WILIAM model to analyse, correct and validate preliminary results with the aim to provide feedback to modellers in order to improve the model before producing final results. This has allowed us to identify inaccurate model inputs and wrong assumptions and assess its impacts to the model results. Different methods have been used, mainly varying one-factor-at-a-time, typically testing the effects of connecting/disconnecting one feature, link, feedback, submodule or even full module. The systematic use of SWITCHES (parameters varying between 0 and 1 which connect/disconnect different parts of the model) across the model has been of much usefulness to achieve this in an efficient way.

D8.4 reports also Monte Carlo uncertainty analysis. This method was deemed appropriate given the complexity (high number of variables, non-linear relationships and multiple feedbacks) of the WILIAM model and its higher level of maturity at this stage. Some of the input parameters characterised by uncertainty in the main WILIAM modules and their effects on relevant output variables have been selected for illustration purposes with the goals of covering all the modules in WILIAM, test only one input parameter per experiment to see individual effects, analyse different regions to exploit the regionalization available in WILIAM , test different baseline scenarios.

Cf. D9.2 (de Blas Sanz et al., 2022b) for further details about model validation.

4. SELECTION OF PRELIMINARY RESULTS

This section is dedicated to report a selection of preliminary results by module. For obtaining these preliminary results inputs from WP8 with relation to policies and scenarios have been used (cf. D8.2 and D8.3 for a thorough reporting of scenarios and policies).

4.1. DEMOGRAPHY

Three experiments have been designed to illustrate the potentialities of the demography module (Table 1). The first experiment represents a continuation of current trends. The second experiment aims at showing the effect of immigration in Spain to balance population, and the third one shows how households can dynamically evolve.

Table 1: Description of the experiments configured to get the results.

		Figures
Experiment 1	3 cases of future life expectancy at birth and fertility rates, based on historical data: - High values. - Medium values. - Low values. The objective values are ramped up/down from 2020 to 2030.	Figure 10 Figure 11
Experiment 2	Two migration scenarios for Spain as case study. - Baseline scenario. Medium levels of fertility rates and life expectancy at birth in the world. Low levels of fertility and high levels of life expectancy at birth in Spain. Historical shares of emigration and immigration flows. All policies start in 2030, except the migration policy, which is assumed to start in 2020. - Migration scenario. The percentage of emigration in Spain falls a 50% and increase a 50% in the rest of the world (LROW) since 2020. Increment of a 50% the immigration from LROW to Spain (the same portion is reduced for the contribution of Latin America).	Figure 12 Figure 13
Experiment 3	Scenario of household composition to 2050 in Spain. Assumption of average values of historical changes.	Figure 14 Figure 15

4.1.1. EXPERIMENT 1

Global population has inertia over time in the three scenarios before 2020, bending the projections in the three cases plotted in Figure 10. Out of the three assumptions, only high levels of fertility and low levels of mortality result in an increase in the population for the period. The medium and low trends are insufficient to sustain the maximum achieved in 2030 and 2040, respectively. In our model, the mark of 8000 million of people living in the world is achieved in 2024 in the HIGH and MEDIUM cases, while 2025 in the LOW case. According to latest data, we have already achieved that number at the beginning of this year, 2023. Statistical differences and a limitation in the model related to migration – mentioned in the discussion of Experiment 2 – may be the cause of this difference.

The last scenario (black dashed line) corresponds to the direction Europe is following, i.e., low fertility rates and high life expectancy at birth (low mortality rates). This situation may depict a just demographic transition in which education and independence of woman lead the reduction of annual births while health is increasing.

In a more detailed regional analysis (Figure 11), the dynamics of Europe-27 remains slightly decreasing with narrow differences across scenarios The dynamics in China and India are different from EU27 but declining trends appear for both countries as well in the next decades, with exception of India with high values of fertility rates and life expectancy at birth.

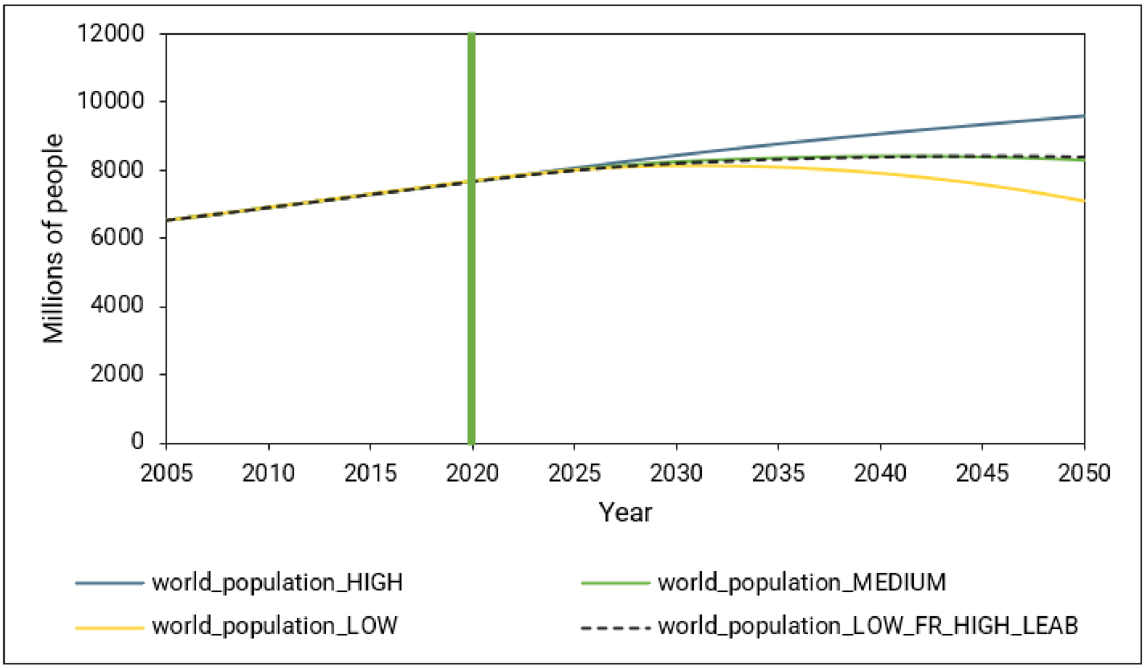

Figure 10: World population in the Experiment 1. The green vertical line marks the end of the historical period. The dashed line corresponds to a scenario with low values of fertility rates and high values of life expectancy at birth.

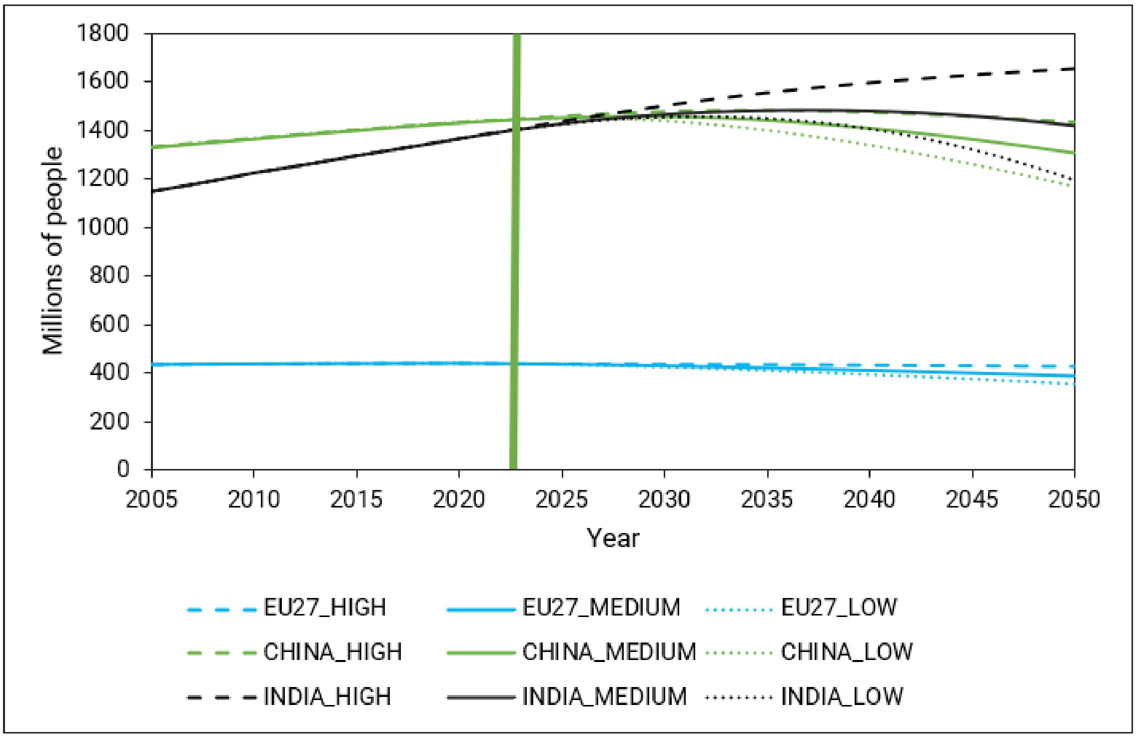

Figure 11: Population in Europe-27, China, and India under the Experiment 1. Units in millions of people. The green vertical line marks the end of the historical period.

4.1.2. EXPERIMENT 2

A strong migration flow to a specific country (Spain) is simulated in this experiment:

- Medium levels of fertility rate and life expectancy at birth in the world. Low levels of fertility and high levels of life expectancy at birth in Spain. The objective values are achieved by 2030, being constant thereafter.
- Growth of 50% in the share contribution from LROW to Spain (the same portion is reduced from LROW to Latin America from 2020.
- Emigration is reduced a 20% in Spain since 2020.
- Emigration is increased a 20% in LROW since 2020.

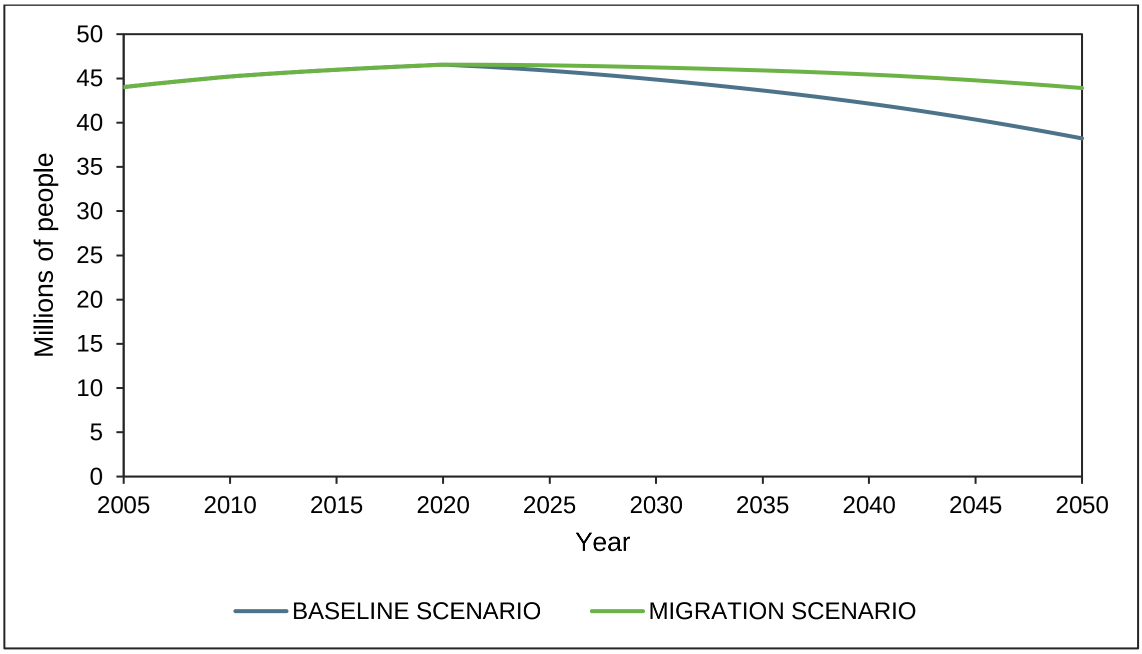

Figure 12: Spanish population. The assumptions of the “baseline scenario” follows constant historical data of migration as Experiment 1, while the "migration scenario" corresponds to the changes described in this subsection (Experiment 2).

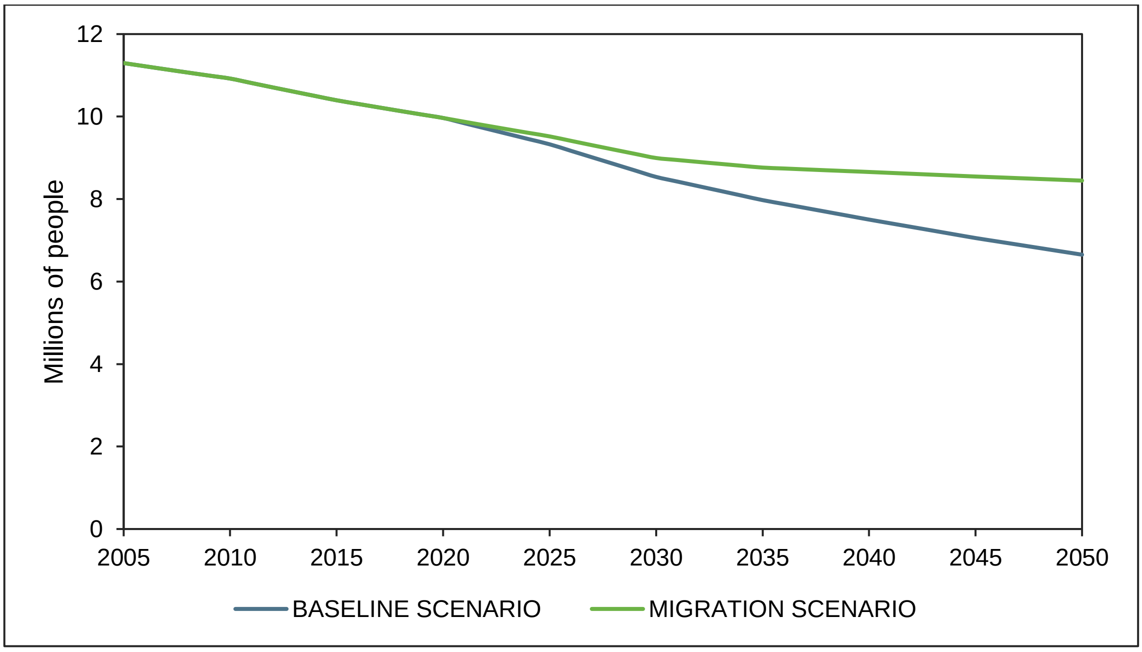

Figure 13: Fertile female population in Spain. The assumptions of the “baseline scenario” follows constant historical data of migration as Experiment 1, while the "migration scenario" corresponds to the changes described in this subsection (Experiment 2).

Figure 12 shows an increase in the total Spanish population due to the increase in migration. The increased level of migration from abroad results in a lower fall in population over time, which stays above 40 million people beyond 2050. Women have a major contribution as the increase in the number of fertile women is considerable (Figure 13). However, a limitation should be highlighted about the current demography module in WILIAM. Migrants do not bring their properties from sending regions; there is no tracking about the migrant properties along generations. This means that, in these results, fertility rates of LROW are higher, but once migrants arrive to Spain, they adopt r fertility rates of Spain. Additionally, since migration profiles are equal, i.e., the same percentage of woman per age arrive, the increment in the total population is a little lower than expected (actual profiles may be loaded from 20-45, so more fertile woman), only due to the net flow of people plus additional fertile women. These two limitations we hope to improve in next steps of the modelling.

4.1.3. EXPERIMENT 3

The demographic analysis can be extended to the household composition. The reference year for the economy, 2015 (Figure 14), presents a dominant role of households with “couple” (46%, where 18% with children and 28% without them), followed by “single” households (27%) and “other” (26.6%). Most of them placed in urban areas (52.4%). The situation changes by 2050 following historical trends (Figure 15), where 48% are “single” (2% with children), 43% are “couple”, and 9% are “other”. In total, 49% of households would be placed in urban areas. Results conclude that, in Spain, population would go into a deeper individualization (higher “singles”) in coherence with the reduction of fertility rates.

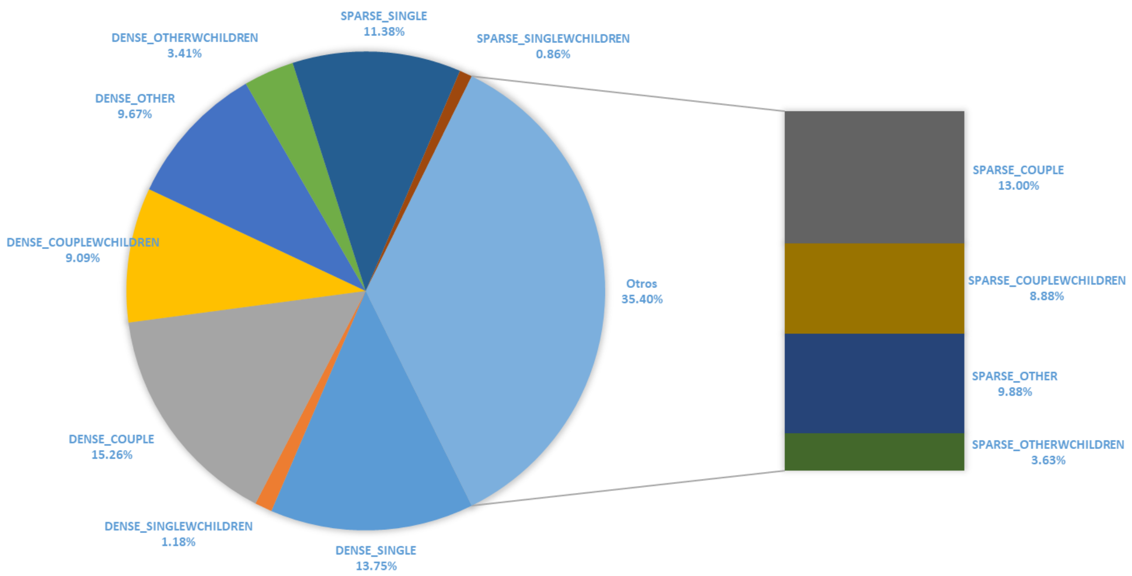

Figure 14: Household composition in Spain (2015).

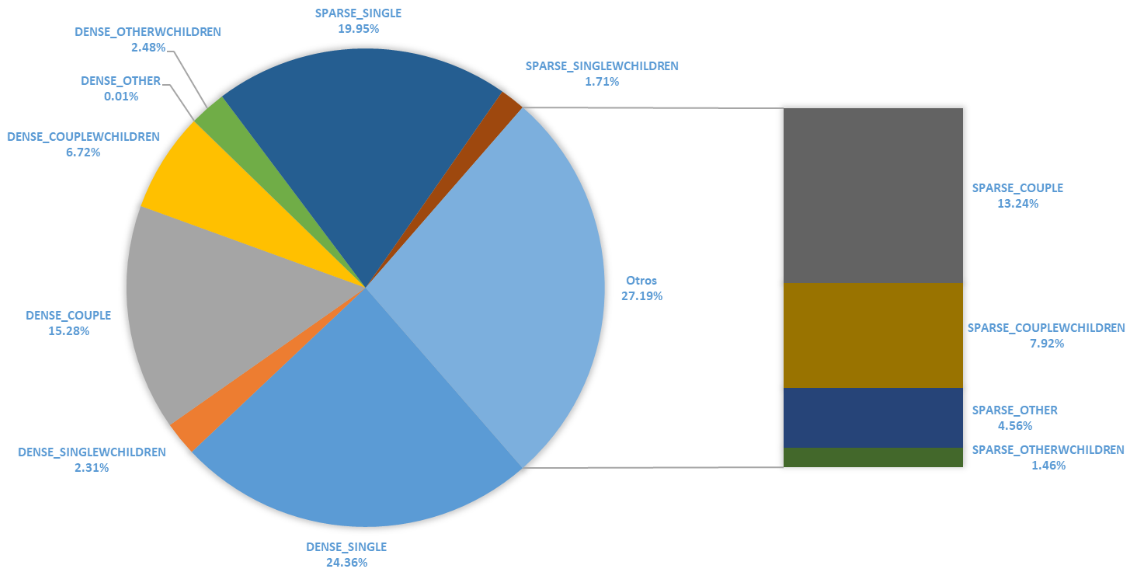

Figure 15: Household composition in Spain (2050).

4.2. SOCIETY

This section presents a selection results from the Society module taking into account the influence of different scenarios on different variables. Considering that this module is primarily influenced by the Economy module, three socio-economic pathways for GDP have been selected as references to study the following scenarios: High GDP, Medium GDP, and Low GDP. During the application of these scenarios, a global region referred to as the "World Region" has been considered, enabling the observation of various changes in real GDP. As shown in Figure 16, the implementation of the policy begins in 2023, and all three scenarios initiate from 87.51 trillion dollars_2015 and subsequently reach high figures of 191.09 trillion dollars_2015 for the high scenario, 171.17 trillion dollars_2015 for the medium scenario, and 155.71 trillion dollars_2015 for the low scenario.

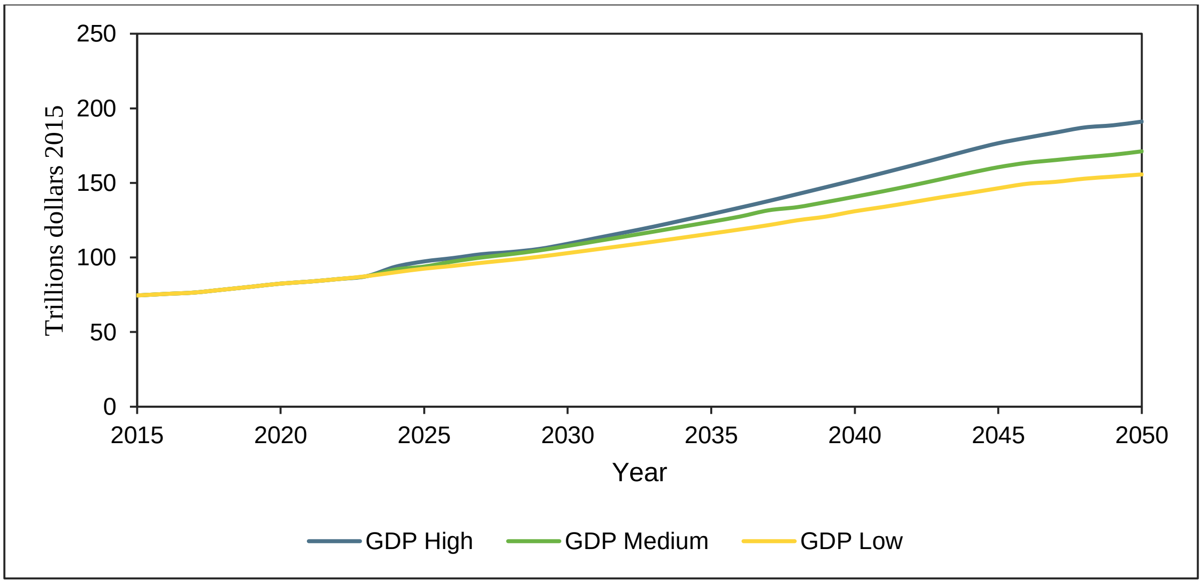

Figure 16: Real GDP world

The next step involves assessing the influence of GDP growth on the GINI coefficient, which enables us to understand the level of income inequality present in a particular region. While we have three depth levels to calculate the Gini coefficient, we have opted to focus on comparing the inequality across the nine global regions covered by WILIAM model. This decision comes after having already assessed the overall evolution of real GDP for worldwide. As we can see in Figure 17, once the policy is implemented, even though the economy seems to increase more, internal inequality within regions also increases. Indeed, in the high scenario, there is a notable increase during the initial years. However, by the end of the simulation, around 2050, the scenario with the highest inequality is the low scenario, continuing with an upward trend, while the medium and high scenarios seem to reach a certain stability. The decline in the highly educated population is primarily attributed to the decrease in cumulative public expenditure on education. Notably, after 2070, expenditure on education a steep decline, directly impacting the proportion of the new labor force categorized by their level of education.

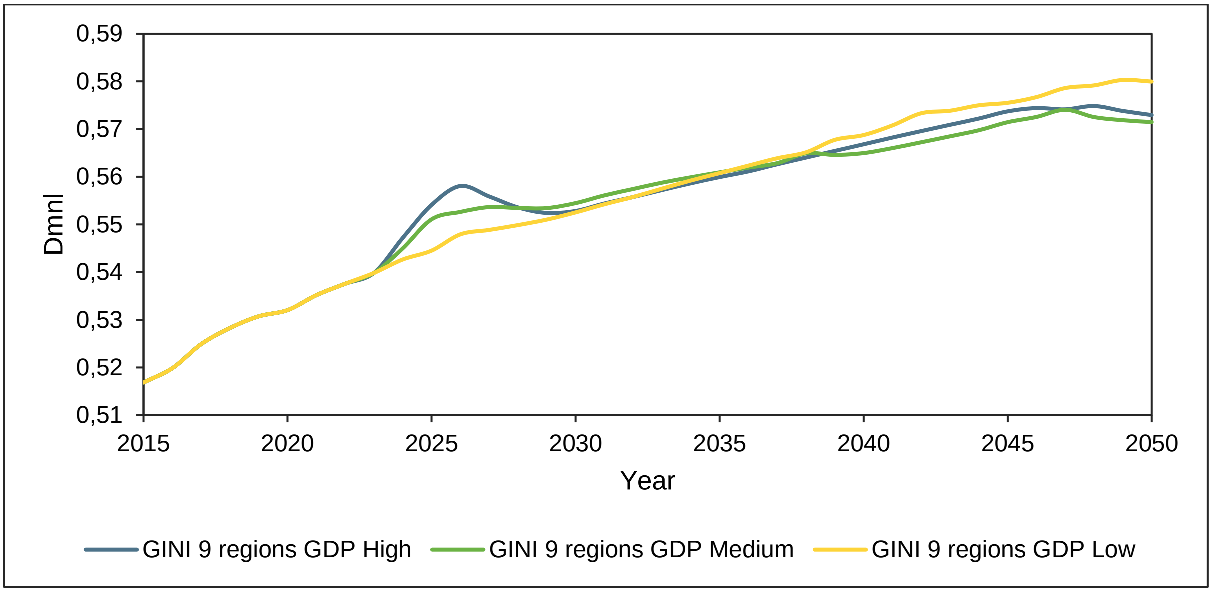

Figure 17: GINI indicator world

Also, it's worth understanding how these three reference scenarios affect one of the main variables in the education sub-module, i.e., the percentage of the labor force at each level of education, distinguishing it by gender. Given the magnitude of these projections, we have focused on a single region that is in this case "France". And this is because it acts as a representative region and allows us to clearly appreciate all the changes that occur after the simulation. Consequently, Figure 18 illustrates that the trend of the proportion of women with a high level of educational attainment is increasing with time for all three scenarios. This trend, although somewhat lower, is the same as the trend for the proportion of men with the same high level of educational attainment. In contrast, as expected, there is a decline in the percentages of both men and women with a low level of educational attainment. Therefore, it can be suggested that higher education is growing at the expense of basic education. Moreover, the labor force share of those with tertiary attainment increases, irrespective of gender, by 15-18% depending on the scenario, while those with only low educational attainment, whether male or female, decreases by around 8% in all scenarios.

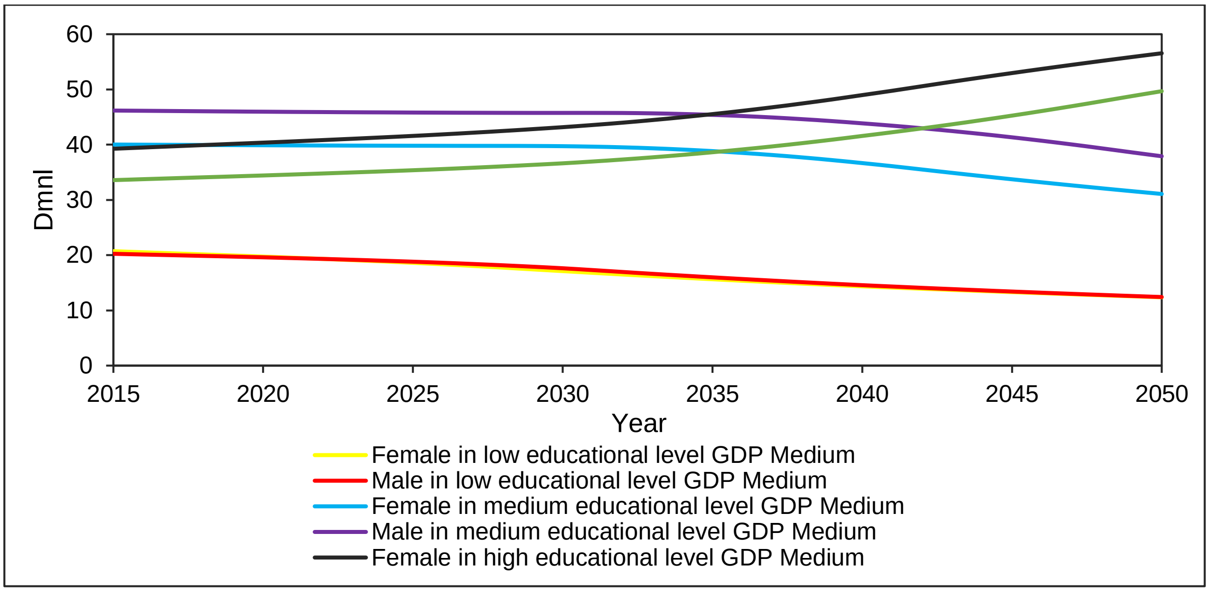

Figure 18: Percentage of workforce in each educational level in France by sex

Finally, we proceed to present results based on the change of one of the policies which despite being exogenous, it is a specific policy that is included in the Society Module, distinct from the various socio-economic scenarios. This policy is related to the Gender Parity Index which calculates the relative access of men and women to education. In this case, it has been designed in the form of a switch. Thus, in the normal conditions it remains switched off. However, for this study, it has been activated to enable the implementation of the policy aimed at achieving gender parity from 2015 to 2050. It is precisely for this reason that it has been decided to extend the simulation over time, extending it to the year 2100 in order to compare the results once this equality is achieved. The results presented here show how variations in this switch affect the labor force classified according to educational attainment and gender for the region of France. Thus, as can be seen in Figure 19, when the switch is deactivated, the number of women in the labor force with tertiary education increases gradually until 2071. Subsequently, it experiences a decline due to the economy in the medium and high scenarios that demands a large amount of resources to maintain their standards of living, leading to a peak in the extraction of fossil resources, specifically oil, before 2050, which directly affects economic growth. In contrast, in the low scenario, the economy grows more slowly and therefore it demands fewer resources, which means that the peak is not reached during the simulation. On the other hand, when the switch is activated, although the number of women increases markedly during the first years, it does not increase as much as when the switch was deactivated. Therefore, by the end of the simulation there is a difference of about 55,000 women between the two scenarios. Conversely, the situation is different for men. Likewise, until just past the midway point of the simulation, the number of men with a high level of educational attainment increases. However, this time, the increase is even more significant when the switch is turned on.

Consequently, by the end of the simulation, there exists a disparity of roughly 58,000 men between these two scenarios. This is explained by the fact that, traditionally, women exhibit the highest rates of tertiary education. Thus, if the aim is to implement a gender parity policy, we should expect these rates to decrease in favor of men. Moreover, an increase in the number of people with higher tertiary education is also an indication that fewer and fewer people are stopping their studies at the lower and intermediate levels. Notably, the switch has the least impact on the distribution of men and women at the lower levels.

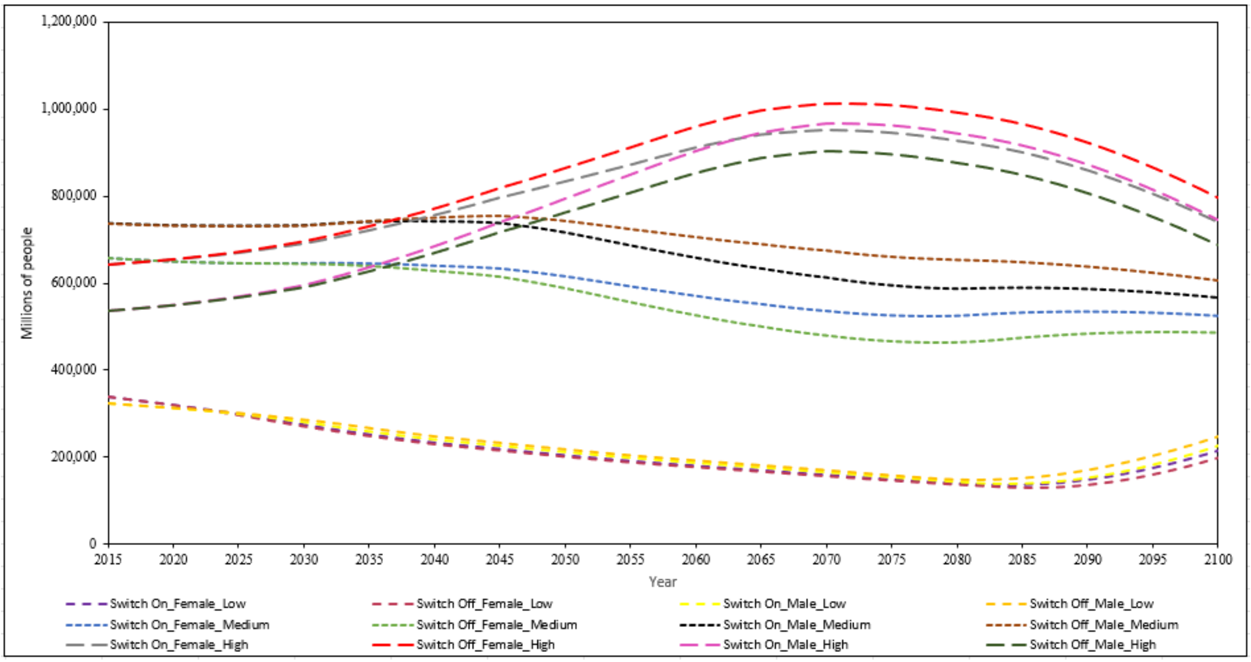

Figure 19: Workforce per educational level by sex in France.

4.3. ECONOMY

This section presents a subset of the results obtained from the Economy module of the WILIAM model. These results specifically pertain to the implementation of the policy of Basic Income (BI), but since it is a very transversal policy it will serve as illustration for the whole economy module. This policy is an innovative and transformative policy concept that has captured the attention of policymakers and scholars worldwide. It is usually conceived as a universal policy, ensuring that every citizen, irrespective of their income or working conditions, receives a regular unconditional payment from the government. Increasing number of research has been analysing the potential impacts of BI on various aspects of society. Previous analyses have explored its effects on inequality and poverty, revealing promising findings that suggest BI could be an effective tool in reducing income disparities (Wright, 2016). Furthermore, studies have also delved into its potential implications for environmental sustainability, with researchers like (Cieplinski et al., 2021) suggesting that BI could reduce inequality and counteract the negative trends related to climate change and the green transition. Another crucial area of interest has been the impact of BI on health outcomes. In this regard, Painter's research (Painter, 2016) shows the positive effects of BI on mental and physical health, highlighting its potential to improve overall well-being. While BI is a policy increasingly discussed in academic debates, it has also been put to the test through localized experiments. One notable example is the case of Manitoba in the 1970s, where a BI pilot project demonstrated encouraging results (Simpson et al., 2017). More recently, Finland carried out a two-year transfer of BI to two thousand unemployed individuals from 2017 to 2019, as explored by (Kangas et al., 2019), shedding light on how the policy operates in real-world scenarios.

A BI policy was introduced in WILIAM, modelled as a universal income equivalent to 10% of the annual average disposable income of each country starting from 2026, which is handed out to each household. Simulations run until 2050. The policy was implemented in the 21 European countries that have detailed data for households in WILIAM, meaning that we are able to study distributive impacts of this policies among different groups. The value of the BI varies according to the heterogeneity of income levels across European countries, as can be seen from the initial values of the BI benefit reported in Table 2 below.

Table 2: Basic Income benefit in each scenario for 2026.

	Wealth Tax		Profit Tax	
Country	Yearly BI	Monthly	Yearly BI	Monthly
Belgium	9.643	804	9.785	815
Bulgaria	1.692	141	1.693	141
Croatia	3.883	324	3.880	323
Cyprus	7.458	622	7.480	623
Czech Republic	4.174	348	4.185	349
Denmark	10.277	856	10.583	882
Estonia	3.807	317	3.828	319
Finland	9.438	786	9.562	797
France	9.341	778	9.398	783
Germany	9.180	765	9.285	774
Greece	5.516	460	5.513	459
Hungary	2.814	235	2.825	235
Ireland	18.046	1.504	18.144	1.512
Latvia	3.618	302	3.627	302
Lithuania	4.487	374	4.494	375
Luxembourg	23.449	1.954	23.670	1.973
Poland	4.496	375	4.521	377
Portugal	5.747	479	5.765	480
Slovakia	5.060	422	5.071	423
Spain	7.130	594	7.148	596
Sweden	9.963	830	10.140	845

In general, the benefits are not high enough to guarantee for a completely substitute for labour income. Figure 20 and Figure 21 depict the evolution of the BI benefit over time in each scenario, as the payments increase proportionally with the average disposable income.

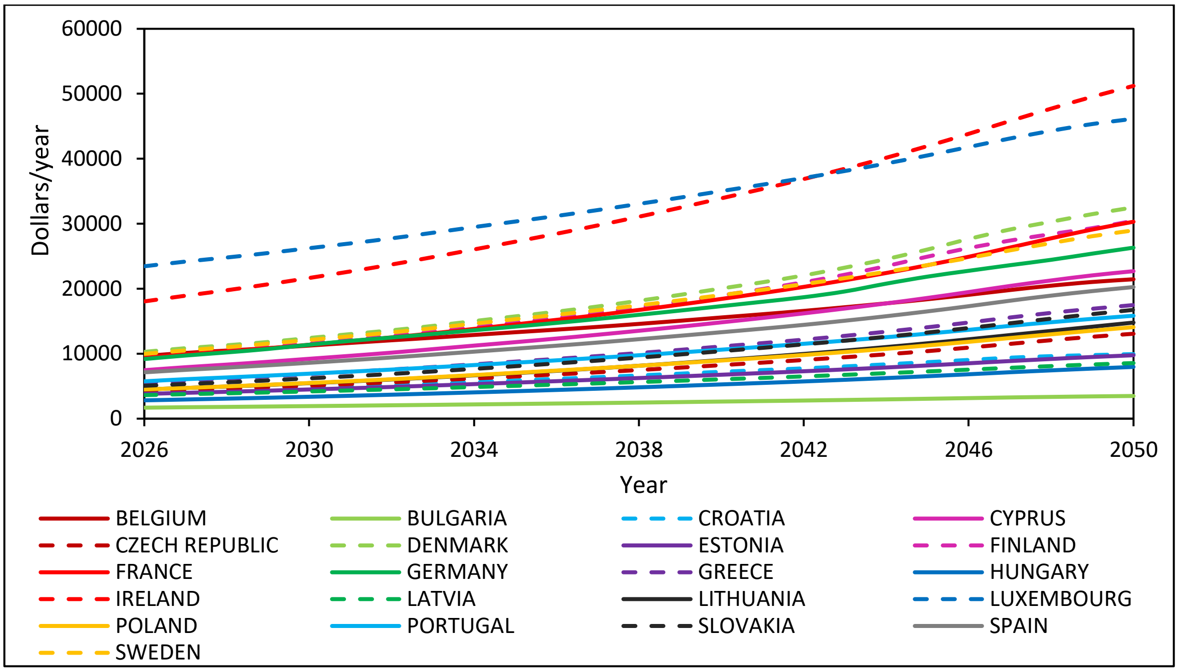

Figure 20: Household Basic Income. BI financed by Wealth tax.

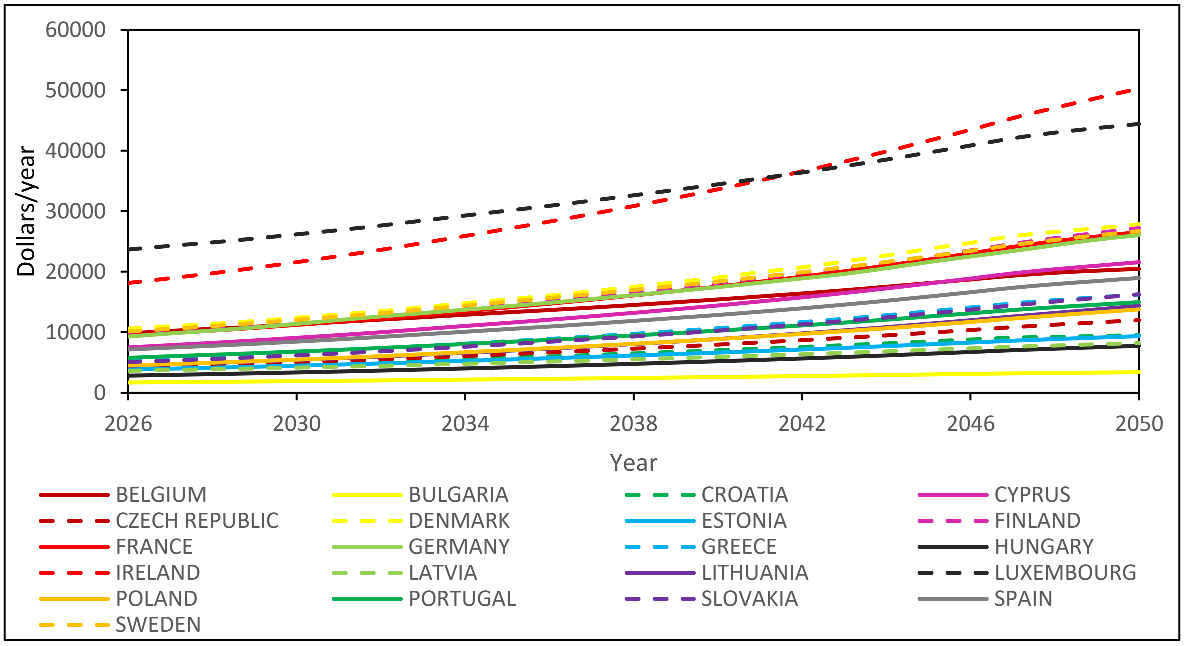

Figure 21: Household Basic Income. BI financed by Profit tax.

Since the introduction of a universal basic income policy implies a great increase in public expenditure, we combine the BI policy with alternative forms of taxation to increase government revenues and offset the negative impact of BI on the public budget. First, we consider the case of a wealth tax, collected from the wealth of households belonging to Q4 and Q5 (i.e., the two top quintiles of the income distribution). Second, we consider the case of an additional tax on the profits of companies. In both scenarios, the tax revenue is equal to the additional spending on the BI policy. Therefore, BI should be, by construction, neutral from the point of view of the public budget. However, the increase in consumption caused by the BI increase's other sources of tax revenue, generating a net positive effect on public finance.

BI generates an increase in total spending due to the redistribution of income in favor of lower income households, which, on average, have a greater marginal propensity to consume. Therefore, BI boosts aggregate demand and output, which explains the positive effect of this policy on GDP and on the unemployment rate. In our model basic income does not lead to a voluntary drop in labour supply. In fact, the labour force increases, because greater labour demand leads to higher wages and thus to a greater participation rate.

Empirical evidence on the impact of BI on labour supply remains scarce, as only a limited number of experiences exist where basic income policies have been implemented with constrained scope and limited benefits. Results of conditional and unconditional cash transfer policies find a fall in the participation and intensity of child labour (de Hoop & Rosati, 2014), and to a lesser extent a decrease of elderly supply of labour (Kassouf & de Oliveira, 2012). Analysing transfers in seven controlled trials in developing economies, (Banerjee et al., 2017) finds no systematic evidence to support the view that cash transfers have a negative impact on employment. For supporting poorer households, cash transfers have positive long-term effects on the inclusion of young people and women in the labour market (Abramo et al., 2019). Scholars studying BI also evaluate research on lottery winners to gain insights into labour supply choices following an unconditional transfer. These studies show that lottery does not affect labour supply (Marx & Peeters, 2008); or has only a modest negative effect on labour supply (Cesarini et al., 2017) or working hours (Picchio et al., 2018).

In general, the two forms of taxation (wealth tax and profit tax) introduced to cover the costs of BI lead to results that go in the same direction. However, social and economic performance is better in the case of a wealth tax, which presents a greater fall in inequality, higher increase in per capita GDP, greater fall in the debt-to-GDP ratio and smaller increase in emissions with respect to the profit tax. The comparison between the two scenarios can be seen from Figure 22 to Figure 31. Results are presented as an absolute or relative difference with respect to the baseline scenario[1], in which no BI policy is in place.

The impact of the wealth tax on the Gini coefficient is more pronounced due to its direct influence on household disposable income. In contrast, the effect of the profit tax is more indirect. The profit tax reduces the profits available for future distribution as dividends, a portion of which typically ends up in the hands of wealthier households, an effect included in the model. These direct and indirect effects are not idiosyncrasies of our modelling approach; instead, they mirror the inherent dynamics of taxation policies and income distribution.

In terms of public finance, the combined introduction of the BI and new taxation policies leads to a fall in debt-to-GDP ratios for all countries in the case of a wealth tax, and the majority of countries in the case of a profit tax. Average drop in the public debt ratio is greater and faster in the case of a wealth tax with respect to the profit tax scenario. These taxation policies offset the increase in public spending and provide an additional effect on reducing inequality.

The counterpart of the fiscal revenue is the burden for taxpayers. We therefore evaluate the costs of BI to taxpayers in the wealth tax and profit tax scenarios.

[1] Absolute difference is calculated as the mathematical difference between the analyzed scenario and the baseline: Scenario – Baseline.
Relative difference is calculated as the ratio between the absolute difference and the baseline scenario: (Scenario – Baseline)/Baseline

- **Gini Coefficient Results:**

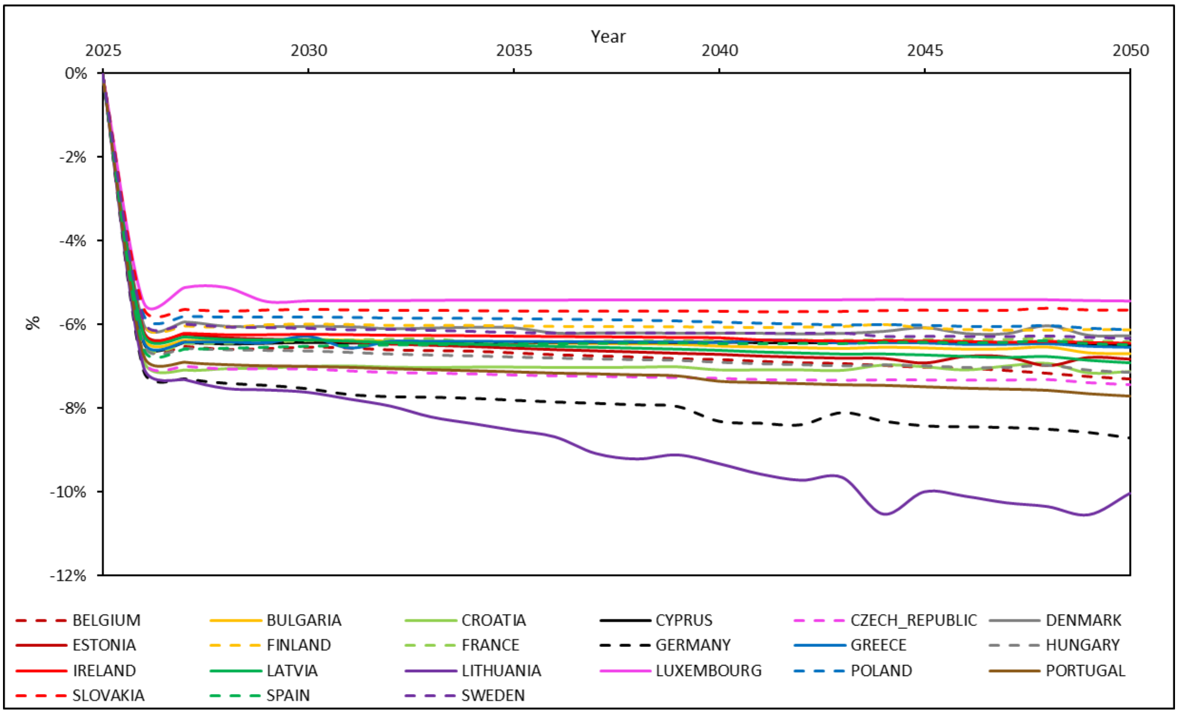

Figure 22: Gini Coefficient. BI financed by Wealth tax – absolute difference with respect to the baseline scenario.

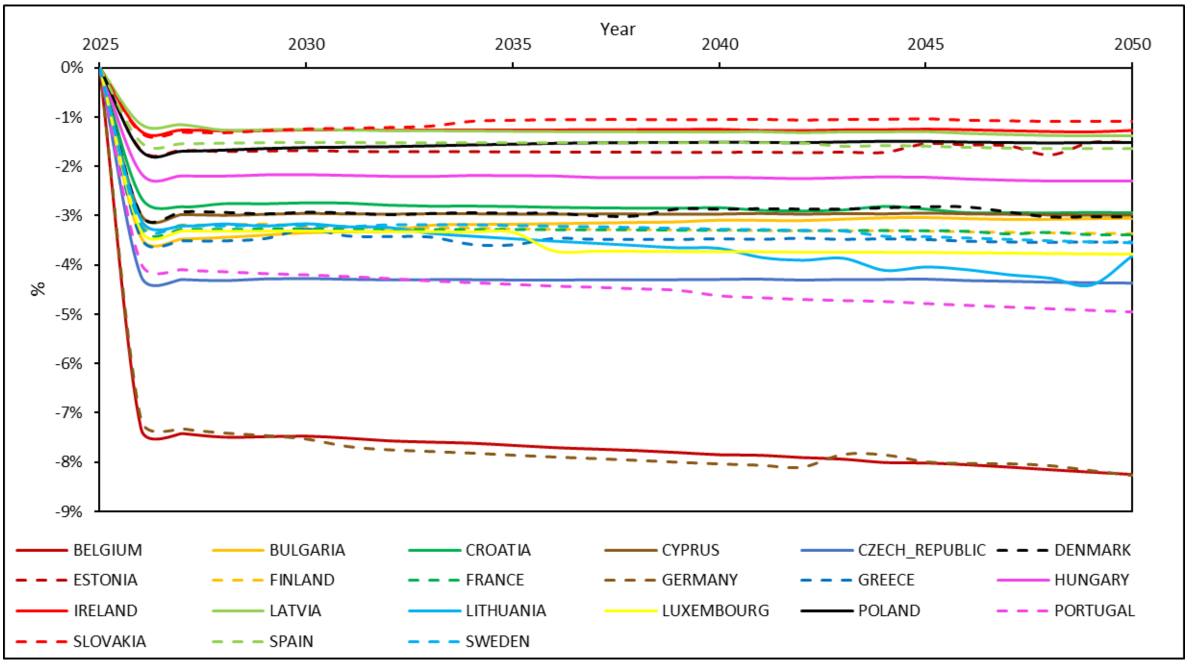

Figure 23: Gini Coefficient. BI financed by Profit tax – absolute difference with respect to the baseline scenario.

- **Unemployment rate results:**

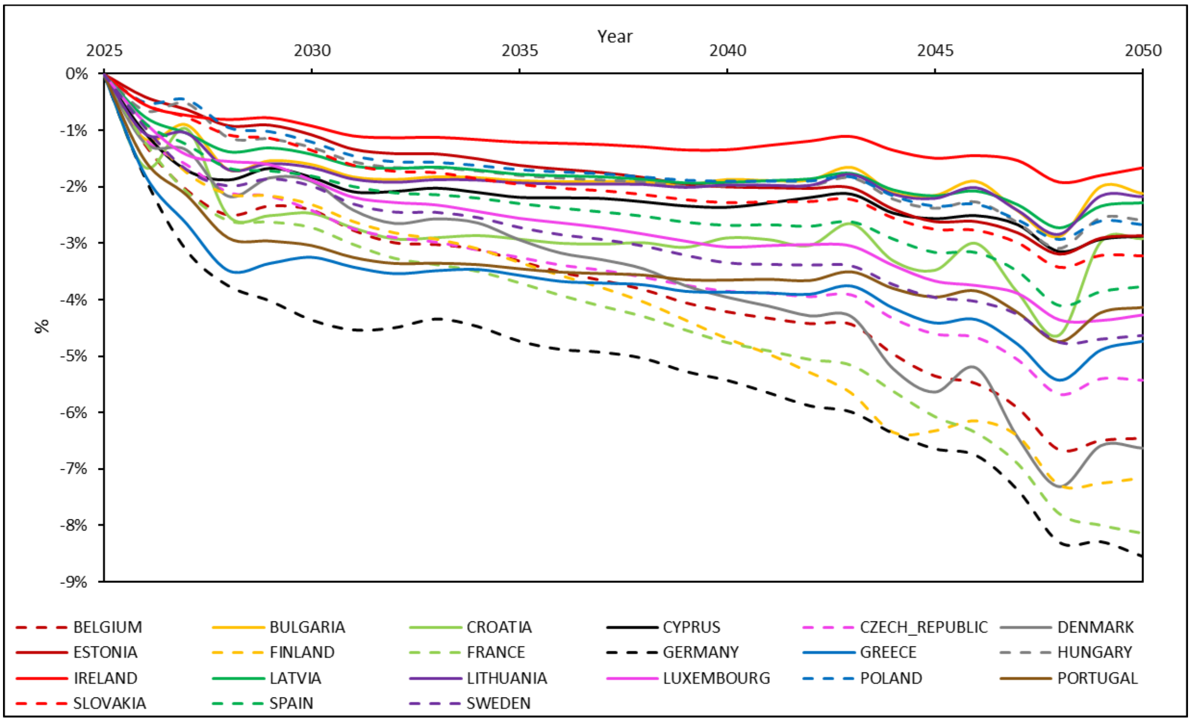

Figure 24: Unemployment rate. BI financed by Wealth tax – absolute difference with respect to the baseline scenario.

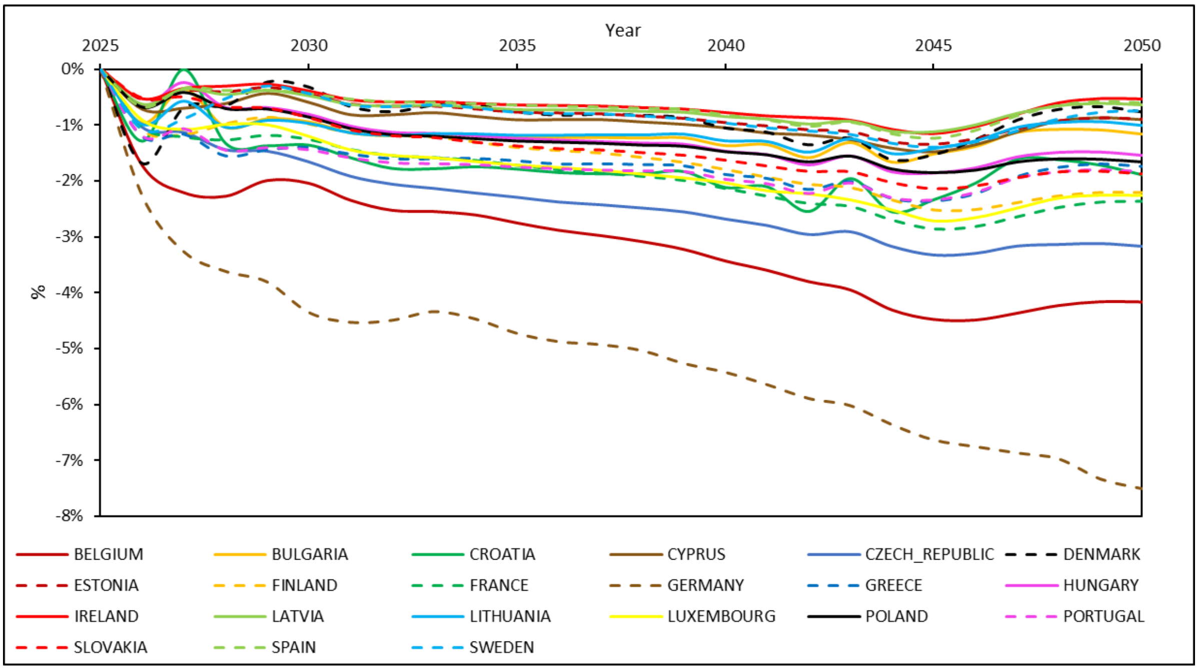

Figure 25: Unemployment rate. BI financed by Profit tax – absolute difference with respect to the baseline scenario.

- **CO2 Emissions results:**

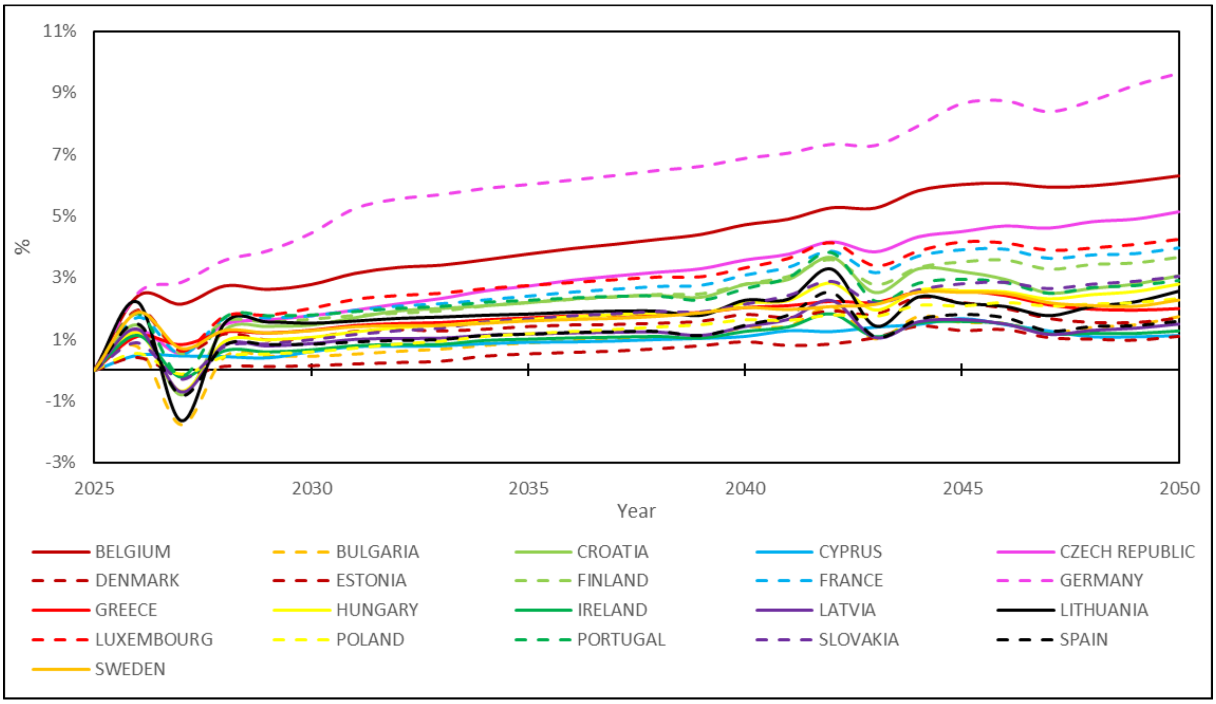

Figure 26: CO2 Emissions. BI financed by Wealth tax – relative difference with respect to the baseline scenario.

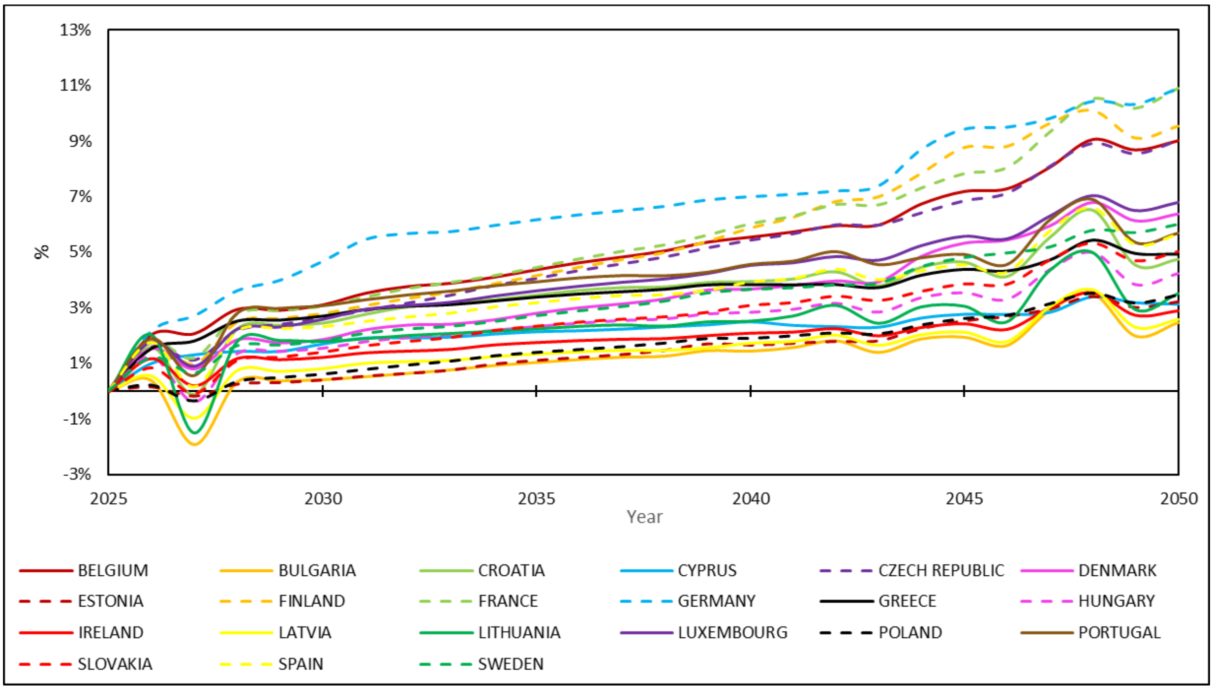

Figure 27: CO2 Emissions. BI financed by Profit tax – relative difference with respect to the baseline scenario.

- **GDP per capita results:**

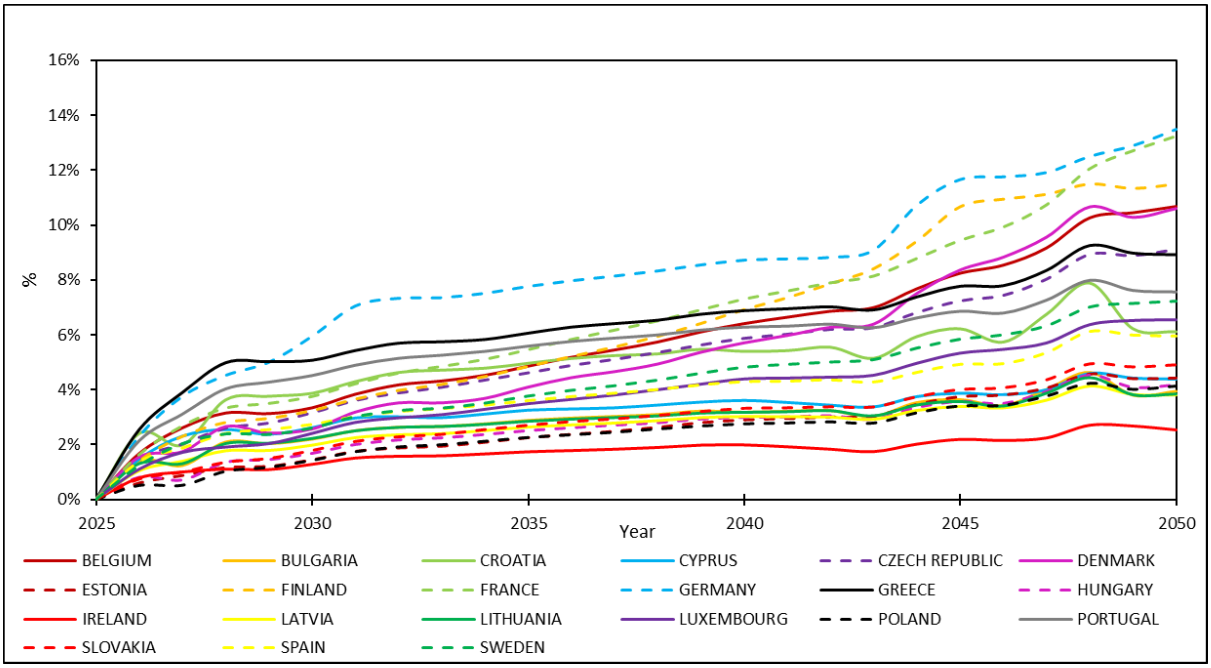

Figure 28: GDP per capita. BI financed by Wealth tax – relative difference with respect to the baseline scenario.

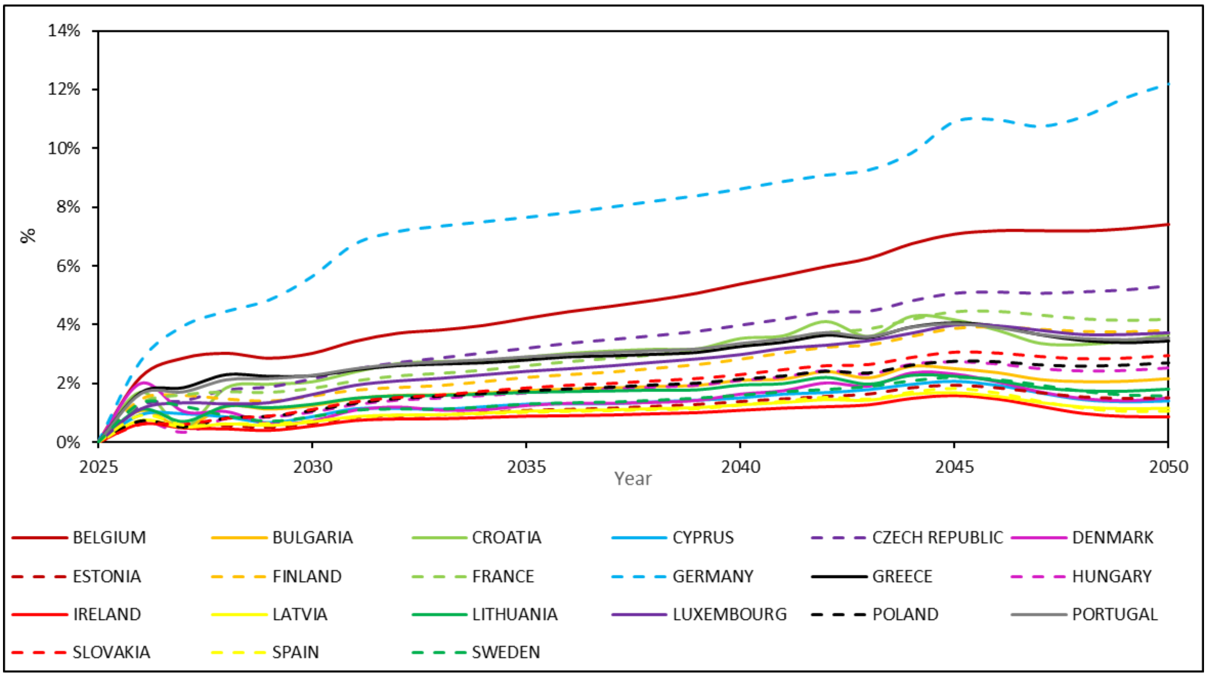

Figure 29: GDP per capita. BI financed by Profit tax – relative difference with respect to the baseline scenario.

- **Public Debt-to-GDP ratio results:**

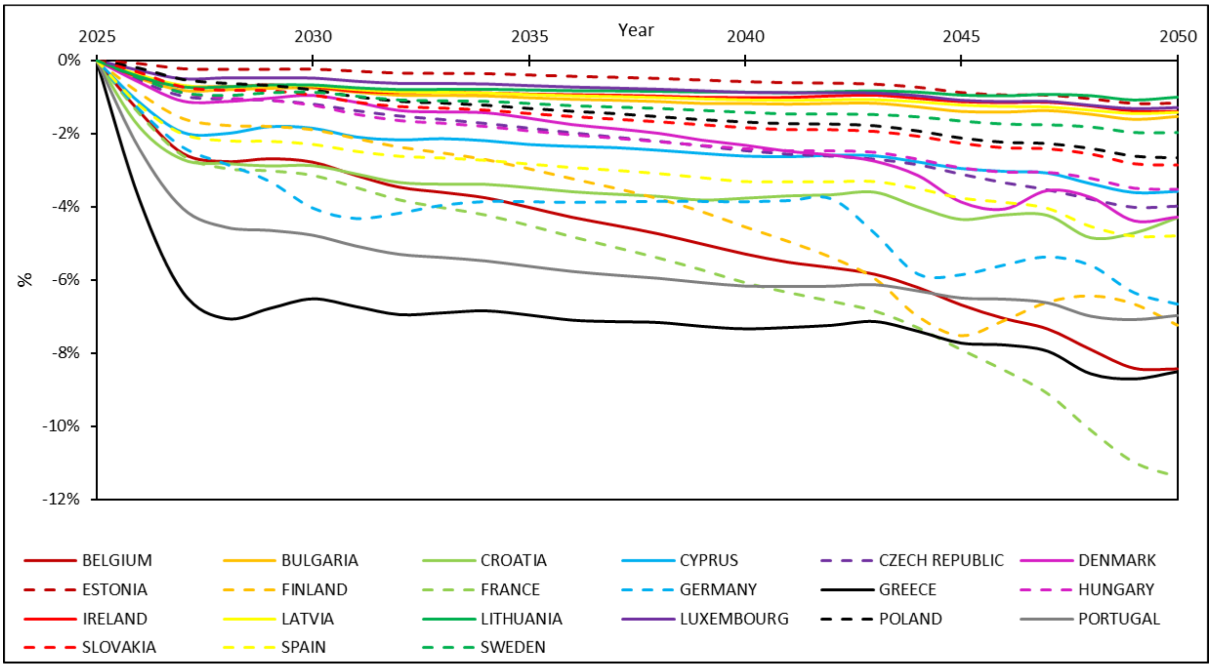

Figure 30: Public Debt-to-GDP ratio. BI financed by Wealth tax – absolute difference with respect to the baseline scenario.

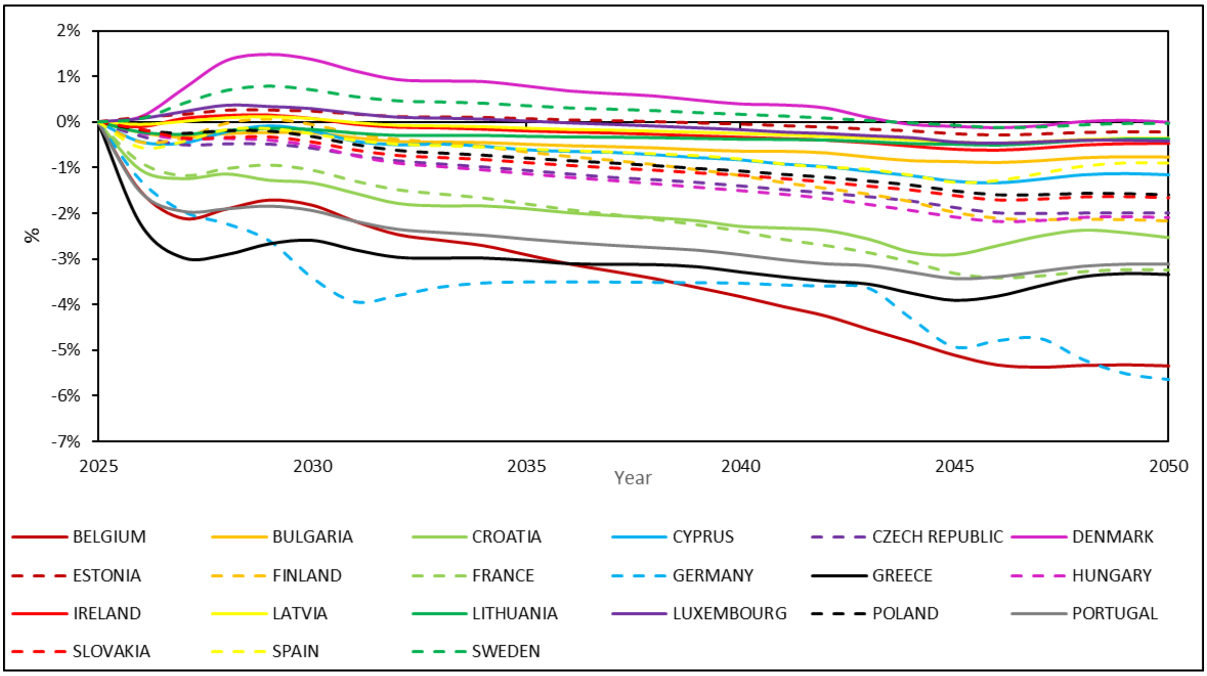

Figure 31: Public Debt-to-GDP ratio. BI financed by Profit tax – absolute difference with respect to the baseline scenario.

Figure 32 shows the wealth tax rate required to finance the BI policy. One important finding is that wealth tax rate is stable at a low level, being sufficient to fund the policy. In fact, wealth tax rates exhibit a gradual decline, indicating that the taxation does not erode the wealth stock. Figure 33 shows the total wealth tax rate, which sums the wealth tax rate of the baseline scenario and the rate related to the financing of BI. Wealth tax rates remain between 1% and 3.5%, within levels currently advocated to reduce inequality (Piketty, 2014; Piketty et al., 2013).

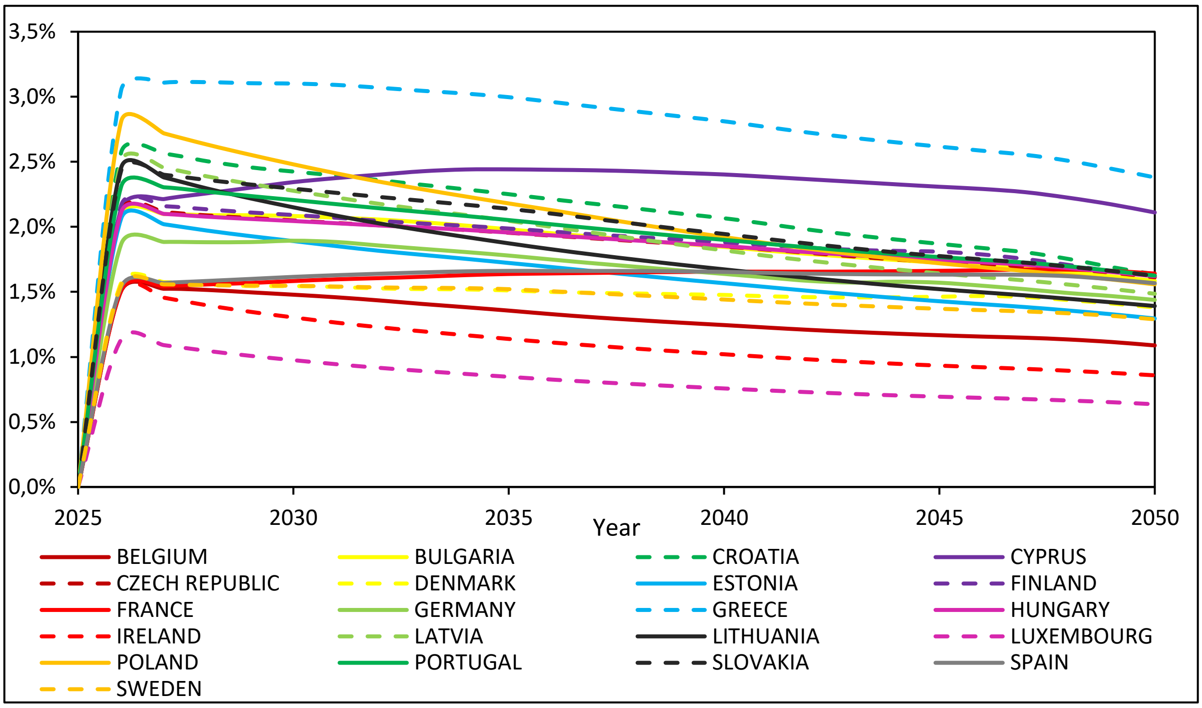

Figure 32: Wealth tax rate to finance BI. Absolute difference with respect to the baseline scenario.

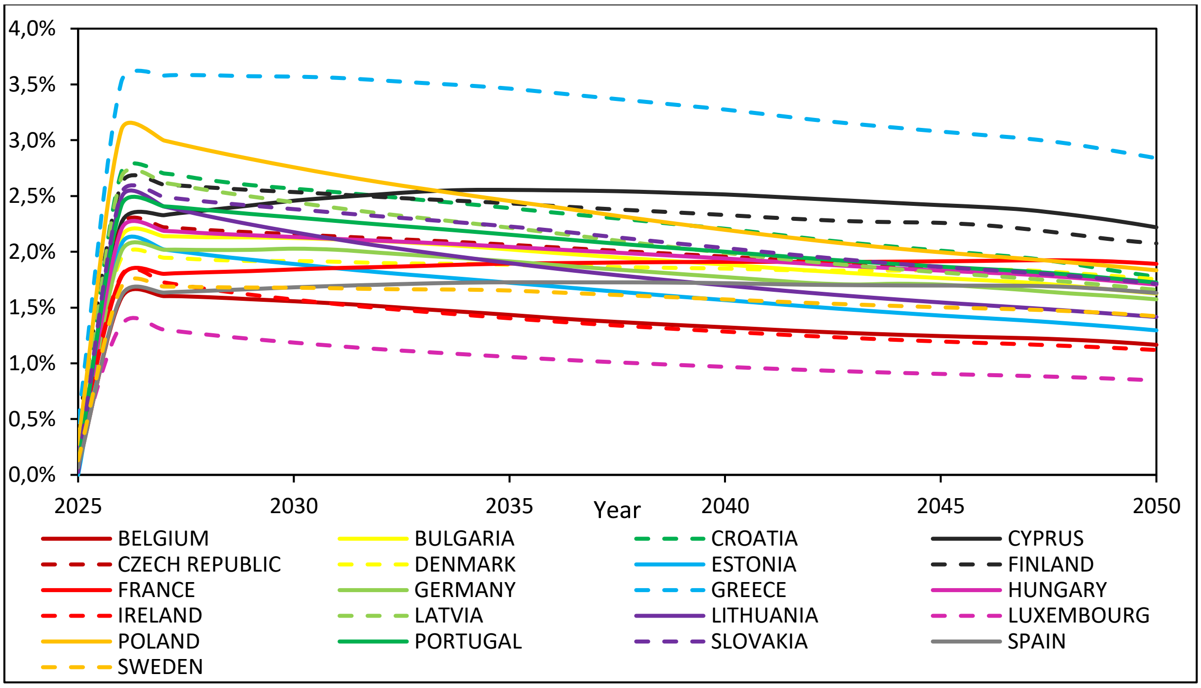

Figure 33: Total wealth tax rate. BI financed by Wealth tax.

Figure 34 shows the profit tax rate required to finance BI policy. The additional profit tax varies between 20% and 50% depending on the country. Therefore, the total profit tax in this scenario amounts to values between 30% to 70%, as seen in Figure 35, since the additional tax adds up to the tax rate existing in the baseline scenario. For many countries, the tax payments made by private companies are considerably high in the profit tax scenario.

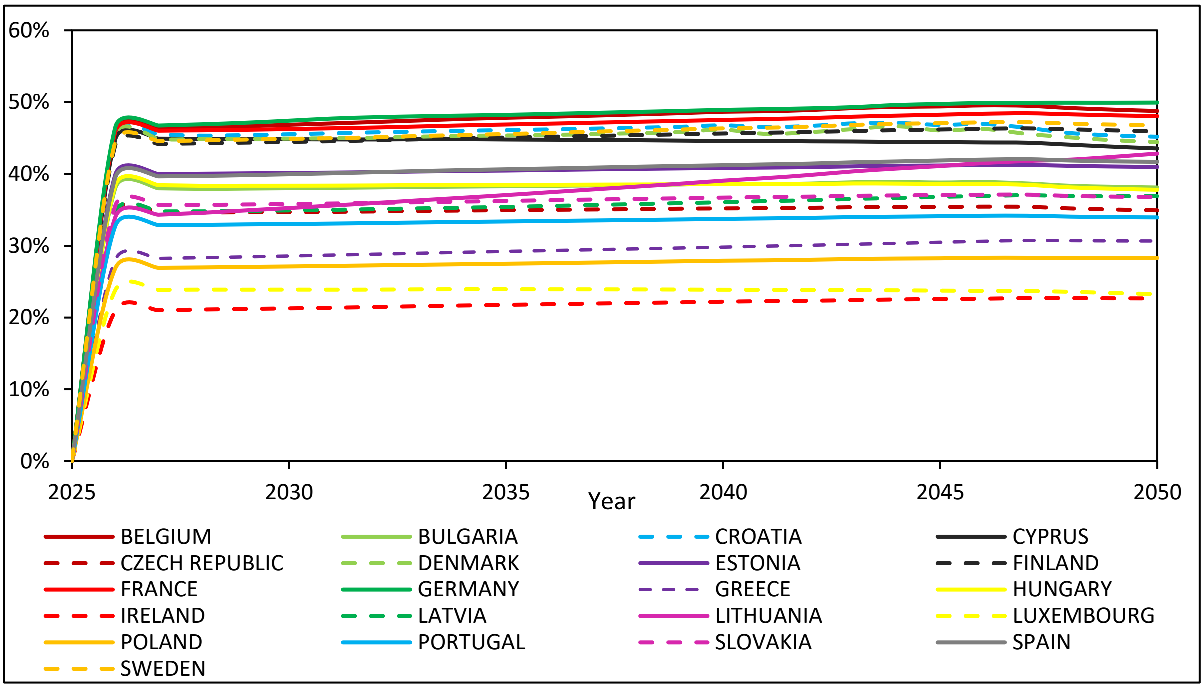

Figure 34: Profit tax rate to finance BI. Absolute difference with respect to the baseline scenario.

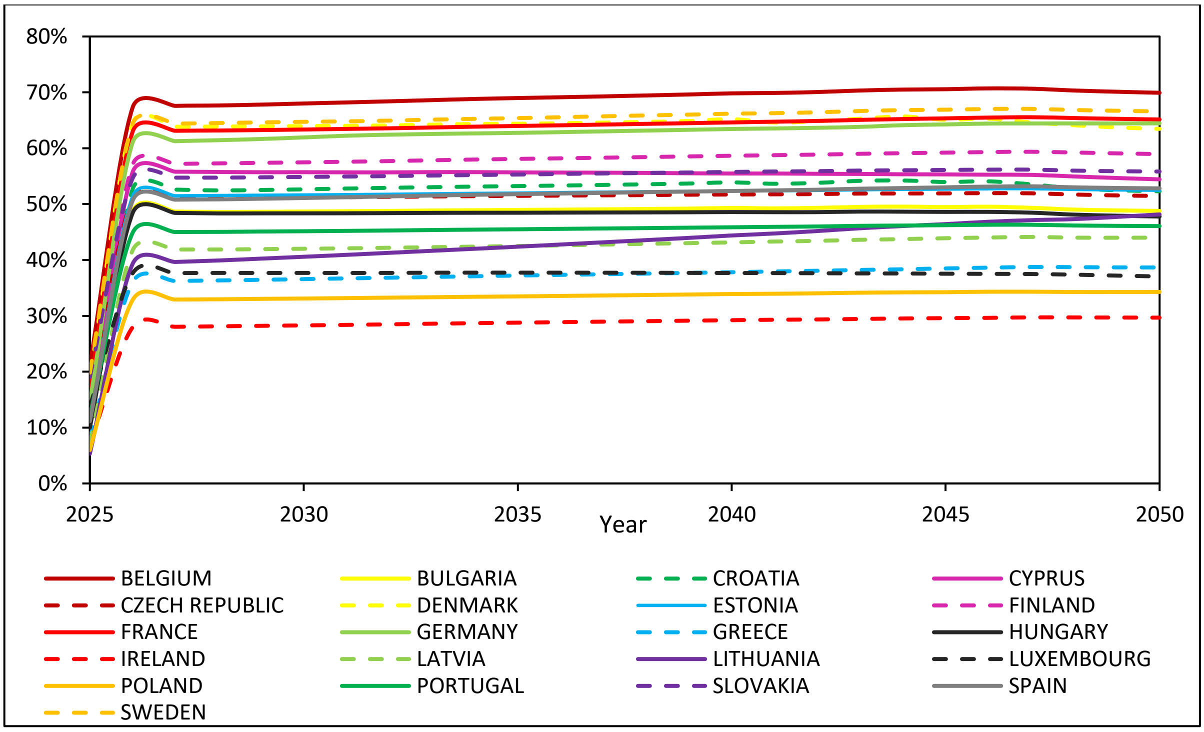

Figure 35: Total profit tax. BI financed by profit tax.

Finally, in the absence of other green policies, the BI increases emissions due to its positive effect on consumption and economic activity. The scenario with a wealth tax presents a smaller increase in emissions, given that the wealth tax reduces the consumption of quintiles 4 and 5 of the income distribution, which tends to be more intensive in emissions. Still, on average, emissions are higher by 3% in the wealth tax scenario and 5.7% in the profit tax scenario with respect to the level in the baseline scenario (the scenario in which no policy is active). Hence, BI is a fundamental policy to reduce inequality and improve the situation of lower quintiles, but it must be considered as part of a broader set of policy alternatives which must include specific policies targeting the reduction in emissions.

Overall, BI substantially reduces inequality, as measured by the Gini index, moderately improves the economic performance, seen in the GDP level and per capita GDP, and reduces the unemployment rate. The positive social and economic outcomes come at the cost of greater emissions (CO_2).

4.4. FINANCE

In this section, the results of simulations are presented on various variables of the model with three scenarios in which the main financial policy variable, the interest rate that operates as a base, which in the case of the model is the interest rate on government debt, is modified. In the three scenarios, the model's initial interest rate for each region is used as a starting point and the interest rate is increased by 0.5%, 2%, and 3.5%, respectively. In order to evaluate the results of the interest rate increases, three regions have been chosen, which will be the ones for which the results will be presented: the European Union (EU27), the United States, Mexico and Canada (USMCA), and China. In general, the interest rate hike has had positive effects. This is broadly because on average the net wealth of most types of households in the model is positive, which generates an increase in their income and thus their consumption, which in turn has positive effects on output and employment, and on future household incomes. This positive feedback loop dominates over the negative feedback loop of government debt. As the interest rate rises, the interest paid by the government on its debt rises, which leads, given a deficit target, to a decrease in its consumption and investment spending and thus to a decrease in output and employment, thus lowering the income of the economy as a whole.

Figure 36 shows that household disposable income per capita in real terms, i.e. deflated by the rise in the price of consumer goods is higher in those scenarios where the interest rate is higher. The causal relationship is as explained in the previous paragraph: a higher interest rate leads to an increase in property income in those households where net wealth is positive, which are the majority, and this in turn leads to an increase in disposable income. Moreover, this increase in disposable income has an effect on consumption, which in turn has a positive effect on output and employment. The opposite effect, which is the reduction in government spending to meet interest payments without increasing the deficit, fails to outweigh the positive effect.

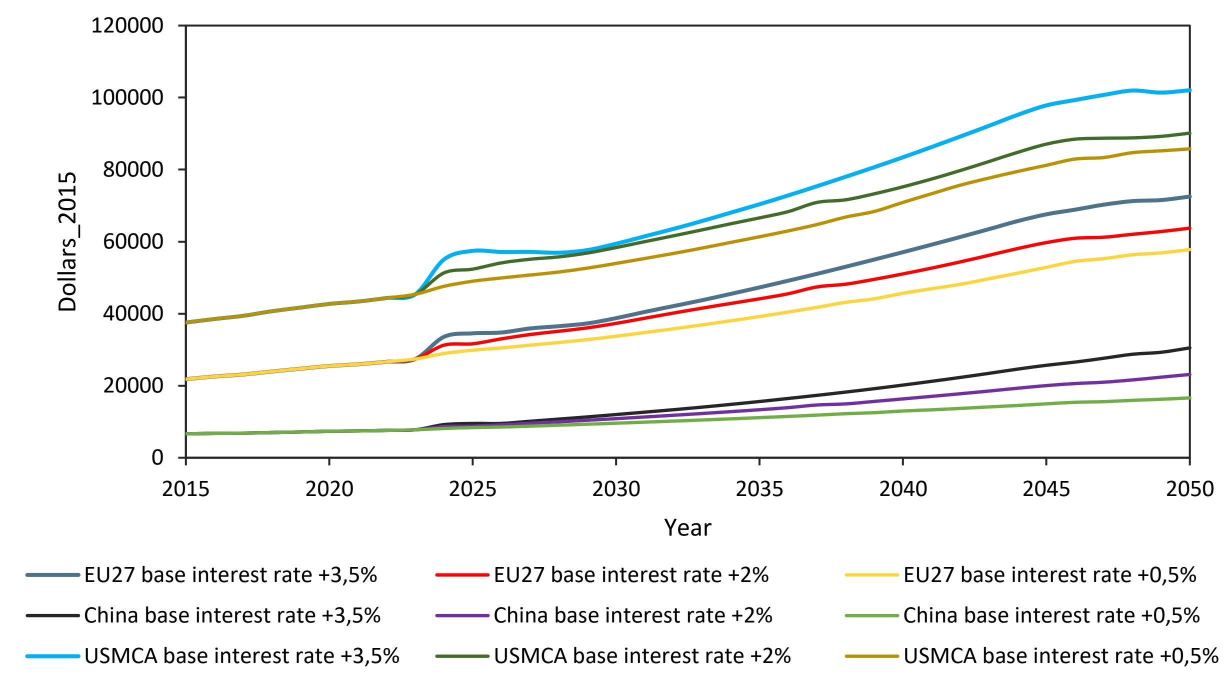

Figure 36: Disposable income per capita in real terms.

On the other hand, Figure 37 represents the real net wealth of households, that is the net wealth deflated, as in the previous case, by the consumer price index. The reasoning that allows us to understand why it is higher in the case of a higher interest rate is the same as in the previous case. It is worth clarifying that in the graph above, per capita disposable income stagnates at the end of the simulation while net wealth only slopes down. This has to do with the peak of oil, which occurs in the simulation at the end of the forties. As disposable income is a flow, it is directly affected by the stagnation of production. On the other hand, since net wealth is a stock, it continues to accumulate even though production has stagnated. It is probable that in a longer term, if production continued to stagnate, it would also tend to stagnate.

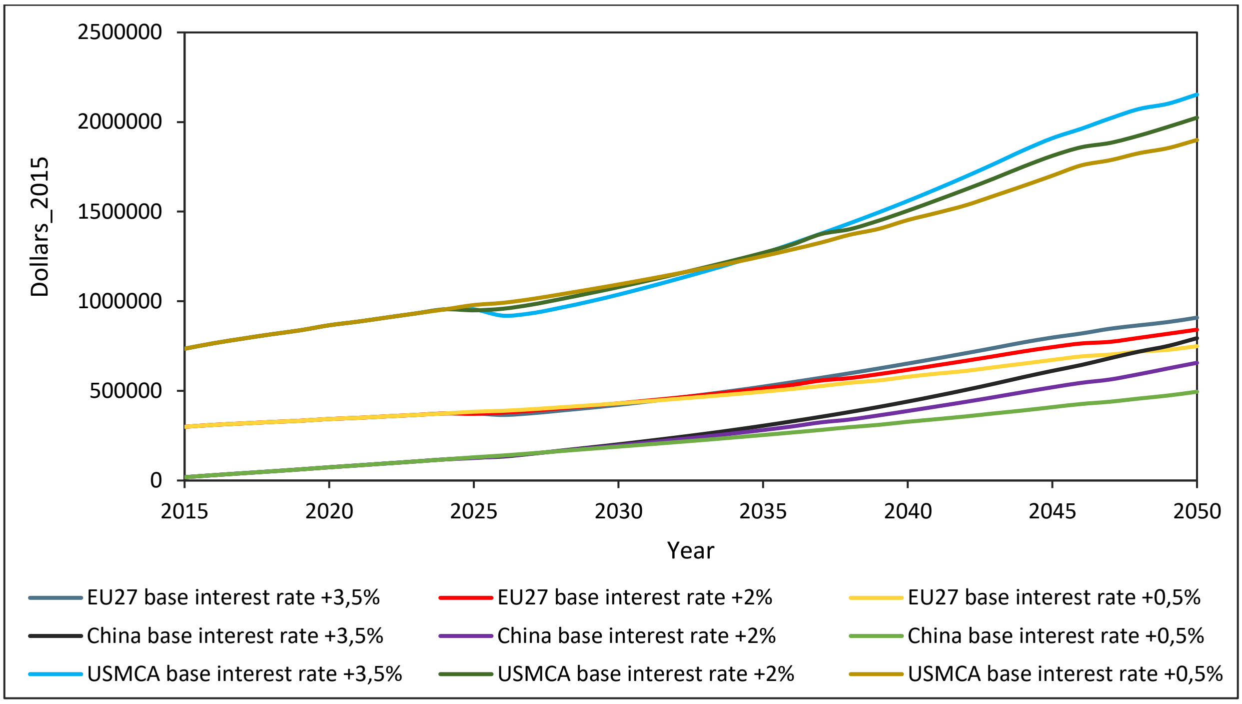

Figure 37: Average real net wealth per household in real terms.

Finally, the Figure 38 has been added showing government debt as a percentage of GDP. As can be seen, the government debt is decreasing in all the simulations and, paradoxically, it is lower when the interest rate is higher. This can be easily explained. In the first place, the downward trend in the three scenarios has to do with the fact that the government's deficit targets for the simulation have been relatively low, so there is no strong tendency for the government to greatly increase its level of indebtedness. On the other hand, the increase in the interest rate does not lead to an increase in the government deficit in the simulation, since the government responds to the higher interest payment with a reduction in the rest of its expenses (and not by maintaining them even at the cost of increasing its deficit). This is why with a higher interest rate, the deficit as a percentage of GDP is the same as with a lower interest rate, while, as we have previously said, GDP does increase, leading to a reduction in the debt-to-GDP ratio.

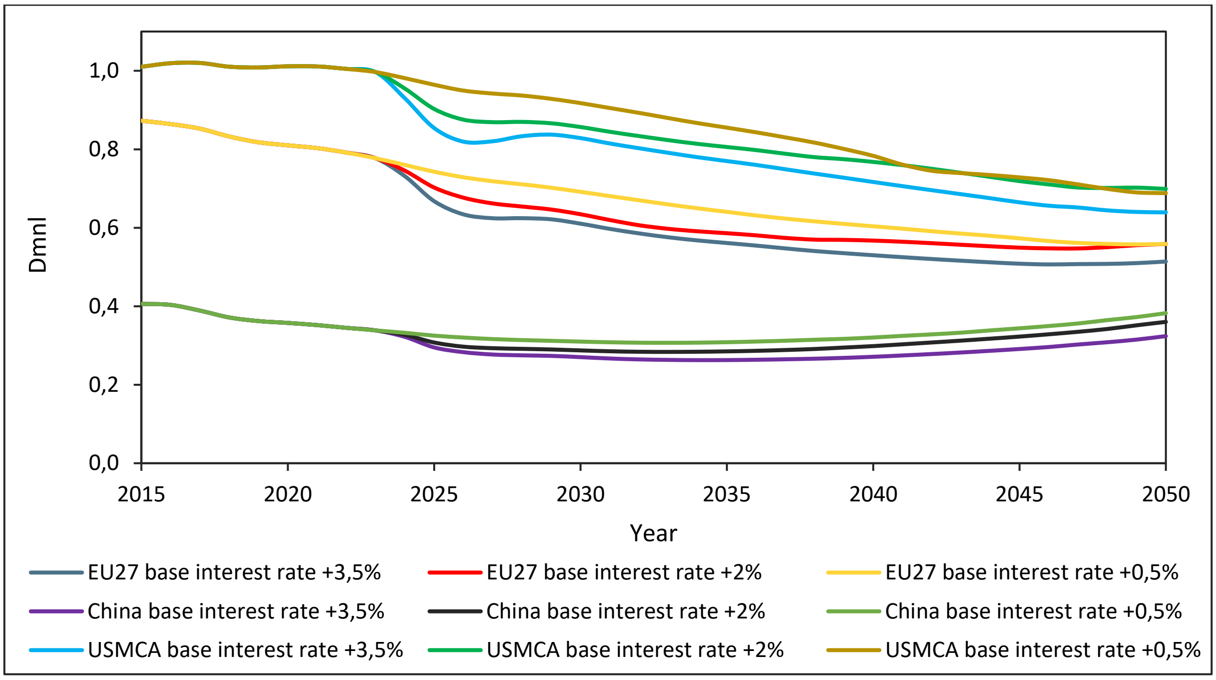

Figure 38: Government debt as a percentage of GDP

4.5. ENERGY

Due to the complexity and many dimensions required for the representation of energy in our world system (9 regions, 40 different energy commodities, 80 different processes and various feedbacks) and in line with task 9.2 a excel based graphical interface for the representation of patterns and changes of the most relevant variables was developed. It allows to select regional results as well as compute global aggregates. This template will be used here to visualize some preliminary results of the energy module in order to demonstrate the main mechanisms and features of the module.

However, it is important to remark that the scenario assumptions made in this exercise do not have the purpose of resembling realistic or plausible future scenarios. Instead, they serve the purpose of modelling rather extreme situations in order to demonstrate the model mechanics and test the potential and limits of the model.

Figure 39 shows the developed synthesis chart of the energy module results obtained from the excel based graphical interface. The top part of the figure (a to d) shows detailed results of the energy transformation process of electricity (a and c) and district heat (b and d) by transformation technology. The top part (a and b) shows the installed capacity stock (in GW), the bottom (c and d) shows the transformation output (in TWh) by technology. The 40 transformation technologies were mapped in order to reduce complexity:

- “WIND” contains offshore and onshore wind,
- “SOLAR” contains open space PV, urban PV and CSP,
- “RoRES” (Rest of RES) contains non-variable renewable categories (Hydropower, oceanic, geothermal, waste, biomass).
- “BECCS” includes bioenergy CHP and power plants with carbon capture and storage,
- “Fossil_CCS” contains fossil plants equipped with carbon capture and storage (CCS) technologies.
- “NUC” refers to nuclear.

- “GAS” includes natural gas and biogas CHPs and power plants.
- “COAL&OIL” includes coal and oil.

The middle part e) of the figure shows the primary energy demand resulting from direct consumption and energy transformation.

The lower part of the synthesis figure (f to k) shows some of most important indicators required to understand the current dynamic in the energy system:

- f) shows the RES share in electricity production, as well as the share of variable RES (mainly PV and Wind) that is curtailed due to intermittency of the selected region.
- g) shows the total GHG emissions of the system (including non-energy emissions).
- h) shows the remaining wind potential (onshore and offshore).
- shows the net land requirements for solar installations.
- j) shows the (endogenous) global oil price (note that gas and coal prices are also modelled, but not represented explicitly in this chart since in the standard parametrization of WILIAM 1.1 oil is the “limiting” fossil resource)
- k) shows the total (endogenous) GDP of the selected region.

Results in this report are focused on global level. The reference scenario (as shown in the Figure 39 below) features moderate electricity demand growth to about 30.000 TWh until about 2035, which flattens out afterwards due to a reduction in economic activity (see indicator j). The reduction in economic activity is induced by high oil prices in the standard configuration of WILIAM, due to continuance of transport trends hence with high share of oil in the short and medium-term, which causes that oil reaches geological restrictions (peak oil) in the beginning of the decade of 2040s. RES shares in electricity reach only about 20 % as electricity is still produced from fossil sources.

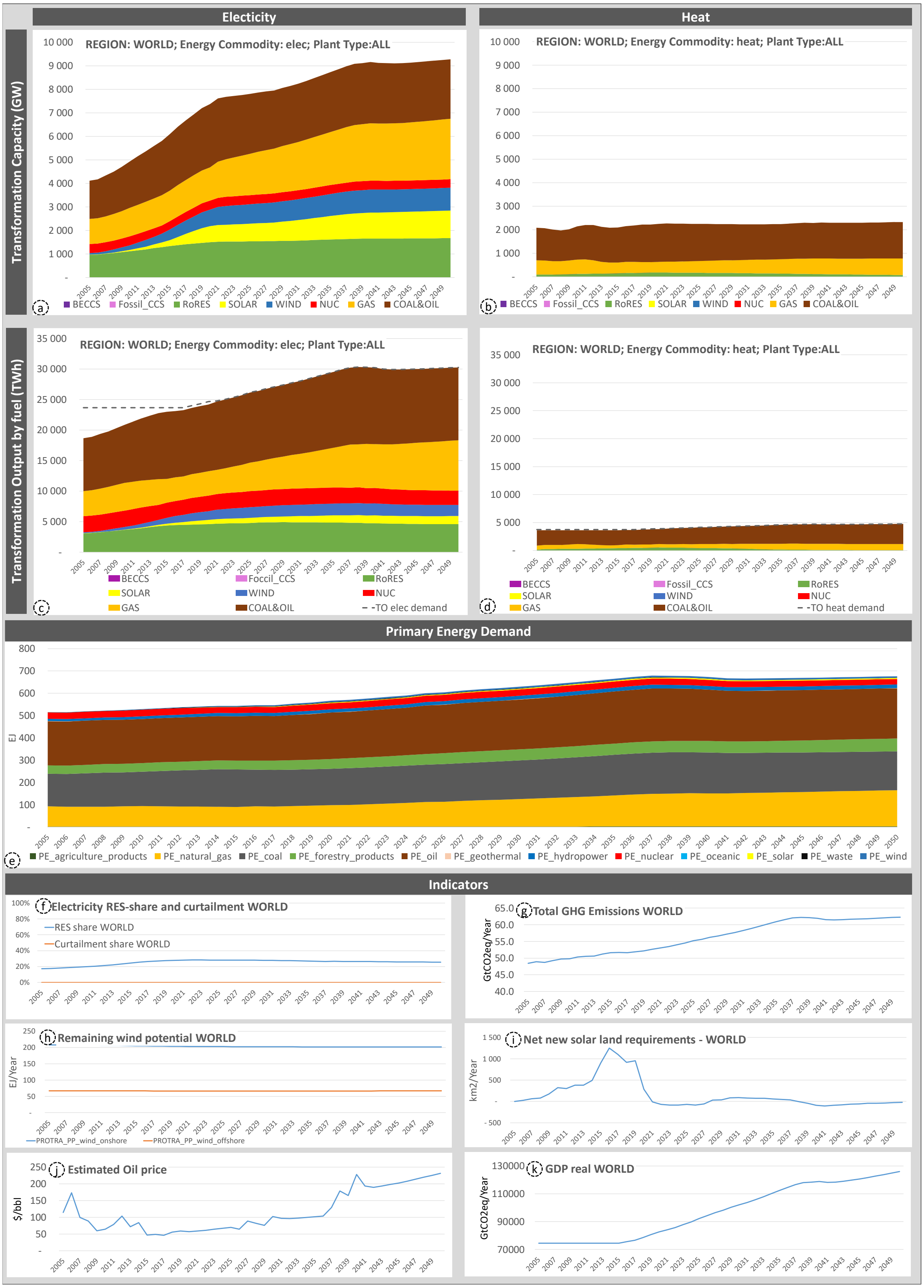

Figure 39: Energy Synthesis Chart – reference scenario

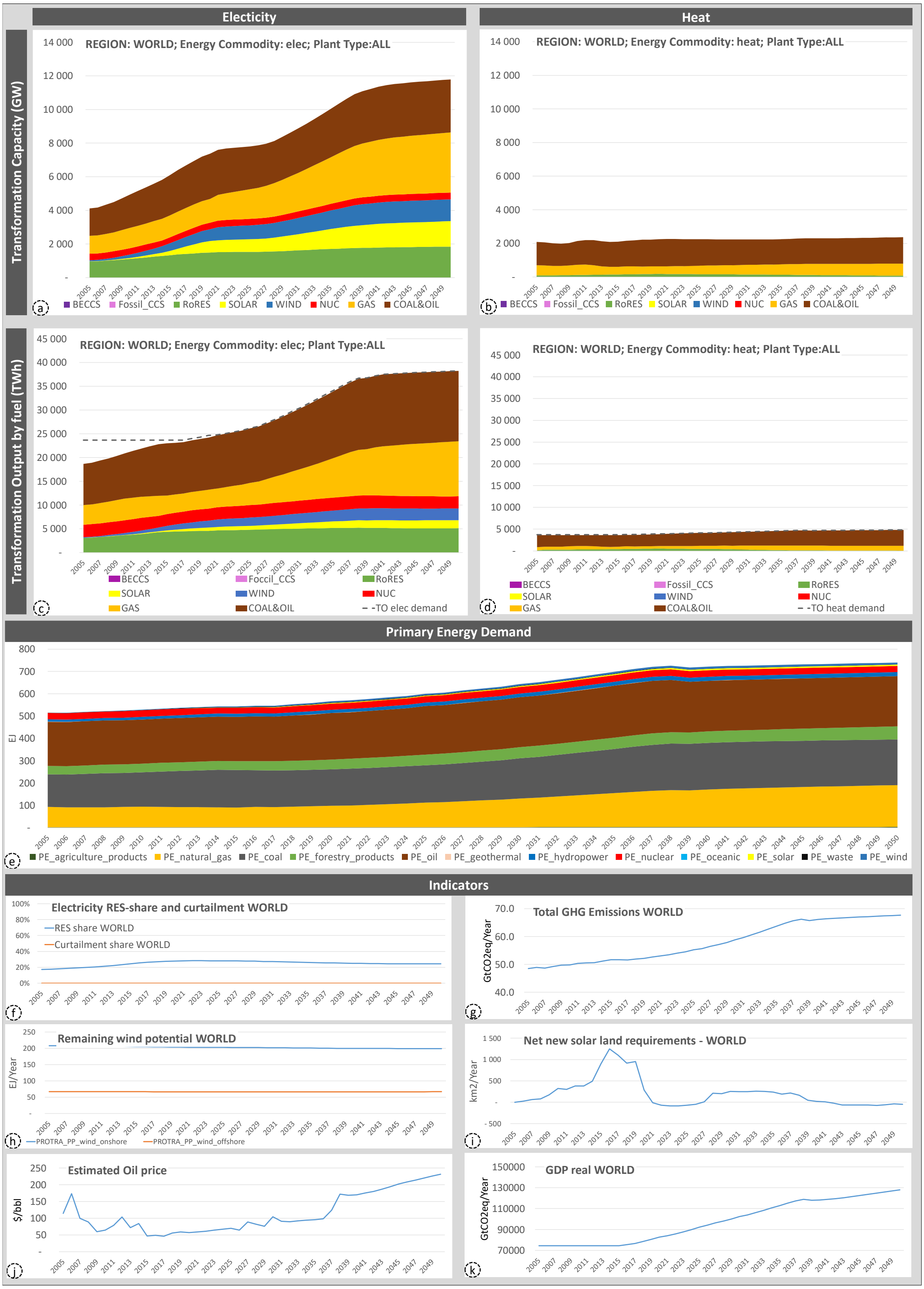

Figure 40: Reference scenario + 5% synthetic fuels

Figure 40 introduces a policy to increase the share in final energy liquids and gases of synthetic liquid and gaseous final fuels, respectively, produced from electrolytic hydrogen from 0 % to 5% between 2025 to 2050. Interestingly the oil price experiences less shocks due to less demand (see fig j, year 2037) compared to the previous scenario (an easier and less resource intensive way to achieve the same would be to change transport patterns). Even such a moderate share of synthetic fuels leads to a drastic increase of global electricity demand by 27 %. Global GHG emissions reach levels of about 68 GtCO2eq (+9 % compared to the reference scenario) because the production of electricity is still largely fossil based.

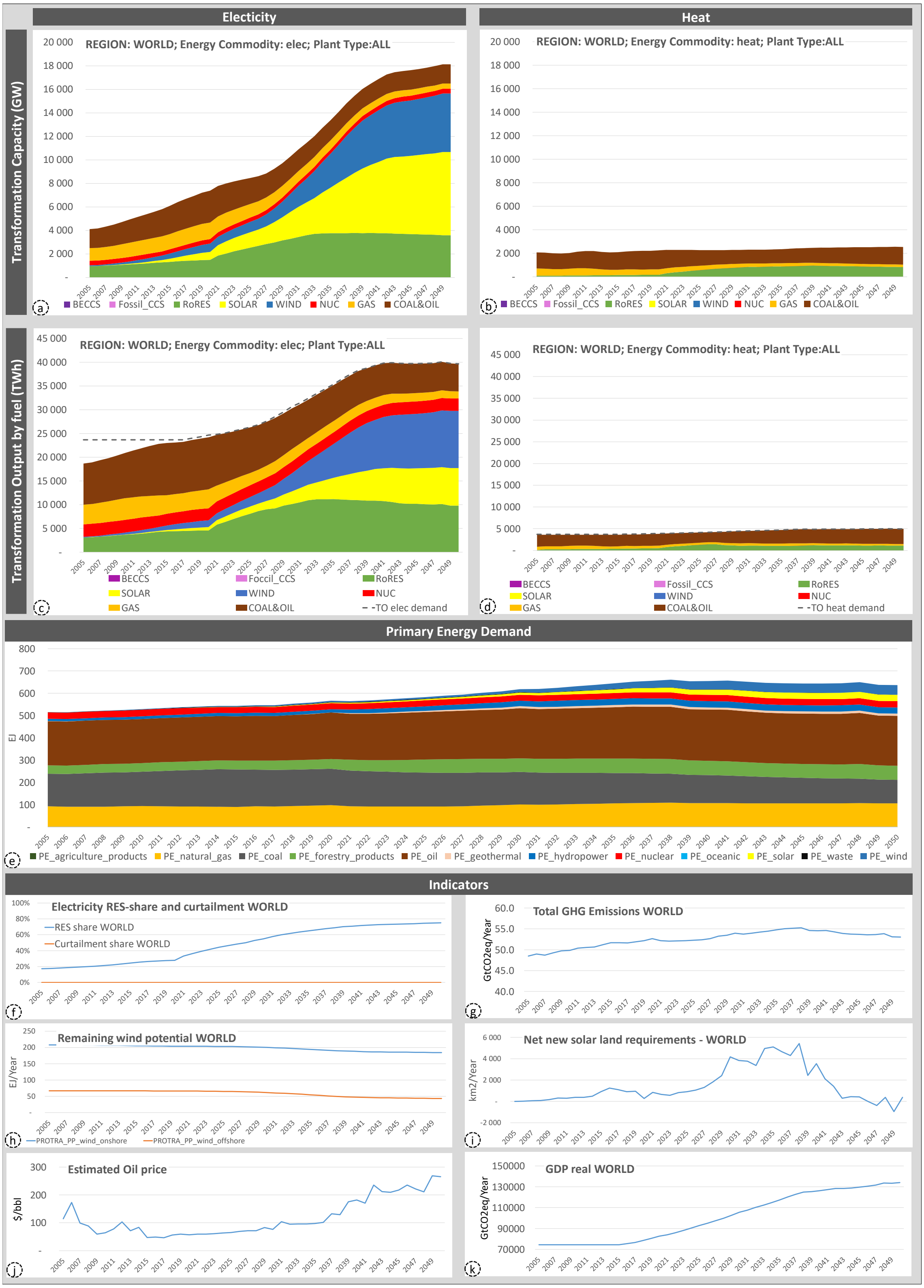

Figure 41: Reference scenario + 5 % Synthetic fuels + priority to RES in capacity expansion

The scenario in Figure 41 changes this by giving priority to renewable technologies in capacity expansion, leading to larger shares of solar and wind compared to earlier scenarios (see especially Figure 41 a) and c) above). GHG emissions are reduced by 22 % compared to the scenario before, the RES share reaches a level of about 75 %. Also note that the economic activity 2050 reaches a slightly higher level. However, in this scenario the flexibility module is still not activated, so vRES are not curtailed.

In Figure 42 the part of the variability management module that estimates curtailment of intermittent renewable electricity generation technologies is switched on. This has several implications on the overall system: as can be seen in part f) of the figure below, we see rising curtailment of electricity reaching a maximum of 16% in 2032 and leading to a sharp drop of the RES share compared to the scenario before, reduced economic output (- 6%) and increased oil price (+6 % in 2030). The energy module reacts installing less RES as they become less profitable due to curtailment.

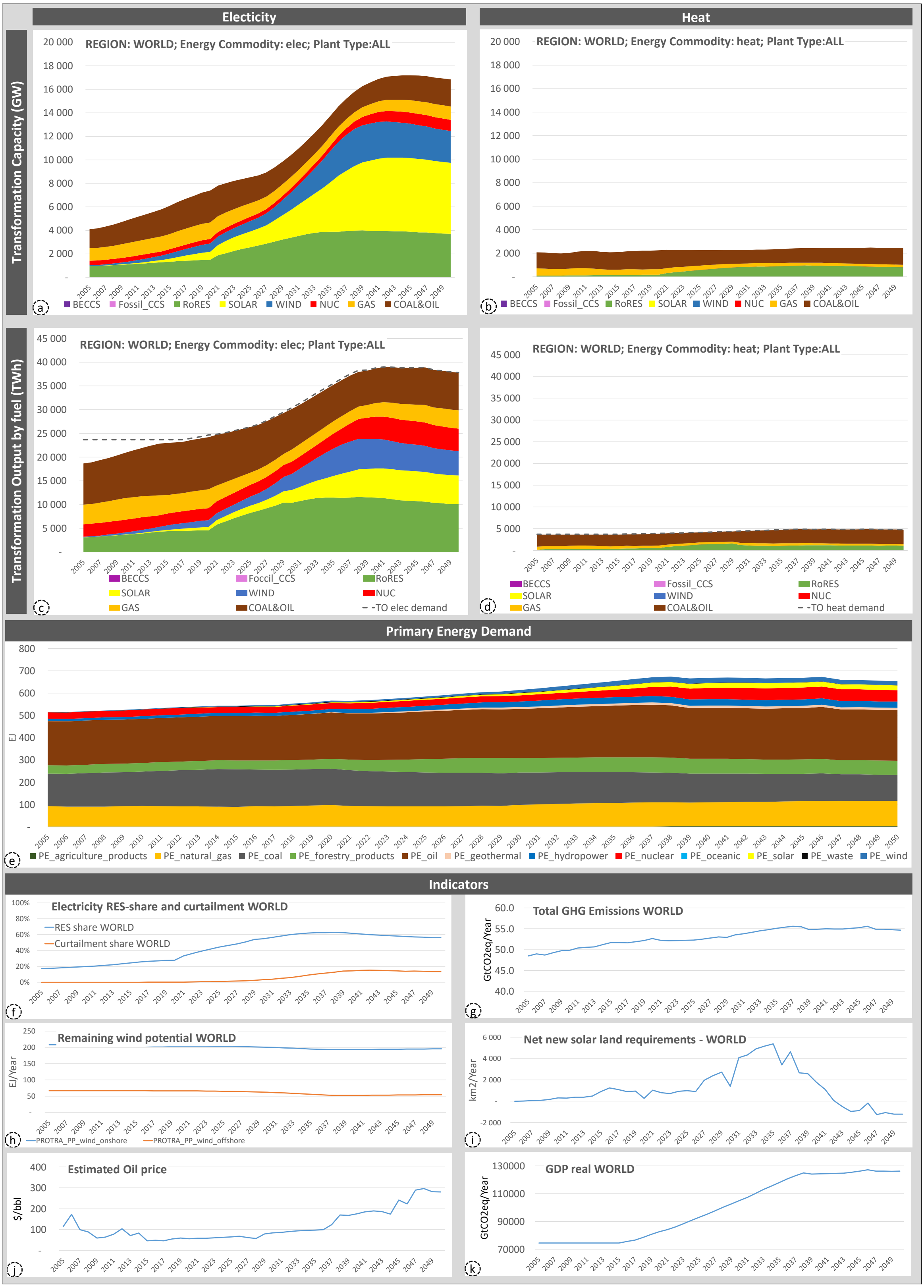

Figure 42: Reference scenario + 5 % Synthetic fuels + priority to RES in capacity expansion + Curtailment ON

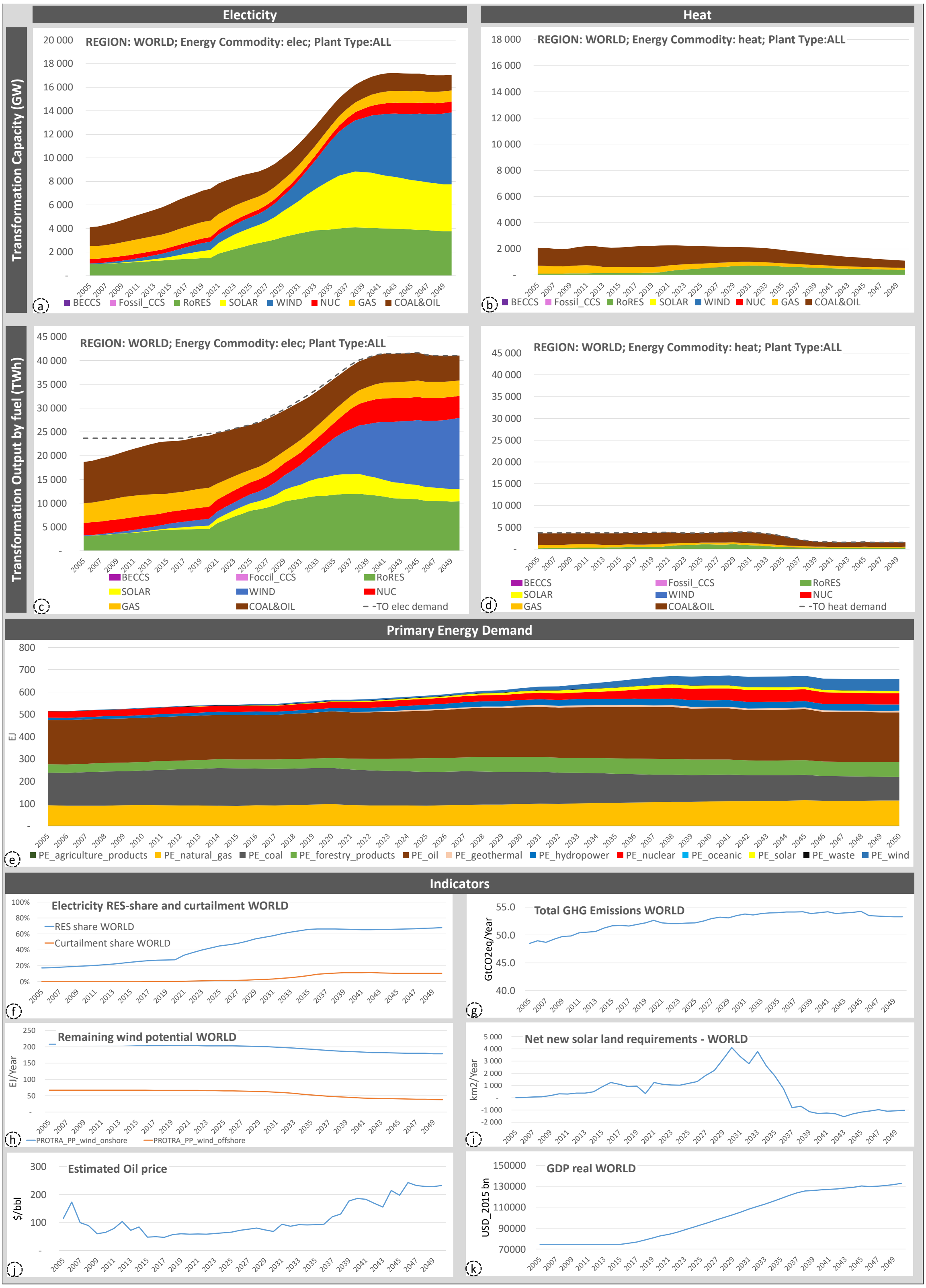

Figure 43: Reference scenario + 5 % Synthetic fuels + priority to RES in capacity expansion + Curtailment ON + Flexibility Options ON

Activating the flexibility options in WILIAM's variability management submodule improves the situation. In the scenario in Figure 43 we assume that 75 % of electric vehicles are available for smart charging by 2050 (starting from 2025), 50 % of electric vehicle battery capacity is also available for Vehicle to Grid, and about 12 % of electricity demand is available for demand side management (DSM). Furthermore, the model is allowed to endogenously increase electrolyser and power2heat capacities for flexibility purposes in case of vRES curtailment. The sum of these functions allows to increase RES share back to about 68 % and reduce curtailment of the whole system to about 10 %. The total GHG emissions drop significantly below 55gtCO2eq, despite the higher TO_elec output (For flexible electrolysers and power to heat).

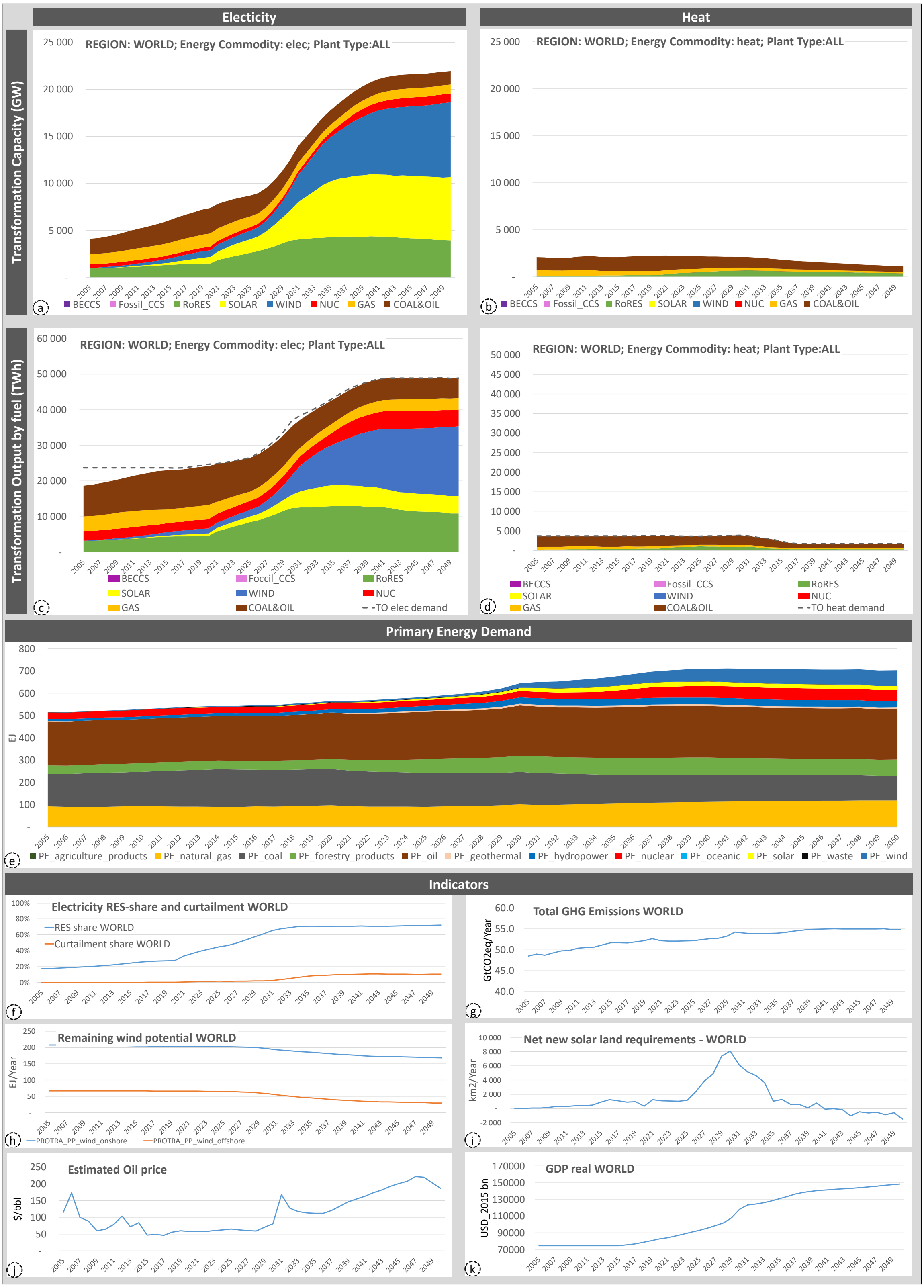

Figure 44: reference scenario + 5 % Synthetic fuels + priority to RES in capacity expansion + Curtailment ON + Flexibility Options ON + public transport & e-Mobility

However, the earlier scenarios left out policies in the domain of behavioural change or end use efficiency. The scenario shown in Figure 44 closes this gap by (1) first reducing the demand for transport by private car by around 20% and then splitting that 20% between buses and trains (60% and 40% respectively) and

(2) introducing a shift to electric vehicles by increasing electric vehicle share of new vehicles by about 50 %.

One might expect a strong decrease of primary energy demand and GHG emissions of such a policy because of the high efficiency gains embodied in such a change. However, results point into the exact opposite direction: Not only does electricity demand increase by 19 % (which is to be expected with a higher share of e-mobility) but also total primary energy demand increases by 7 % compared to the previous scenario and even GHG increase by 3 %. Looking at the economy indicators reveals the reason for these seemingly paradoxical results: Namely that reduced oil demand from transport sector leads to a 20 % reduction of the oil price (fig. j), which in turn increases global economic output by about 12 % (fig k) compared to the previous scenario without transport policies. In other words, the efficiency gains of behavioural and technological change in passenger transport were overcompensated by a rebound effect, leading even to an increase of total GHG emissions. This exercise serves to exemplify the importance (1) of designing scenarios with policies to comprehensively cover all relevant dimensions and (2) of using integrated modelling tools, such as WILIAM, that are able to capture such complex feedbacks, in order to not arrive at wrong conclusions. The tested scenarios show how a selective implementation of policies leads to rebound effects and perverse dynamics given the interconnections between the different economic sectors and countries.

Figure 45 finally summarizes the RES share of electricity that could be reached in the different scenarios in one combined graph.

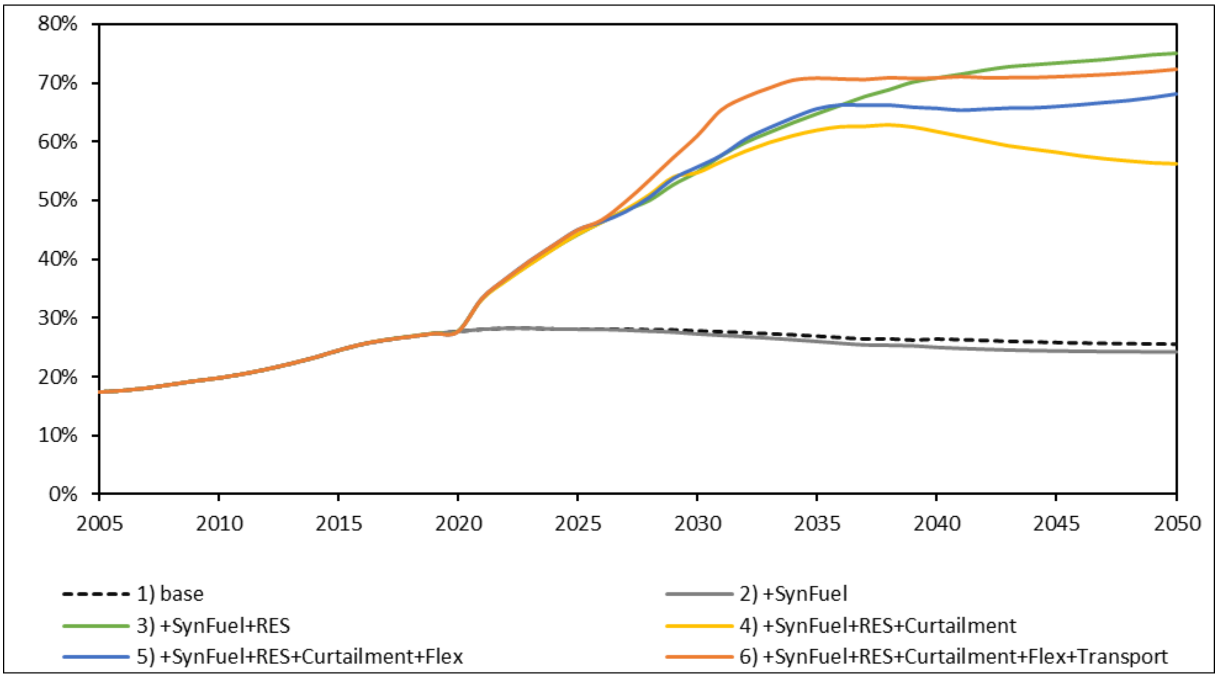

Figure 45: Comparison of electricity RES share for the scenarios discussed.

Of course, an extensive model like WILIAM offers hundreds of relevant indicators. In the last part of this chapter, we will briefly discuss some additional indicators, that are not part of the synthesis charts, to give an idea of what additional information can be drawn from the model. In the model we do compute the investment required for the different transformation- and flexibility technologies. Figure 46 shows this figure as share of GDP. Note that while this information is already embedded in the model, it is one of the pending tasks to link them to the investment matrix of the Input-Output model in order to better capture the effects of these investments on the intermediary demand and output of the different sectors (See section 5.2.1).

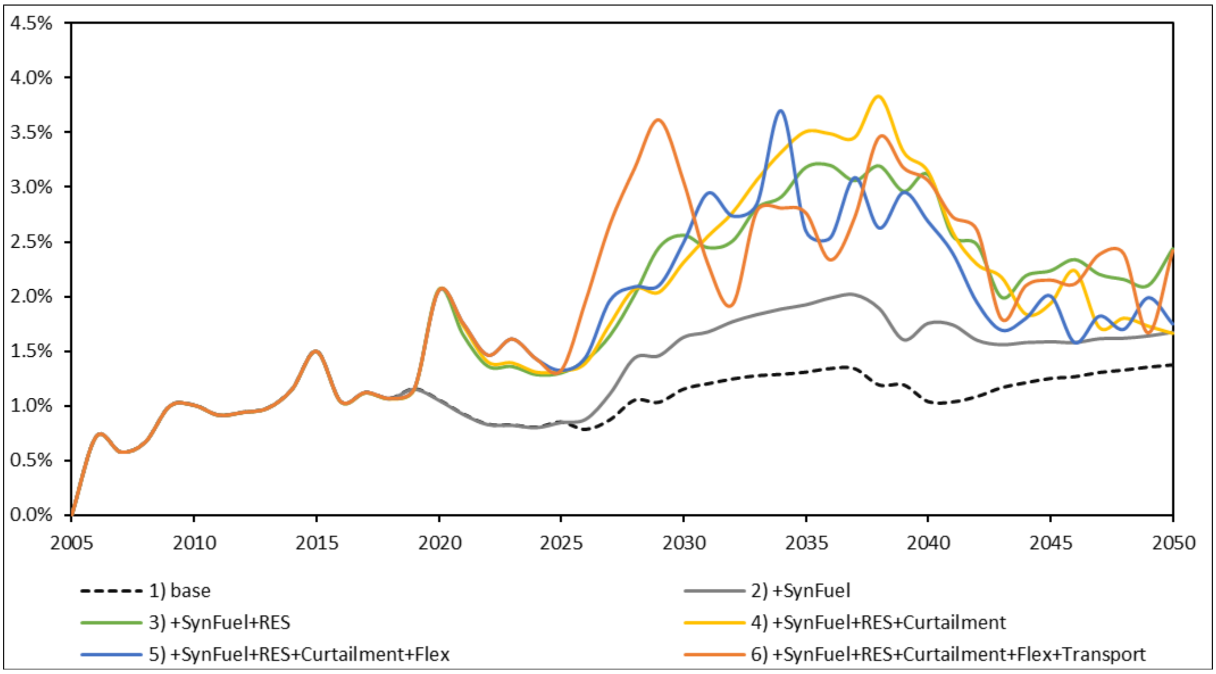

Figure 46: Global total energy capacities investment cost (including transformation technologies and flexibility technologies such as electrolysers) as share of total GDP by scenario.

In WILIAM we calculate not only the monetary investment required to provide energy infrastructure, but also the energetic requirements. Figure 47 shows the resulting global EROIst of the energy system, which in the denominator accounts for these energetic requirements. However, it must be taken into account that the energy investments associated to stationary electrolysers and flexibility options -excepting for electric stationary batteries- do not contribute to the energy investments. So, the obtained results for scenarios 5 and 6 are in fact an overestimation. In the denominator it is taken into account the actual generation of energy, hence in scenarios with curtailment the EROIst of the system will tend to decrease. Hence there are dynamic factors of different sign operating into the EROIst. As you can see, the fossil-based scenarios (1 and 2) outperform the other scenarios on this metric, featuring a higher EROIst in line with current trends (ranging 12-14:1) (given that we are -optimistically- not considering a reduction of the EROI of fossil fuels with cumulated extraction). For the scenarios including a fast penetration of RES the EROIst of the system drops sharply, reaching a minimum value between 3:1 and 6:1, and thereafter recovering until 8-10:1 when the speed of new RES capacities installed per year is reduced (this is also visible in Figure 46 related to monetary investments, when after mid-2040s the amount of new capacities levels off with relation to the previous decades in the scenarios with more RES).

We must recall that the variation of the EROI of the system would imply in reality a change in the economy module in terms of investments and energy expenditures, feedback which in WILIAM has still not been yet modelled due to its complexities. If the EROI falls from 12:1 to e.g., 5:1, this means that the amount of energy dedicated to have a functional energy system would pass from 1/12~8% to 1/4=25%, hence making the system less efficient.

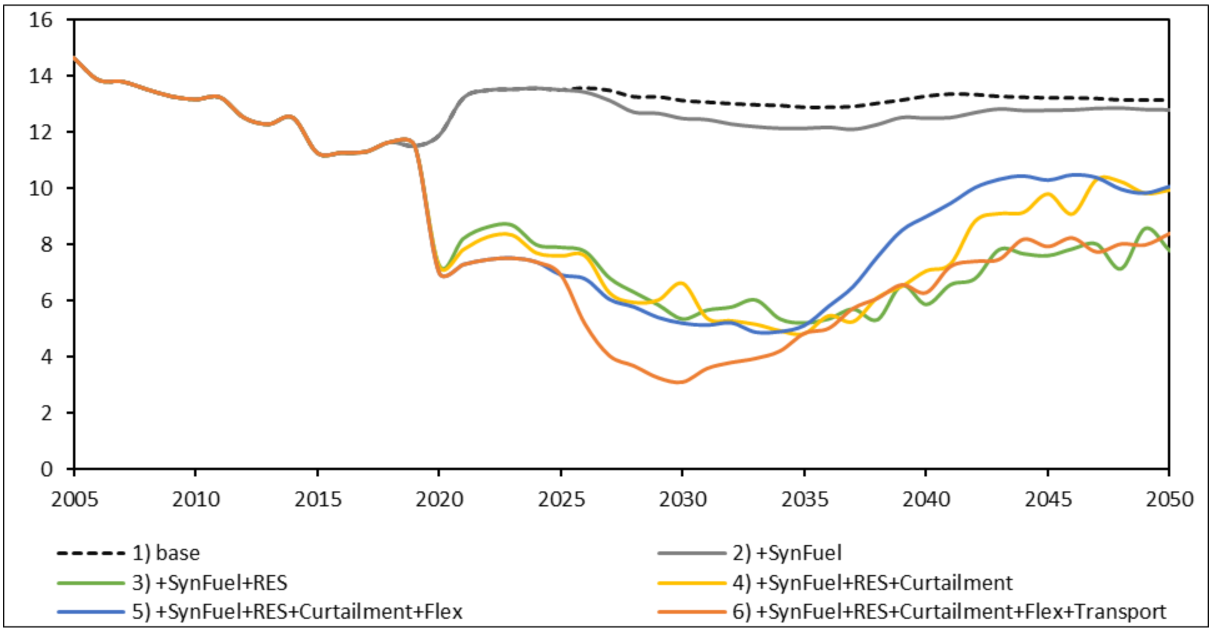

Figure 47: Global EROIst of the system by scenario.

In the 6 experiments above we demonstrated the capabilities and model mechanics of the energy module. We conclude that, while it wasn't the goal of this exercise to parametrize realistic future scenarios, the model yields plausible results and allows to capture a wide variety of interesting and integrated results. Further work will be directed to solve pending issues (cf. section 5) and develop scenarios in coordination with the rest of modules of WILIAM.

4.6. MATERIALS

In this section, the preliminary results of the Materials Module are outlined and categorized into three parts. The first part presents the outcomes pertaining to fossil fuel sub-module, specifically emphasizing the results of the oil analysis. Progressing to the second part, the focus shifts to showcasing the results of the metals sub-module, with copper results taken as an illustrative example. Finally, the third part addresses the results concerning the material requirements of energy technologies sub-module. As a case in point, the results concerning electric batteries are examined.

4.6.1. FOSSIL FUEL SUB-MODULE: CASE STUDY OF OIL

The partial results are based on the integrated fossil fuel, economy, and energy modules of WILIAM. This research introduces a cutting-edge model that delves into fossil fuel extraction, which is crucial for understanding the societal, economic, and environmental ramifications of transitioning to low-carbon pathways amidst our current reliance on fossil fuels. As a component of the Within Limits Integrated Assessment Model (WILIAM), the fossil fuel sub-module encapsulates elements such as resources, reserves, supply, demand, and pricing of oil, coal, and natural gas. The macroeconomic module utilizes these prices to gauge the requisite production to meet the demand for diverse goods and services, which in turn it is transferred to the bottom-up energy module, which determines the primary fossil fuel demand. The fossil fuel sub-module then processes this demand to discern production, pricing, investment in new production capacities, and shifts in resources and reserves. Central to the model's functionality is the demand-price mechanism, which stems from the tension between supply and demand: escalating prices reduce fossil fuel demand and propel investments in extraction capacity, considering resource availability and escalating depletion rates. Activating these price influences in the energy module not only increases renewable resource use and expansion but also fosters substitution with alternative fuels, thus reshaping energy intensities. This price mechanisms are combined with a peak fossil fuel approach in the fossil fuel sub-module, where extraction of resources is hampered as we get closer to the geological relative (flow) and absolute (stock) limits. The novelty in the here presented approach stems from the difference in the modelling approaches. Other Integrated Assessment Models (IAMs) mainly use supply-cost curves, where the marginal monetary cost of resource extraction ascends in tandem with cumulative extraction. This asserts that initial deposits exploited are the most readily accessible and economically advantageous. The availability of a fossil resource is thus determined by a preset association between the accessible resource volumes and corresponding extraction costs, with occasional adjustments due to technology-led, exogenous cost reductions over time. The key shortfall of this method is that many IAMs use the general assumption of ample fossil fuel availability and marginal cost increase, which contrasts with significant cost hikes detected in a dynamic approach during periods of high supply-demand tension. Moreover, supply-cost curves wield a marginal influence on modelled demand, while the methodology proposed in this chapter introduces direct feedback mechanisms. To enhance the method proposed herein, it would be beneficial to incorporate varying oil quality profiles and their corresponding extraction costs, enriching the presented approach The modelling for oil, gas, and coal, as well as its linkage with the economy and energy modules follows the same principles and modelling structure. Three illustrative case studies on oil underpin the potentialities of this modelling, highlighting its capability to model long-term patterns based on resource accessibility as well as short to mid-term phenomena like a lockdown or OPEC strategies.

In this deliverable, for the sake of synthesis and given that the modelling of fossil fuels follows the same principle, we focus oil model. To demonstrate the model's capabilities, we conducted simulations on the following three distinct case studies:

1. Examining model sensitivity to varying oil available resource estimates.
2. Investigating the effects of both low and high oil spare capacities from OPEC countries.
3. Mimic the effect of a lockdown as a quick and sharp reduction in household transportation demand .

These simulations are designed to highlight the interconnections between economic, energy, and materials modules, emphasizing the feedback loop between supply/demand quantities and their associated prices. To exclusively focus on these interrelationships, we've turned off connections with other WILIAM modules (like the impact of climate change, price associations with metals and other fossil fuels, demographics, etc.). Notably, these simulations exclude potential technological advancements such as energy efficiency enhancements, fuel substitutions, or shifts in transportation modes that might be initiated by fluctuations in oil prices. Within our simulations, oil price changes predominantly lead to:

- An upward adjustment in household spending on various transportation modes, based on the altered price points of these services and income levels.
- A contraction in disposable income for purchasing other non-durable items due to increased transportation costs.
- A decrease in overall real-term household expenditure.

➢ **Case study 1: Sensitivity to oil resources estimates.**

The first case study is investigated the interplay between economic activity (GDP growth), oil demand, and extraction capacity under various Remaining Ultimately Recoverable Resources (RURR) assumptions. The different Remaining Ultimately Recoverable Resources assumptions are based on a literature review. The literature review on oil endowment estimates was conducted to gather data for a sensitivity analysis on a model's behaviour. The review wasn't systematic but aimed to cover both official agency data and independent scientific assessments. It's important to note that different studies offer different metrics, such as reserves, resources, and URR, and their definitions can vary. The Figure 48 graphically presents the data and outlines three levels for the sensitivity analysis:

- **Low**: Represents the smallest URR estimates, which can be seen as a policy of keeping oil unextracted.
- **Middle**: Uses a URR value of 5000 Gb from one source, though this is viewed as optimistic. A more recent paper by Laherrère in 2023 suggests a more likely URR of 3800 Gb.
- **High**: Combines reserves and resources from official agencies with cumulative extraction and potential new discoveries.

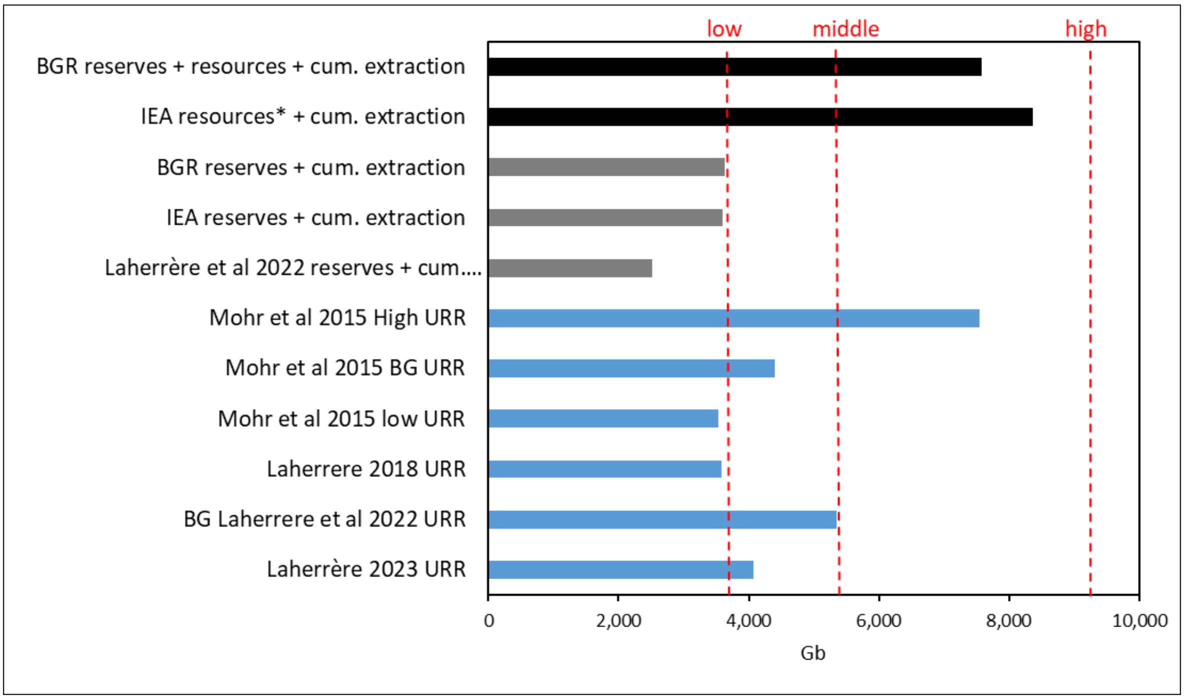

Figure 48: Synthesis of different literature-based estimates for the URR, reserves and resources, own work.

The key findings are:

- **Without Oil-Price Feedback:** In scenarios where oil prices don't influence demand:
  - Global GDP grows annually by ~2.3%.
  - Oil demand rises by 2.6% annually.
  - Total oil demand over the simulation surpasses feasible extraction limits, signalling an unrealistic economic path without technological advancements.
- **With Oil-Price Feedback:** When this feedback is activated:
  - GDP growth varies drastically based on RURR assumptions: 0.83% for High resource estimate, -0.34% for Medium resource estimate , and -1.41% for Low resource estimate.
  - GDP would peak before the end of the century, with exact timings varying by RURR scenario.
  - In the three scenarios global GDP would peak before the end of the century: by the year 2086 in the high resource scenario, by 2047 in medium resource scenario and by 2027 in Low resource scenario. In the case of the high RURR scenario, the peak in the GDP would be followed by a “steady state”, while in the Med and Low scenario GDP would drop by 20% and 70% respectively with respect to the levels of 2015.

  - The GDP paths display strong interdependencies with the demand of oil in the three scenarios. In the low resource scenario oil demand peaks in 2024, in the medium resource scenario in 2046 and in the high resource scenario in 2076.
  - The relation between GDP growth and oil demand isn't linear, with tensions between supply and demand varying based on RURR levels. (Applies also for point 3 to 5)
  - As oil resources diminish, prices rise, impacting economic activity and long-term oil demand.(applies also for point 3 to 5)
- **Oil Wells and Infrastructure (with oil price feedback):** As over half of the recoverable resources are extracted:
  - Investments in oil wells initially compensate for resource depletion.
  - However, rising oil prices eventually affect GDP and subsequently oil demand.
  - The number of active wells and their longevity varies by RURR scenario, with the High RURR scenario maintaining the most wells for the longest duration.
- **Regional Analysis(with oil price feedback):** Examining GDP trajectories for different regions under the medium RURR scenario:
  - Regions like Russia and the Rest of the World (including oil-exporting countries) experience less economic impact due to rising oil prices.
  - Major oil-importing regions like EU27 experience significant economic decline due to escalating oil costs.

- **Comparison with Other Studies:** The study's results were compared with estimates from Laherrère (Laherrère et al., 2022; Laherrère & Hall, 2018) and Mohr (Mohr et al., 2015). Laherrère's estimates align closely with the study's Low RURR scenario, while Mohr's "Best Guess" and low scenarios fall between the study's low and medium RURR outcomes.

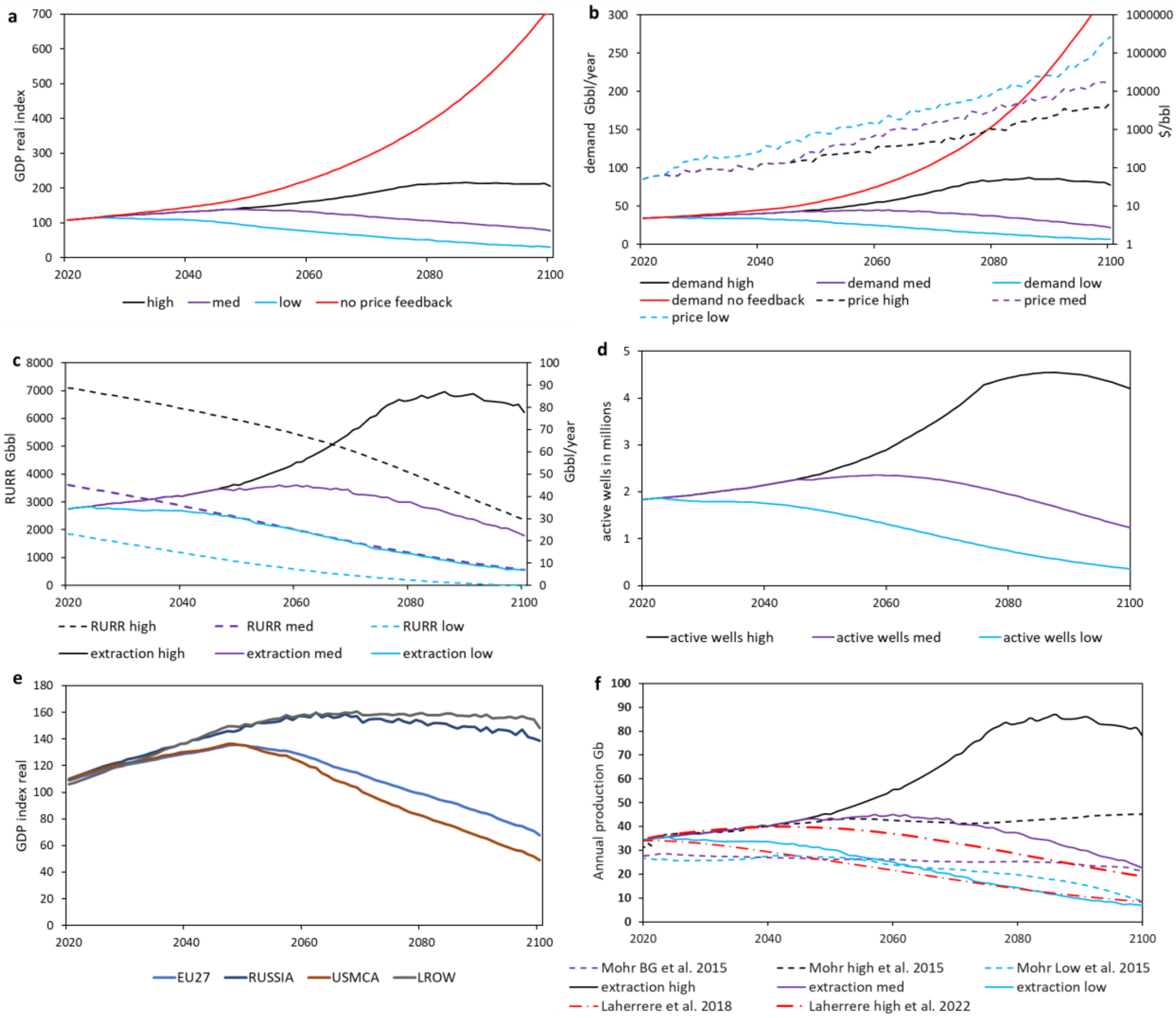

Figure 49: Figure (a) shows the GPD real index under the different RURR scenarios; Figure (b) shows the oil demand and oil price developments under the 4 scenarios; Figure (c), the oil extraction per year and the 3 different RURR estimates in Gb; Figure (d) shows the number of active wells under the 3 RURR estimates; Figure (e) shows results of GDP real index in the medium RURR estimate; Figure (f) shows the 3 scenarios comparison to results of Laherrère (Laherrère et al., 2022; Laherrère & Hall, 2018), and Mohr (Mohr et al., 2015).

The model is able to represent the dynamics of GDP growth, oil demand, and oil extraction as intrinsically linked (as shown in Figure 49), and these relationships become more pronounced and critical as the availability of recoverable oil resources decreases. The study underscores the need for technological advancements and the need to reduce the dependencies on oil to avoid economic crises if economic growth is to be pursued. Furthermore, it becomes evident that countries with plenty of resources available will be less likely to be affected as negatively by scarcity as major oil-importing regions like the EU 27. Therefore, it is relevant for these regions to plan for the end of their dependence on oil.

➢ **Case study 2: Effects of OPEC's management of its spare capacity.**

The second case study is exploring the influence of OPEC's oil supply strategies on the economy-energy-oil system, two scenarios were investigated between 2025 and 2030:

1. High OPEC Spare Capacity (SC): OPEC aims to hike oil prices by reducing output, increasing spare capacity from 3 million barrels per day (Mbd) to 6 Mbd.

2. No OPEC Spare Capacity (SC): OPEC aims to lower prices, discouraging investments in new wells by cutting its spare capacity from 3 Mbd to 0.

After 2030, both scenarios revert to a spare capacity of 3 Mbd. The findings suggest:

- **Oil Prices**: High OPEC Spare Capacity (SC)leads to a notable rise in oil prices, while No OPEC Spare Capacity (SC) results in a modest price drop. This is due to the price equation's responsiveness to spare capacity changes, especially when supply-demand tension varies.
- **Oil Demand & Investment**: Higher oil prices in the High OPEC Spare Capacity (SC) scenario cause a drop in oil demand but spur investments in new wells. As a result, prices later decline due to increased spare capacity, allowing demand to recover gradually. Conversely, the No OPEC Spare Capacity (SC) scenario sees a first a price decreases due to increased spare capacity, but when OPEC nations in the year 2030 are reverting to withhold an additional 3 Mbd of capacity, the price surges from this diminished spare capacity causing a decline in demand.
- **Long-term Impacts (2045-2050)**: Investment decisions made before 2045 led to distinct price and demand patterns in both scenarios. The No OPEC Spare Capacity SC scenario experienced a more significant price surge due to a steeper drop in spare capacity, driven by fewer earlier investments.
- **Global GDP Impact**: The High OPEC Spare Capacity SC scenario, with its higher oil prices, resulted in a GDP decrease. In contrast, the No OPEC Spare Capacity SC scenario, benefiting from lower oil prices, reflected a higher GDP trajectory.

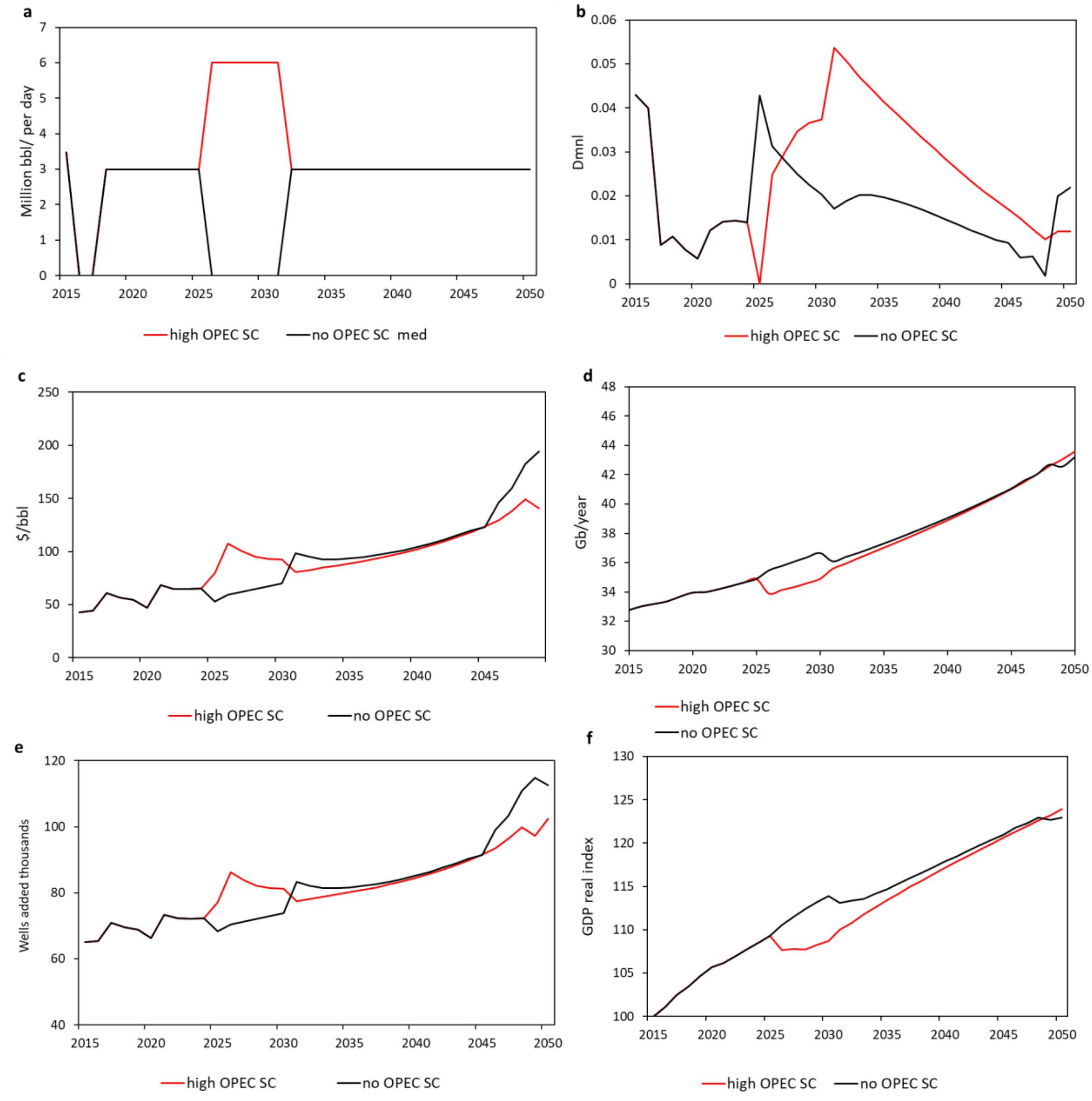

Figure 50: Figure (a) shows the capacity withholds or released to the market under the two scenarios in Mbd; Figure (b) depicts the availability of spare capacity entering the price equation; Figure (c) shows the estimated oil price; Figure (d) shows the oil demand under the two scenarios; Figure (e) shows the wells added in thousands; Figure (f) shows the global GDP real trajectories under the different scenarios.

In essence, OPEC's spare capacity management significantly influences oil prices, demand, investments in wells, and global GDP, underscoring the economy's profound dependence on oil dynamics. The results (Figure 50) clearly show that the OPEC countries can have a strong influence on the global economy if the global economy remains so dependent on oil consumption.

- **Case study 3: Mimic the effect of a lockdown as a quick and sharp reduction in household transportation demand.**

The third case study examined the effects of a short-term reduction in household transportation demand, mimicking the effect of a lockdown on the global market dynamics of the oil market and demand for oil.

Specifically, we impose a reduction of 20% by 2030 of household consumption of transportation services, covering both private vehicle fuel expenses and public transport. It was assumed that post-2030, transportation levels would revert to pre-lockdown figures. The study was based on Medium-RURR and a moderate OPEC target price trajectory.

Key findings include:

- **Oil Demand**: 7% decline in oil demand versus the baseline scenario (Figure 51 (a)).
- **Spare Capacity and Prices**: The lowered demand during the lockdown increased oil spare capacity (Figure 51 (b)), causing a relaxation between supply and demand. As a result, oil prices decreased by 7.3% compared to the baseline (Figure 51 (c)). This drop in prices then deterred the addition of new oil wells (Figure 51 (d)).
- **Post-Lockdown Rebound**: By 2031, after the lockdown's end, both demand and spare capacity quickly returned to their original trajectories, followed by a steady normalization of prices and well investments.
- **OPEC Target Price Influence**: From 2030 to 2033, the estimated oil price gradually converged with the OPEC target price. In 2032, once this target was achieved, OPEC spare capacity was released (Figure 51 (e)), causing an initial drop in oil prices and a slight demand boost. However, without the extra capacity to tap into, the no-lockdown scenario saw oil prices bounce back, resulting in a subsequent decline in demand.

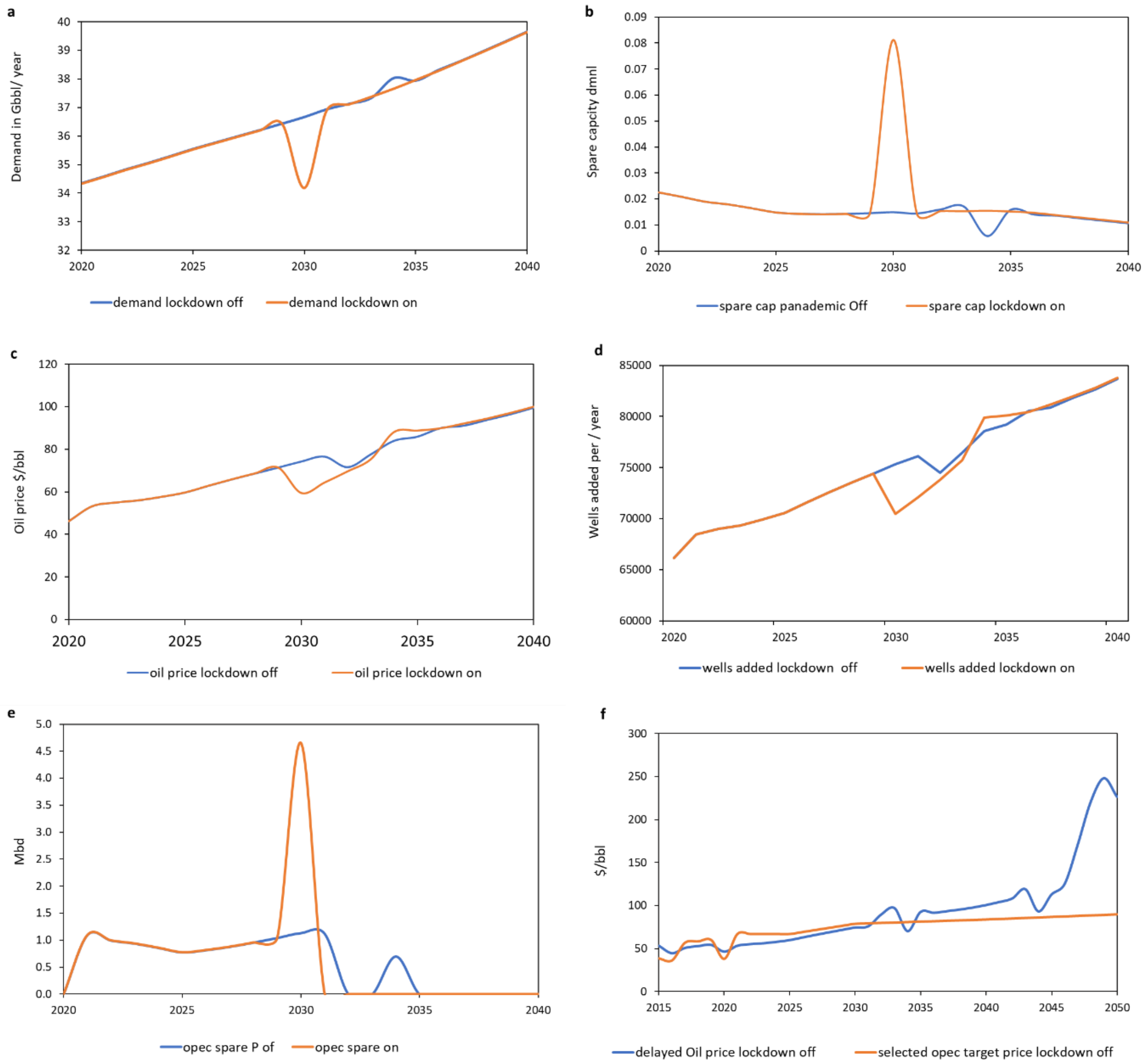

Figure 51: Figure (a) shows the oil demand development under the lockdown and no lock down scenarios; Figure (b) shows the development of the spare capacity under the two scenarios; Figure (c) shows the development of the oil price; Figure (d) shows the number of wells added; Figure (e) shows the behaviour of OPEC spare capacity; Figure (f) shows the oil price and the OPEC target price under the no lockdown scenario.

The results of case study three (Figure 51) show the oil market's sensitivity to external disruptions. Based on the results, we can conclude that the model can be used to analyse the effects of short-term disruptions and their consequences for society.

In conclusion, the model articulates the multifaceted interactions between oil supply and demand, illustrating how price dynamics influence both. Prices arise from supply-demand relationships, subsequently affecting new investments, income distribution, and consumption structures. Unlike traditional IAMs, which rely on supply-cost curves, WILIAM emphasizes dynamic feedback mechanisms, aiming for a more holistic representation. WILIAM's all-encompassing approach, featuring endogenously calculated variables such as GDP, oil demand, and oil prices, distinguishes it from models like TIMES-Austria and TIAM-UCL, which either assume infinite fossil fuel supplies or utilize cost-supply curves. Unlike the IMAGE model, WILIAM's feedback loop completion provides potentially richer results.

4.6.2. METALS SUB-MODULE: CASE STUDY OF COPPER

The partial results are based on the integrated metal and economy modules of WILIAM. As a component of the Within Limits Integrated Assessment Model (WILIAM), the metal sub-module encapsulates elements such as resources, reserves, supply, demand, and pricing of copper, iron, aluminum, and nickel. The partial results will introduce a novel approach for linking the economy module with the material module on the example of the copper sub-module.

Copper, with its current applications inbuilding infrastructure, electronics, renewable energy, electric vehicles, solar panels, and wind turbines, is an indispensable element in modern technological advancements. Given its central role in these burgeoning industries, it's imperative for society to closely monitor available copper resources, reserves, prices and understand evolving demand patterns to ensure sustainable growth and to anticipate potential supply challenges in the future. The copper sub-module calculates the resources, reserves, exploration investments, extraction capacity, extraction costs. actual production, recycling, losses, stock in use and prices. Monitoring the aforementioned variables is essential for understanding the societal, economic, and environmental ramifications of transitioning to alternative low carbon pathways amidst our current reliance on copper for several key technologies.

Copper mining's basic driving mechanism originates from profitability and the availability of a mineable reserve, as used in the model. This factor is influenced by mining costs, capital costs, and ore grade. The mining process for copper includes extraction from both primary and secondary sources, with copper sometimes being a co-product, adding another dimension to the extraction process.

In the sub-module, copper is divided into several ore qualities: rich quality, high-quality, low quality, ultralow quality, trace quality, and ocean ore grade quality. The higher the quality, the higher the copper content in the host material. A higher quality is also associated with a lower cost for extraction and production. A lower ore grade implies that more rock must be moved to mine the metal, meaning that a higher copper price is needed to maintain production levels. The price must exceed production costs and is determined by supply and demand tension. Supply encompasses the amount of metal moving to the market plus the amount of metal in the market stock, with demand coming from the Economy module.

The quantity in the trade market depends on the balance between copper production deliveries, the amounts recycled from copper end of life (EOL) scrap and the amount of new copper scrap. The profit is driven by the copper price and the amount extracted, offset by extraction costs. The price in the sub-module is based on econometric estimations and is calibrated to follow the trend of the historical price. For copper extraction to continue, profit must exceed production costs and copper must be available to extract. The copper price, feeds back into the Economy module at the next time step, impacting goods and services prices via the supply chains of the multi-regional input-output model. Different households across the 35 regions respond to these price changes based on a predefined set of income and price elasticities. Trade structures also shift due to the changing price ratio between domestic and imported goods. Ultimately, copper price fluctuations influence the level and composition of demand for the 62 goods/service types, affecting various aspects of the Economy module—production, investment, wages, employment, income, profits (including from copper mining), government revenue, and expenditure. These economic changes subsequently lead to the endogenously calculated new copper demand for the next time step, which feeds back into the Metal sub-module. The novelty in this method lies in the link of the copper price to the Economy module, corresponding to the 'COPPER MINING' sector and the endogenously calculated demand within the Economy module linking back to the Copper sub-module. Demand comes from historical data for the timeframe from 2005 until 2015 and from the Economy module from 2015 onwards.

The partial results are based on the WILIAM 1.1 version with no further changes, the model is following the current trends. The only modification made are to modifications to the end of life (EOL) recycling rate of copper. The difference between the three tested scenarios is described below:

There are two possible settings for the end of life (EOL) recycling rate; in one setting, the price also drives the urge for copper recycling (price affecting the recycling rate), base run. In the second setting, the user has the option to set an exogenous end of life (EOL) recycling rate, scenario 2 and 3. The changes made in the scenarios two and three are introduced at the year 2025.

- Scenario 1 Base run: Recycling rate is affected by the price, where increase in copper price drives and increase in the recycling rate.
- Scenario 2 Med recycling: Recycling rate is set by the user- medium recycling rate for EOL copper is chosen, with 50 % of EOL copper is getting recycled on a global scale.
- Scenario 3 High recycling: Recycling rate is set by the user- High recycling rate for EOL copper is chosen, with 80 % of EOL copper is getting recycled on a global scale.

Substitution effects caused by copper prices are switched off in all the here illustrated simulations.

- **Results**

Figure 52-(a, b, c, d, and e) show the effect of the three different EOL recycling rate scenarios.

Figure 52-a demonstrates that the base run scenario, where the price influences the recycling rate, leads to a more pronounced rise in copper prices compared to Scenarios 2 (Med_recycling) and 3 (High_recycling). In these latter scenarios, the end-of-life (EOL) recycling rate is adjusted to either 50% or 80%. The findings suggest that increased recycling rates contribute to reduced copper prices.

Figure 52-b presents the impact of the three recycling scenarios on the extraction of copper from both primary and secondary mineral sources. The base run yields the most substantial annual extraction, especially when compared to Scenarios 2 (Med_recycling) and 3. The recycling rate has a beneficial influence in reducing the pressure on mining. In the base run, the function determining the recycling rate was calibrated to align with historical prices and end-of-life (EOL) recycling rates. These historical rates appear to be lower than the preset rates of Scenarios 2 and 3. Consequently, only a significant increase in price prompts the function to produce a recycling rate comparable to those of the preset scenarios. Thus, inherent dependencies on past trends of the price and the EOL recycling rate can result in a more conservative recycling rate in the base run, see Figure 52-c.

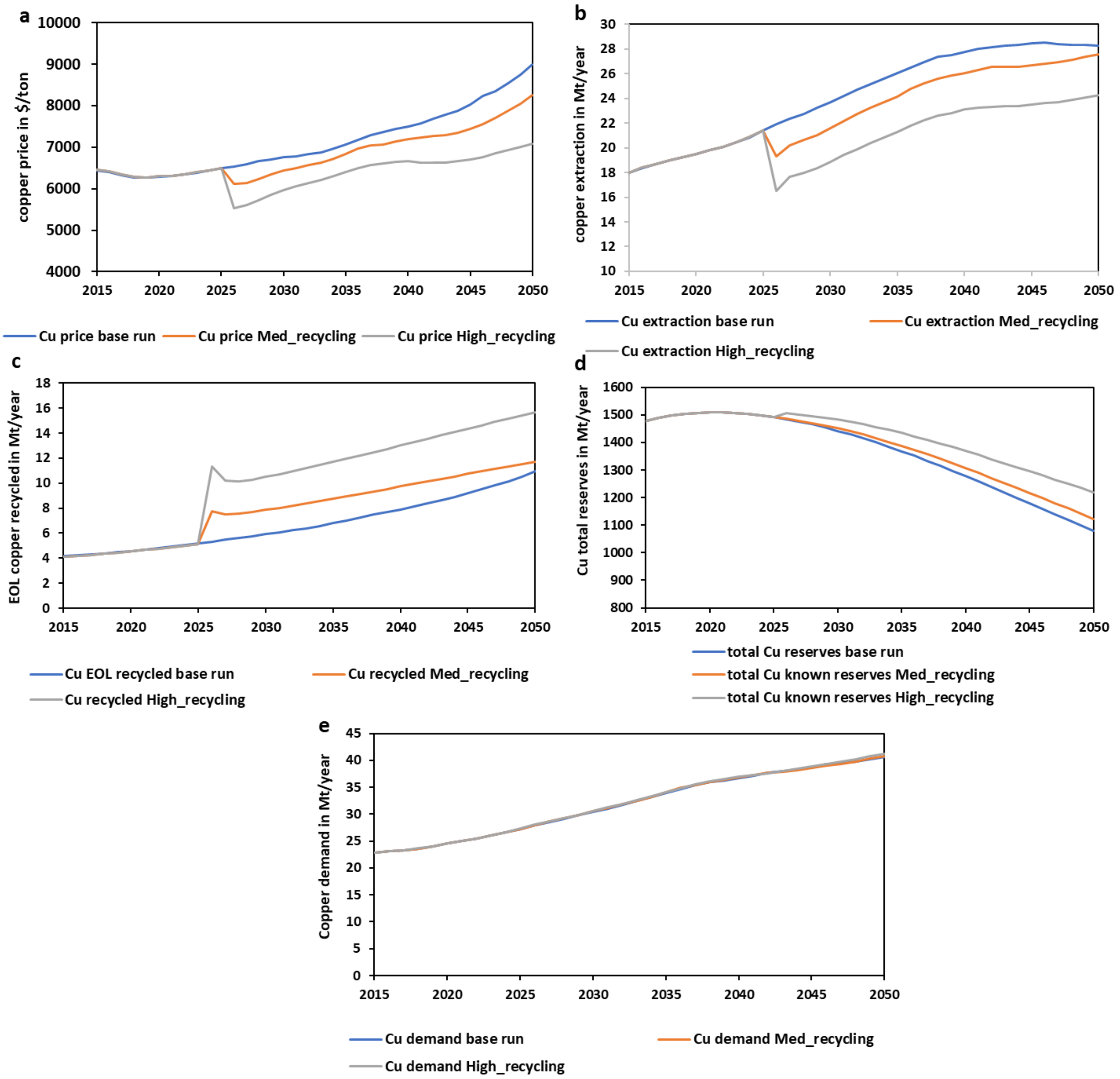

Figure 52: Figure (a) shows the effect of the three recycling scenarios on the price of copper; Figure (b) illustrates the effect of the recycling scenarios on the extraction/mining of copper; Figure (c) shows a comparative Analysis of three distinct recycling scenarios, Illustrating amounts of copper recycled per year from the scrap stock; Figure (d) shows the effect of the recycling scenarios on the total available copper reserves; Figure (e) shows the development of the copper demand from 2015 until 2050 under the different recycling scenarios.

Figure 52-c depicts the quantities of copper transitioning from the scrap stock to the copper market across the three recycling scenarios. Scenario 3 (High_recycling) exhibits the maximum copper recycling, followed closely by Scenario 2 (Med_recycling). The base run scenario recycles the least amount of copper in comparison.

Figure 52-d shows the impact of Scenarios 1 through 3 on the total reserves of copper. Reserves are more abundant at elevated end-of-life (EOL) recycling rates. Scenario 3 retains the most reserves, followed by Scenario 2, with the base run showing the fewest reserves. The data suggests that while higher recycling rates lessen the demand on primary copper mining, significant quantities of copper from mining are still required across all three scenarios, see Figure 52-b.

Figure 52-e displays the progression of the copper demand over time for each of the three recycling scenarios. In all scenarios, the copper demand remains relatively stable due to minimal price fluctuations

that are insufficient to influence demand either positively or negatively. The reliance on copper persists, also given that no substitution effects are activated. Within the modelled scenarios, no copper scarcity is observed, which would otherwise elevate the copper price and reduce the copper demand.

The influence of the recycling scenarios on the copper price is attributable to the eased tension between demand and supply resulting from increased recycling levels, and therefore more EOL copper getting recycled, as seen in Figure 52-a and Figure 52-c. This alleviation is also due to the decreased strain on primary copper mining, as depicted in Figure 52-b and Figure 52-d. As a result of this reduced mining pressure, larger quantities of high-quality ore remain accessible, ensuring the copper price stays lower compared to the base run. In the base run mining of lower quality ore at an earlier time is taking place, which leads to an increase in the copper price.

The data presented in Figure 52 emphasizes the profound impact of end-of-life (EOL) recycling rates on copper's market dynamics. Notably, copper prices, extraction practices, and total reserves are all significantly influenced by recycling rates. Specifically, increased recycling not only reduces the copper price but also lessens the demand on primary mining, suggesting a critical role for recycling in ensuring sustainable copper management. The base run, relying on historical trends and prices, reveals a conservative recycling rate which, in turn, increases reliance on mining, particularly of lower-quality ores, leading to an uptick in copper prices.

Recycling rates play a pivotal role in shaping the copper market's future, with increased rates promising both economic and environmental advantages. It is imperative that sustainable practices, particularly in recycling, are adopted to ensure a balanced and efficient use of this crucial resource.

4.6.3. MATERIAL REQUIREMENTS OF ENERGY TECHNOLOGIES SUB-MODULE: CASE STUDY OF ELECTRIC BATTERIES

The capability of the submodule of material requirements of energy technologies is illustrated in this report for the case of transport electrification. Four global decarbonisation transport scenarios have been simulated targeting a GHG reduction of 80% GHG. For the sake of simplicity, the rest of the model follows current trends. The four simulated scenarios are:

- Expected EV trends: the target modal and vehicle share in 2050 is determined by the extrapolation of observed trends.
- High EV: very high electrification in land transport. By 2050, it is assumed that all personal cars, buses, and motorcycles, as well as light duty vehicles, will be replaced by battery electric vehicles and that 80% of heavy vehicles will be hybrid.
- E-bike: This scenario promotes personal mobility mainly based on very light electric vehicles (2-wheeled electric vehicles, electric bicycles, and non-motorized modes). Light-duty vehicles shift to electricity. A significant part of freight shifts to railway.
- Degrowth: reduction of transport demand combined with a modal shift of private transport to light and public modes and train for freight. Changes in urban planning are not modelled given the global scale of the applied model, which does not explicitly represent cities and the structure of urban areas.

The results showed here correspond to the ones published in (Pulido-Sánchez et al., 2022). Despite that paper used MEDEAS-W, since the submodule of materials for transport has been implemented in WILIAM very similar results are obtained with WILIAM.

Figure 53 shows the EV battery power put into service annually (TW/year) by scenario. The capacity installed in all scenarios increases strongly from current ~0.7 TW and reaching by 2050 from almost 5 TW in the Degrowth scenario, ~15 TW for E-bike and EV trends, and 40 TW for EV high.

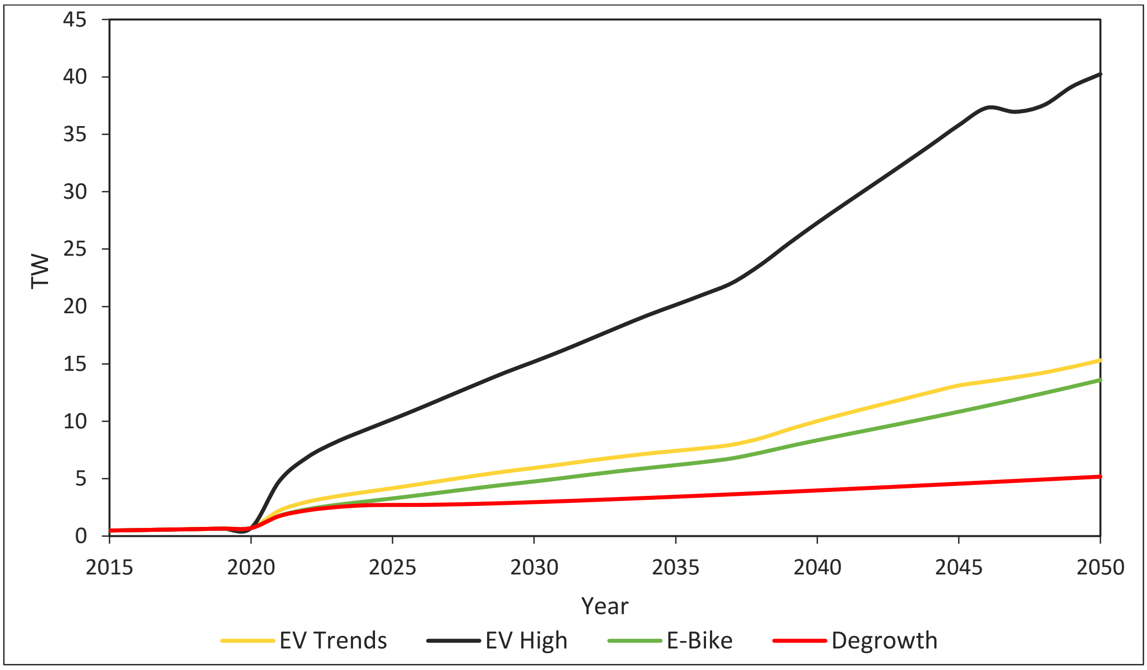

Figure 53: Battery power put into service in EVs annually (TW/year) by scenario. Source: (Pulido-Sánchez et al., 2022).

The evolution of the EV battery technology share over time from 2015 for the different types of batteries and scenarios evaluated in the analysis is shown in Figure 54. A similar dynamic between the different technologies is observed in all simulations. In the first years, the dominant technologies are NCA and NMC. However, when nickel and to a lower extent cobalt start to become scarcer, the share of LFP increases very fast. The LMO battery represents a negligible share during all period for all simulations. The main driver is its low dynamic EOSI, and from 2030 the scarcity of manganese hampers its usage.

The LFP battery is the dominant technology during the studied period in all scenarios (and notably in the Degrowth one), reaching market share values around 30% in 2050. This is mainly due to the fact that it has a reasonably good dynamic ESOI with relation to the other sub-technologies, and it is not dependent on the most critical materials (nickel, cobalt and manganese) as it is the case for the NMC and NCA. In second place follows the NCA battery, reaching market with shares around 25% by 2050, and notably in the EV high scenario it reaches similar market shares than the LFP. The market share of the NMC battery ranges slightly lower values at around 20% in 2050.

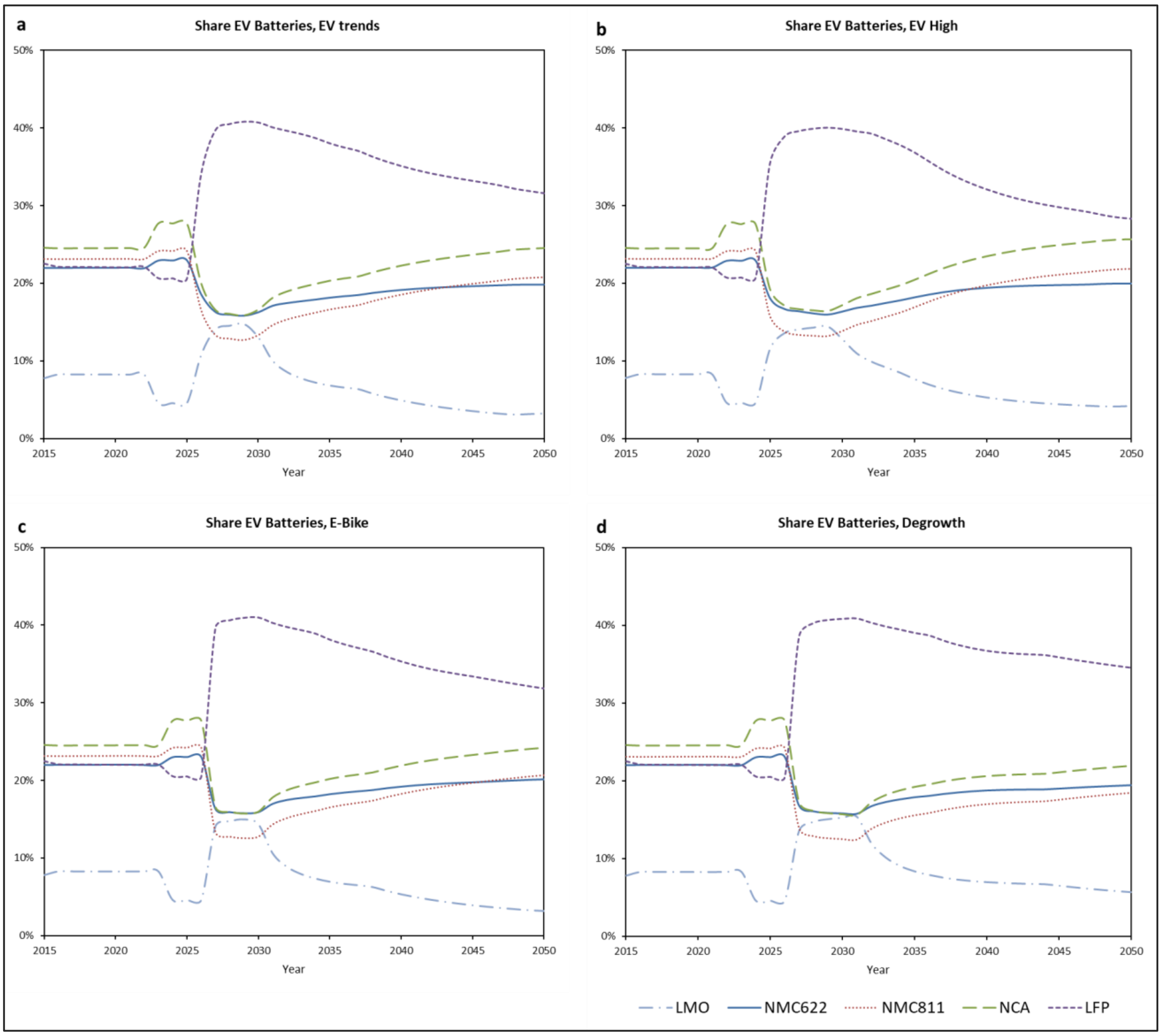

Figure 54: **Market share of EV batteries over time by scenario. Source:** (Pulido-Sánchez et al., 2022).

Figure 55 shows the share of total cumulated primary demand by 2050 (transport electrification technologies and rest of economy) for the main materials studied in this work with relation to their reserves. Copper, cobalt, lithium, manganese, nickel, and graphite surpass in at least one of the scenarios the level of current reserves. The demand from the rest of the economy is fairly similar (excepting for the Degrowth scenario where significantly lower levels are obtained). Copper has a high demand from the rest of the economy, but also has a significant demand from EV batteries, the rest of components of the EV vehicles and its charging and grid infrastructure as well as from railway. Cobalt is in high demand because of the manufacture of EV batteries with the exception of the LFP battery that does not use this material, while its demand from the rest of the economy is generally lower. Lithium has a very high demand from all EV batteries and a lower demand from the rest of the economy, which may be explained by the very large difference in weight of EV batteries and electronic appliances.

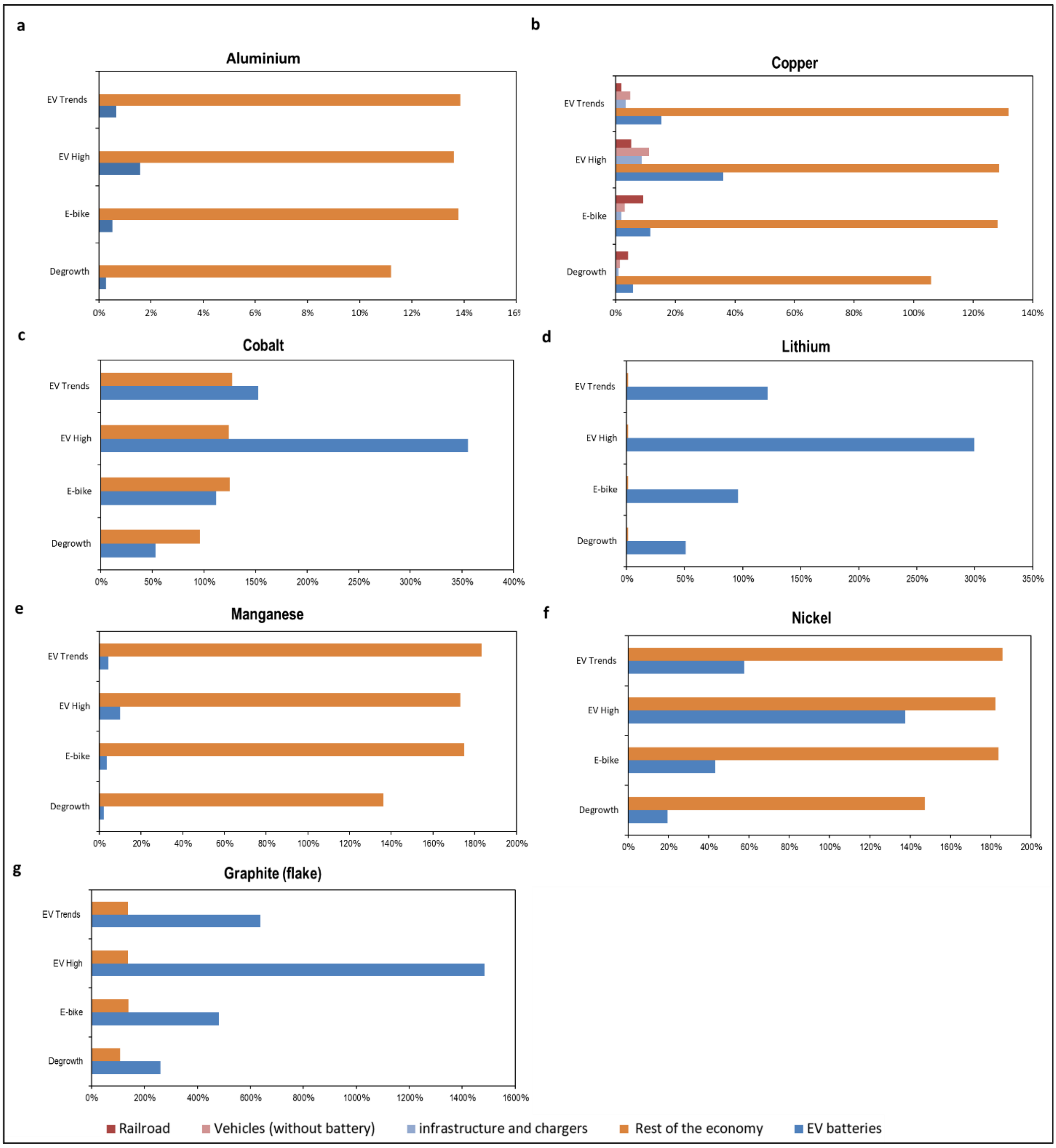

Figure 55: **Cumulated primary material demand until 2050 with relation to current reserves in the 4 scenarios. Source:** (Pulido-Sánchez et al., 2022).

4.7. LAND AND WATER

The section presents a selection of results from the Land and Water module. It begins by presenting the results of the land model and subsequently moves on to the results of the water model.

4.7.1. LAND SUBMODULE

The Land model of Land and Water Module of WILIAM model considers the relationship between many dynamics and variables and can be used to review policies related to:

- Energy-land interaction (biofuels, solar energy land, sustainable biomass demand from forests, …)
- Competition for land use and emissions derived from land use changes.
- Effect of behavioral changes on diets and urban density.
- Changes of agriculture management (industrial, low input and regenerative agriculture).
- Impact of oil availability on agriculture and the possibilities for transitioning to more sustainable agricultural practices.
- Capacity of agricultural methods and forests to serve as carbon sinks.

However, this study is focused on one aspect as an example that the module can treat: the competition between biofuels and food production, which has implications for land use.

4.7.1.1. INPUTS FROM OTHER MODULES

The Land and Water Module receives various inputs from different modules of WILIAM model. Since the objective of this section is only to describe the Land and Water Module, some inputs from other modules are taken as an exogenous input for the studied module, and the most important inputs are the *population* variable from Demography Module, the *gross domestic product per capita* variable from Economy Module, and the *biofuels* and *forestry products for energy* demand from Energy Module. These variables are described as follows:

- *Population*:

The *population* variable in the Demography Module in WILIAM model evolves for 9 regions and from 2005 to 2050. From 2005 to 2020, it is calculated using historical data of life expectancy at birth and fertility rate from each studied region (data from World Bank national accounts data). From 2020 to 2050, it follows an exogenous scenario based on historical data of fertility rate and life expectancy at birth. The *population* data are used in the Land and Water Module to calculate the demand of food.

- *Gross Domestic Product per capita* (*GDPpc*):

The *GDPpc* variable is calculated in the Economy Module for the 9 studied regions. From 2005 to 2015, the *GDPpc* data are historical data with a constant price in 2015 (data from World Bank national accounts data, and OECD National Accounts data files). From 2015 until 2050 it growths at rates similar to those of the past that are calculated on the Economy Module. This parameter is used in the Land and Water Module to calculate *diets* and wood demand for the industry.

- Biofuels demand (agriculture products):

The *biofuels demand* is calculated in the Energy Module, and it is an important input for the Land and Water Module because it is related directly to the crops demanded for energy. From 2005 to 2019, historical data of biofuels demanded for energy are used (data from OECD Agriculture statistics database). From 2019 to 2050, an exogenous scenario is used in this work.

4.7.1.2. SCENARIOS

In this deliverable, two global scenarios (Scenarios 1 & 2) are examined and compared to baseline scenarios (BASELINES 1 & 2) in order to test the interaction of biofuels with food for the use of land. These scenarios are not intended to be realistic scenarios based on best guesses of the parameters (such as the SSPs), they are extreme scenarios that allow to extract preliminary conclusions about the basic dynamics and limits of a specific problem. Both scenarios showcase the effect of increasing biofuel consumption by an amount that reaches in 2050, the amount needed to substitute 20% of the oil consumption used today in transportation (see Figure 56). This amount of biofuels is an arbitrary value chosen ad hoc, but it enables us to see the effect of oil substitution by biofuels with modest substitution targets.

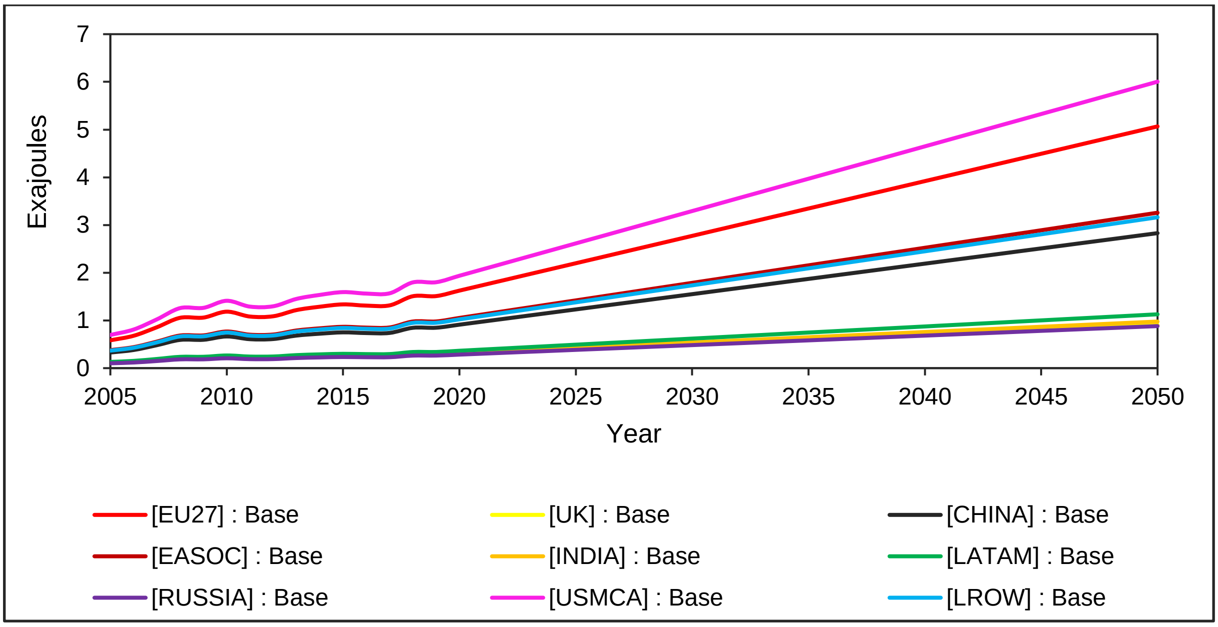

Figure 56: Biofuels demanded for energy by region.

The hypotheses used in baseline scenarios and scenarios 1 & 2 explained above are documented and listed in Table 3.

Table 3: Hypothesis used in the baseline scenarios and scenarios 1 & 2.

Hypothesis	***BASELINE 1***	***Scenario 1***	***BASELINE 2***	***Scenario 2***
Demanded biofuels from crops	*Constant to 2019 value*	*20% of 2019 oil consumption for transportation*	*Constant to 2019 value*	*20% of 2019 oil consumption for transportation*
Increase in cropland area	*0% relative to 2015 cropland area*	*0% relative to 2015 cropland area*	*10% relative to 2015 cropland area*	*10% relative to 2015 cropland area*
Increase in yields	*0% relative to 2019 yields of industrial croplands*	*0% relative to 2019 yields of industrial croplands*	*30% relative to 2019 yields of industrial croplands*	*30% relative to 2019 yields of industrial croplands*

4.7.1.3. RESULTS AND DISCUSSION

4.7.1.3.1. RESULTS AND DISCUSSION OF SCENARIO 1:

In this section, we apply the hypotheses listed in Table 1 to Scenario 1 and analyse the corresponding results.

Figure 57 illustrates the changes in the global availability of crops in Scenario 1 compared to the BASELINE 1. It reveals a significant decrease, reaching 25% in the year 2050, as opposed to the 15% decrease in the BASELINE 1, as depicted in the same figure. These results demonstrate the impact of applying Scenario 1 on crop availability. Note that in the historical period from 2005 until 2019, it has been close to one, considering that the availability has adjusted to the demand.

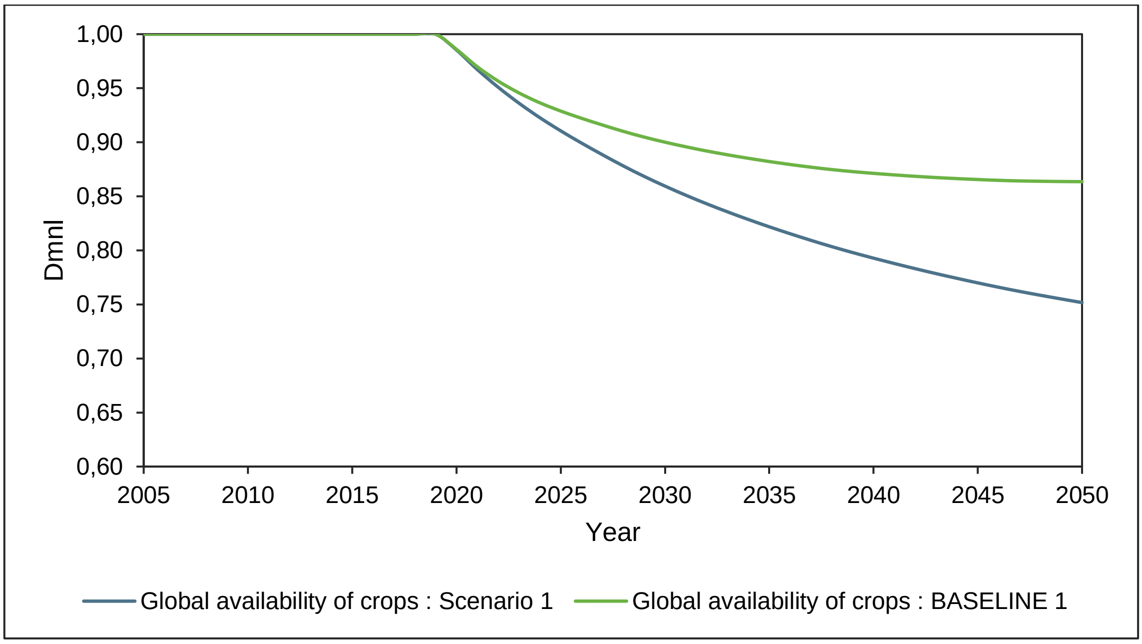

Figure 57: Global availability of crops [BASELINE 1 & Scenario 1]

In order to distribute available land products into uses and into regions, we have given equal priority to all regions, and all uses. This means that, if one use demands more than another, it receives, proportionally, a greater amount. That is what we observe in Figure 57: the demand of crops ends up being higher because of the high demand of biofuels for energy, therefore, the allocate function assigns more resources to energy. In future works the priorities of these allocation functions can be changed to observe the effect of factors that could affect these distributions, such as the relative income of regions or policies of food protection.

It is worth to observe how the demand for certain types of crops behaves, and to compare the crops demanded for energy and food with the amount allocated for energy after the distribution. For these purposes, we calculate the results for specific crops where competition for land can have significant impact. The ratio of crops used for biofuel production in these scenarios have been kept constant and equal to the ones observed in recent years. It should be noted that sometimes the demand cannot be met for one or both uses (energy or food in this case) due to production limitations (cropland and/or yields restrictions).

As shown in Figure 58, for corn, the quantity demanded for biofuels ends up being greater than that for food, and this highlights the magnitude that biofuel demand can have on corn demand, even for modest goals of fossil fuel substitution. In Figure 58 the demand of corn cannot be met in 2050 for both energy and food uses.

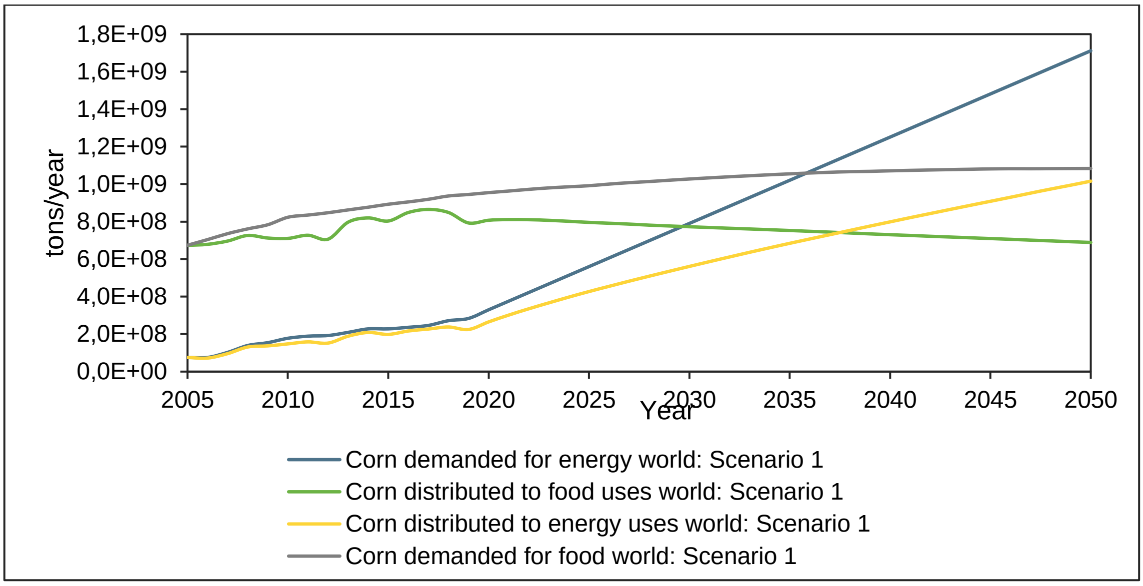

Figure 58: Corn demanded and distributed for energy and food [Scenario 1].

In this Scenario 1 and in the case of corn (Figure 58), the demand is not met for either of the two uses (energy and food) by 2050. Furthermore, in the case of cereals other and oilcrops, which are used very little for energy purposes compared to food, it is clear from Figure 59 and Figure 60 that there is a marked difference between cereals other and oilcrops demanded and distributed for food. This is because other crops, such as corn and sugar crops are displacing cereals other and oilcrops in terms of land use. The changes of land allocation among crops are done in the Land and Water Module proportional to the relative availability signal of each crop, therefore, the crop with more demand displaces the others. In this scenario, other signals such as the relative market price of crops are not used for these allocations.

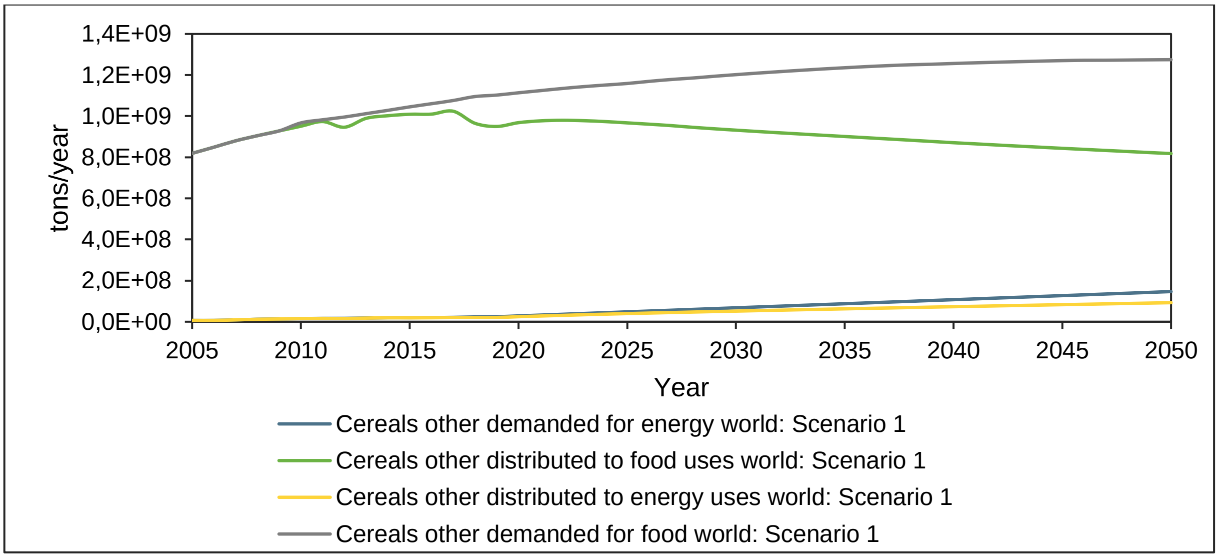

Figure 59: Cereals other demanded and distributed for energy and food [Scenario 1].

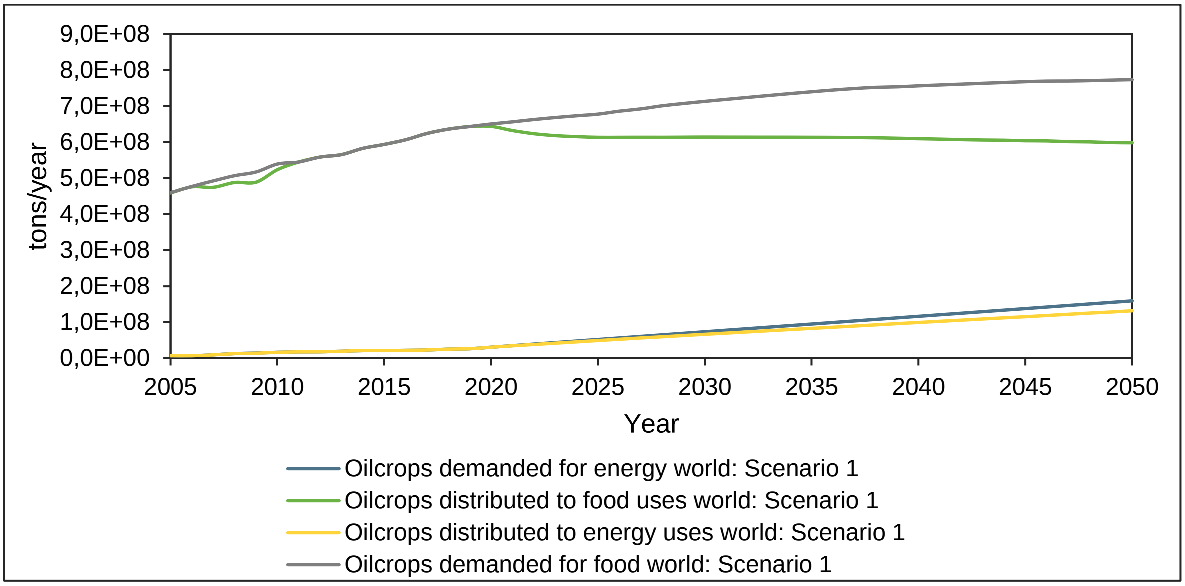

Figure 60: Oilcrops demanded and distributed for energy and food.

It is important to note that in the case of cereals other and oilcrops the competition between biofuels and food is evident. And this is because food crops are being abandoned despite their demand, as the demand for biofuels needs the use of certain land products. As the equal priority is given to the demand of all crops (allocating resources to the one with the highest scarcity, hence the one with higher demand), and the demand for biofuels is very high, they displace the crops demanded for food.

This competition is modelled in a simplified way, with equal priority given to all foods proportionally to their demand, the implementation of policies of food protection or the use of the relative elasticises of products for each use to change the priorities of allocation would change these results and move the shortage more towards energy uses. However, even though it is a first valid approximation to the problem, it provides guidance on the levels of competition that can exist when no specific use is prioritized, and distribution is solely based on relative demand. In fact, there is already a high competition between energy and food uses, which aligns with the experiences of recent years where land grabbing for biofuels has been blamed for worsening food security in certain regions of the world (Matondi et al., 2011).

4.7.1.3.2. RESULTS AND DISCUSSION OF SCENARIO 2:

This section presents and discusses the results of several variables based on the application of the hypothesis in Scenario 2.

As shown in Figure 61, a deficit of 7% has been found by calculating the global availability of crops. Nevertheless, these results indicate a significant improvement when compared to BASELINE 1 and Scenario 1, which had deficits of 15% and 25%, respectively. This improvement can be attributed to a 10% increase in cropland area relative to 2015 and a 30% increase in crop yields relative to 2019. Indeed, when examining Scenario 2 in contrast to BASELINE 2, it becomes evident that an expansion of cropland area with an increase in crop yields, and without a concurrent rise in biofuels demand, leads to a surplus of crop availability, as illustrated in Figure 61.

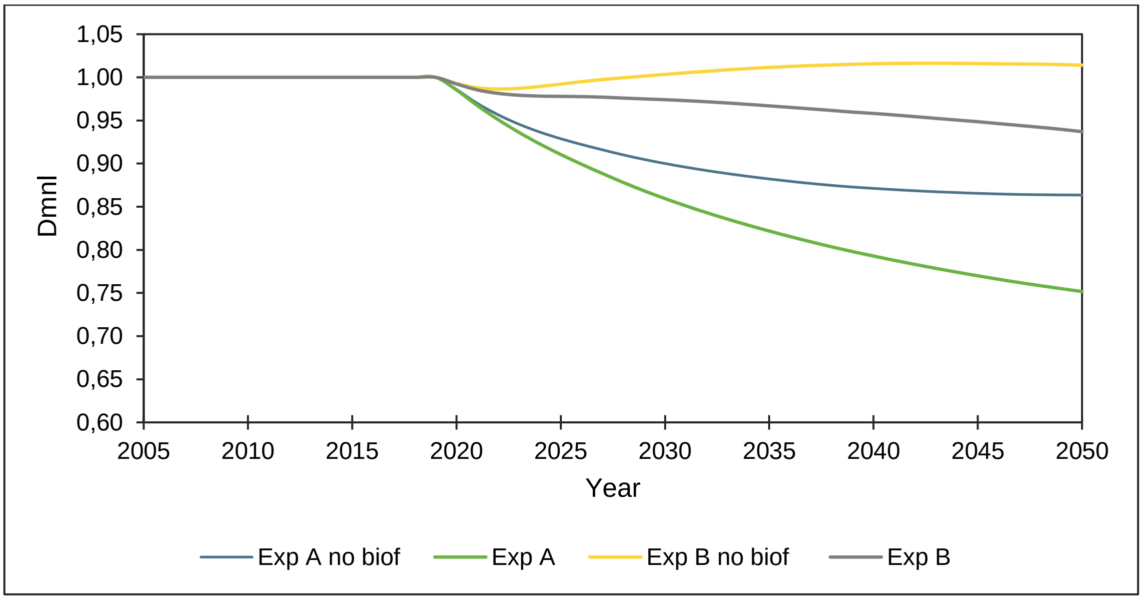

Figure 61: Global availability of crops [BASELINES 1 & 2 ; Scenarios 1 & 2]

Figure 62 represents the impact of implementing Scenario 2, illustrating the distribution and demand of corn worldwide. This figure clearly demonstrate that Scenario 2 successfully narrowed the gap between the demanded and distributed corn for both energy and food uses. By examining the data presented in Figure 58 (Scenario 1) and comparing it to the results shown in Figure 62, we can observe how Scenario 2 achieved commendable progress in addressing the corn allocation challenges.

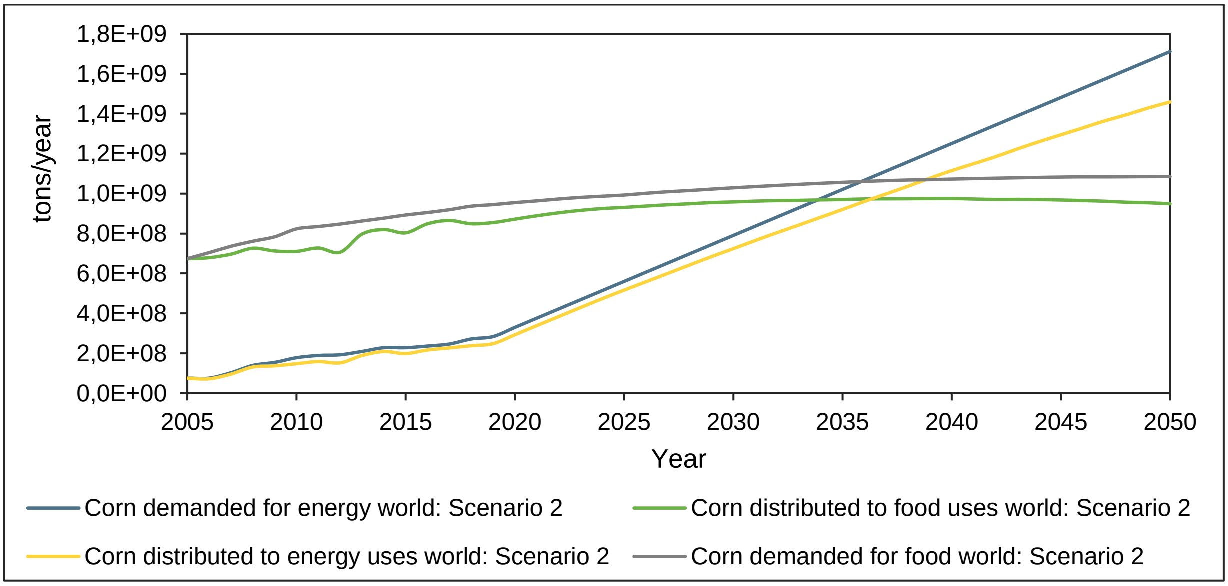

Figure 62: Corn demanded and distributed for energy and food [Scenario 2].

Regarding Cereals other and oilcrops (Figure 63 and Figure 64, respectively), the amount used for biofuels is significantly lower in proportion to its use as food, in contrast to corn. However, Cereals other and oilcrops cultivation faces displacement due to the cultivation of corn and other crops used for biofuel production.

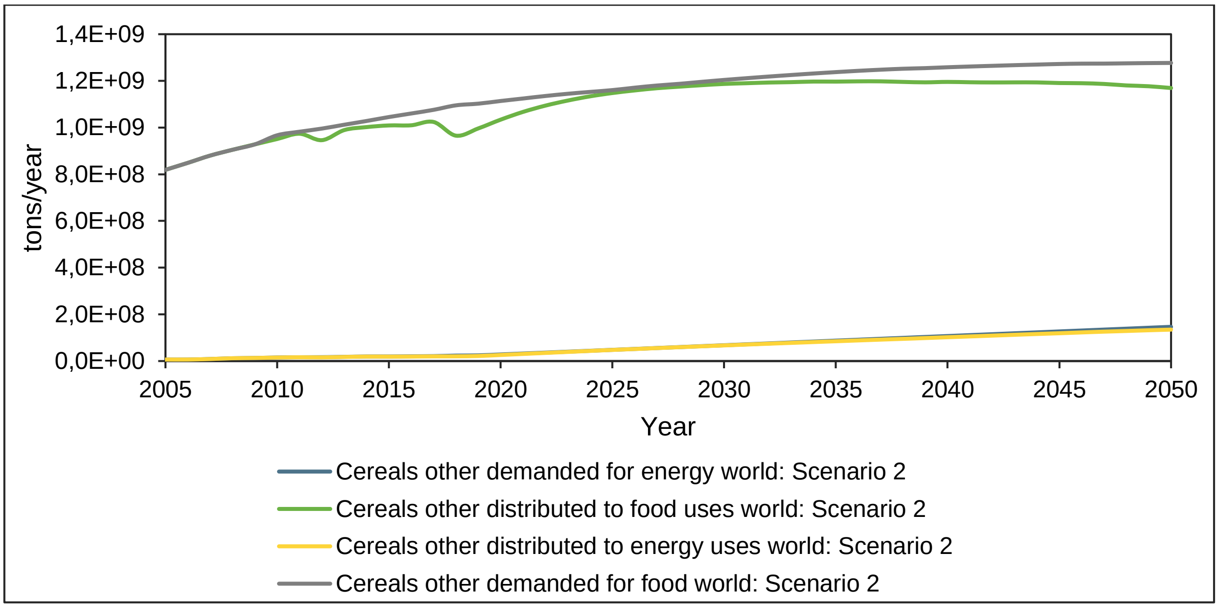

Figure 63: Cereals other demanded and distributed for energy and food [Scenario 2].

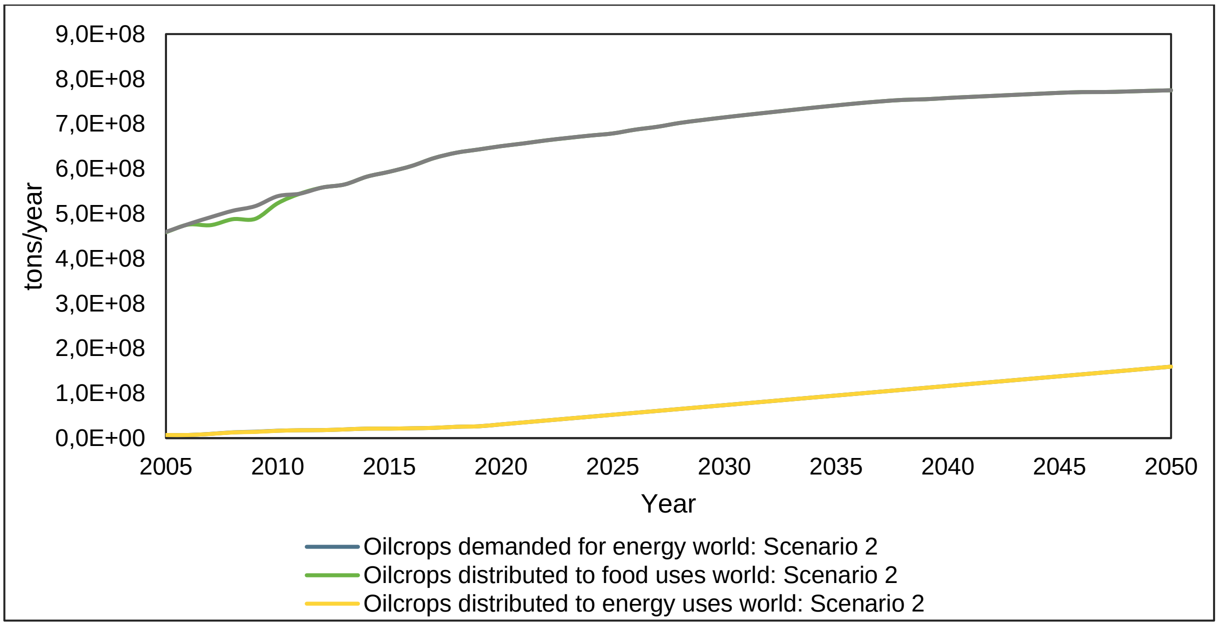

Figure 64: Oilcrops demanded and distributed for energy and food [Scenario 2].

The purpose of the scenarios studied in this work is to observe the basic dynamic trends of the current land-competition problem. Although they serve as a reference rather than a clear result, they already show us a clear effect of the strong competition between biofuels demand for energy and food demand in the case of no increase in cropland area and yield, and in case of slight increase of cropland area (10%) and yield (30%).

A more detailed discussion of the food-energy-land competition problem should address the possibility of changing diets, redistributing resources among regions in a different way, using land more efficiently, setting realistic yield limits, and considering the effect of fossil-fuel availability (specifically oil), among other factors. Those functions, beyond the scope of the present deliverable, can in principle be tested in this Land model of Land and Water Module.

4.7.2. WATER SUBMODULE

- Water availability:

The water availability is the amount of water for irrigation or consumption by humans and strongly depends on the precipitation and evapotranspiration. Water availability was projected for the future using the baseline scenario and it is expected to will decrease in the almost all LOCOMOTION regions (Figure 65). However, the exception is in India, mainly due the possible increase of evapotranspiration across the world and decrease or not sufficient increase of precipitation, depending on the region. The decrease of water availability can be more visible in LATAM (decrease of 10% in 2050) and EU27 (decrease of 8%) and near stable in China (-0.5%). Nevertheless, it is anticipated a decrease of water availability, that can reach 10% in 2050.

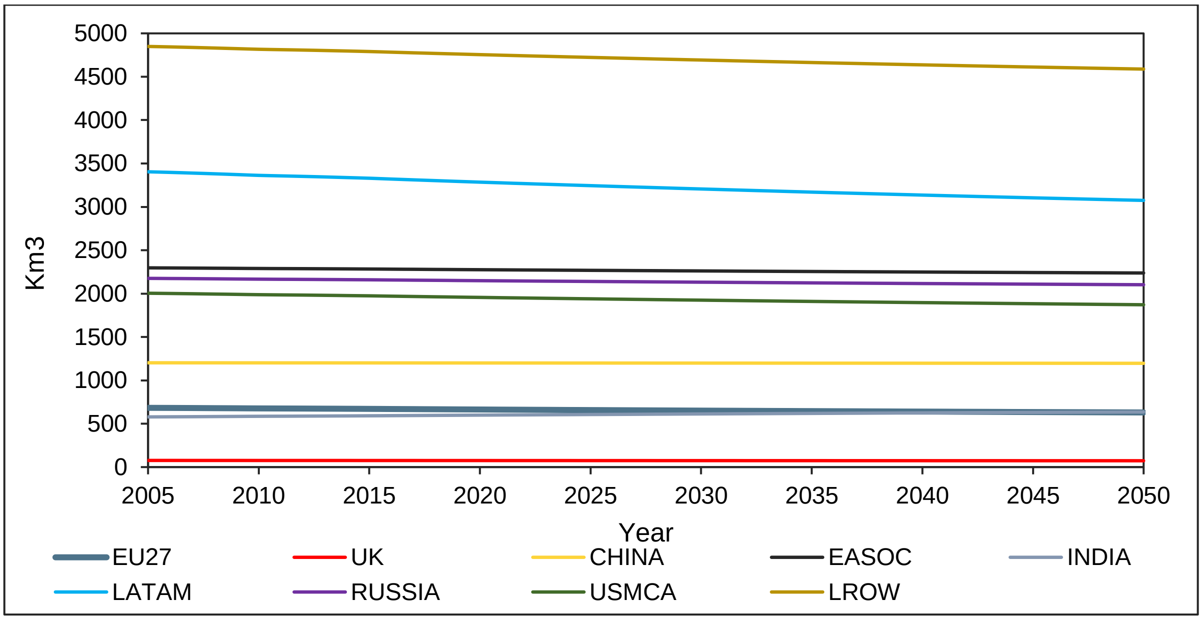

Figure 65: Water availability by region.

- Water stress:

The water stress s relates the water demand to the water availability, with high values meaning that water demand is reaching the water availability amounts and, consequently, it is possible water scarcity and poor water quality. Water stress was projected for the future using the baseline scenario and it is expected to increase in most of the regions (Figure 66), except for India, where is projected to decrease 9% until ~40% by 2050. However, it is important to note that India has the highest water stress values, mainly due to relatively high blue water demand in the agricultural sectors. UK has also high values of water stress because the water availability is computed using only blue water values, that accounts water used from lakes, rivers, and reservoir, including water used for irrigation. However, agriculture in the UK almost does not need irrigation. In the other regions, the water stress can increase due a combination of less water availability (caused by a possible decrease in P/E) and increase in blue water demand, ranging from an increase of 6% in China and an almost stable projection (0.003%) for Russia, in 2050.

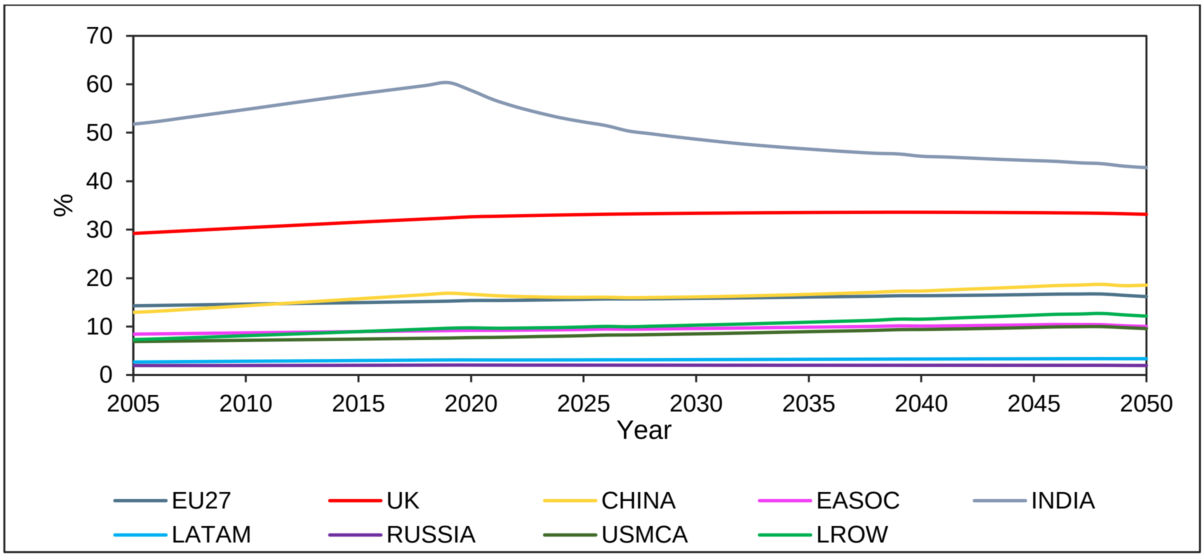

Figure 66: Water stress by region

4.8. CLIMATE

The Climate module depicts the main climate outputs of the simulations of WILIAM. It can be considered a module that allows to check the current trends and future climate change impacts derived from it (in the Business as Usual, BAU, scenario), and/or the effectiveness of the climate policies applied regarding mitigation or adaptation in case of "Policy-action" scenarios. The main outputs of interest are the following:

- Total GHG emissions (including those from energy use, agriculture and LULUCF activities).
- Concentration of each of the GHG in the atmosphere, taking into account the special relevance of the concentration of CO2 (in ppm) in the atmosphere as a key indicator of climate change due to its evolution in the last decades. This indicator represents the atmospheric accumulation of this emissions from natural and human sources.
- Global mean surface temperature change (°C).
- Ocean acidification (global average pH of the ocean)
- Global average sea level rise (m).
- Regional temperature change (by WILIAM regions).

For this Deliverable we present some preliminary results of the version 1.1 of WILIAM model. This version is stable and capable to represent the BAU scenario: baseline scenario for main socio-economic drivers: population, GDPpc, etc. For this reason, the results focus on the BAU scenario, taking advantage to present the comparison with historical data for checking the calibration with past information.

➢ **Total GHGs emissions:**

In this section, the preliminary results of the main three gases emissions that are calculated endogenously in WILIAM model are presented. Figure 67, Figure 68, and Figure 69 represent the global CO2, CH4, and N2O emissions evolution in the baseline scenario, respectively.

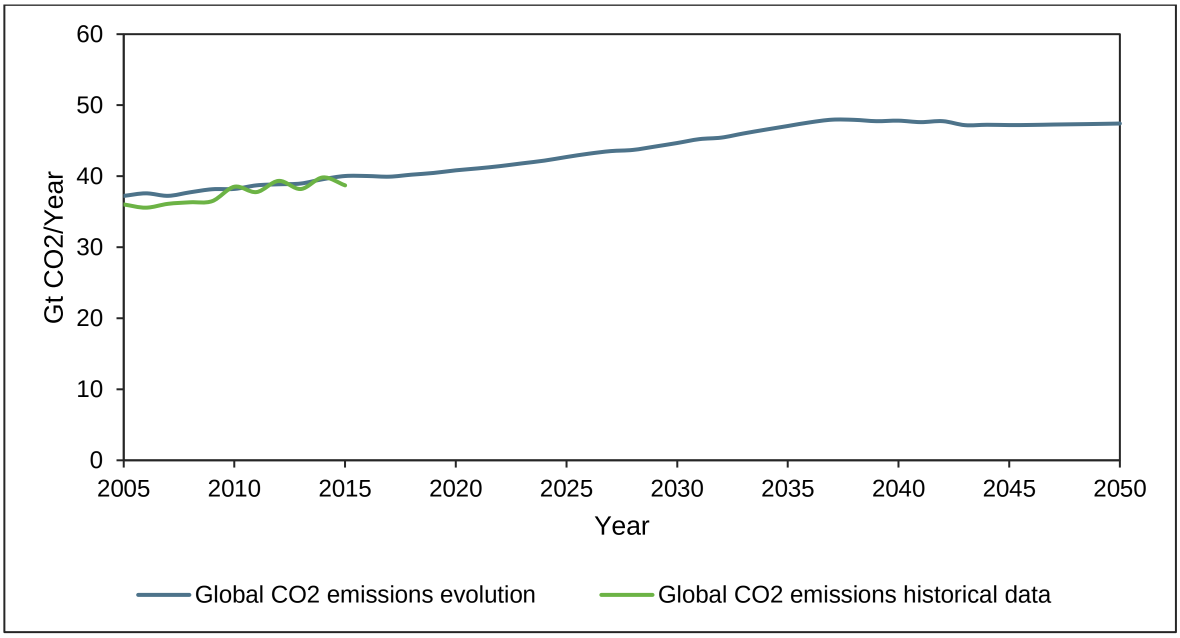

Figure 67: Global CO_2 emissions evolution in the Baseline scenario.

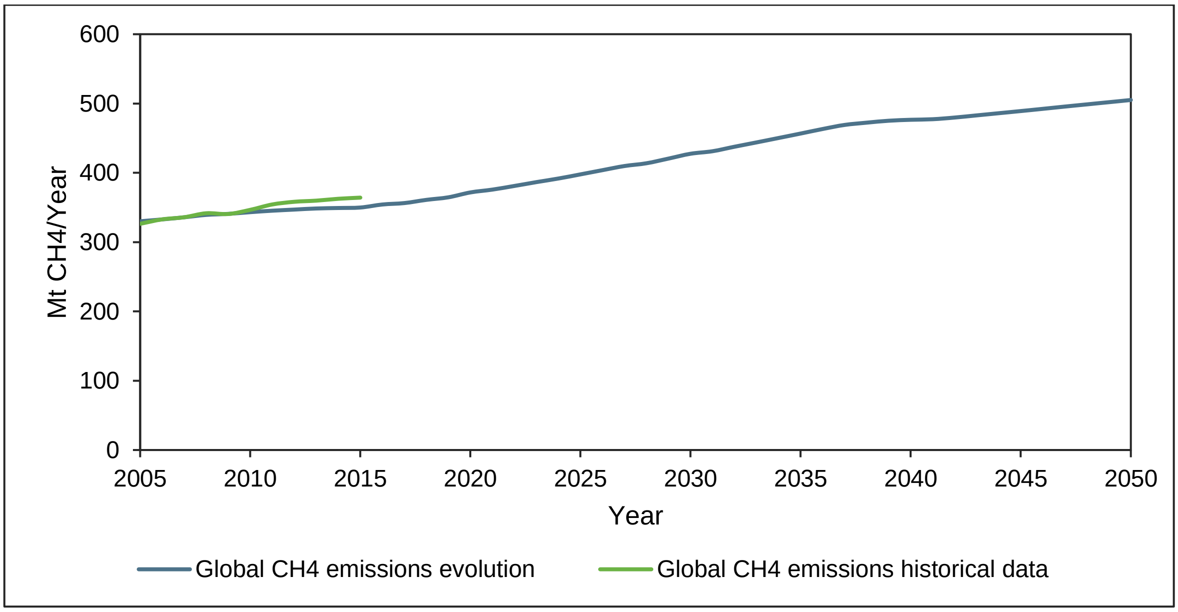

Figure 68: Global CH_4 emissions evolution in the Baseline scenario

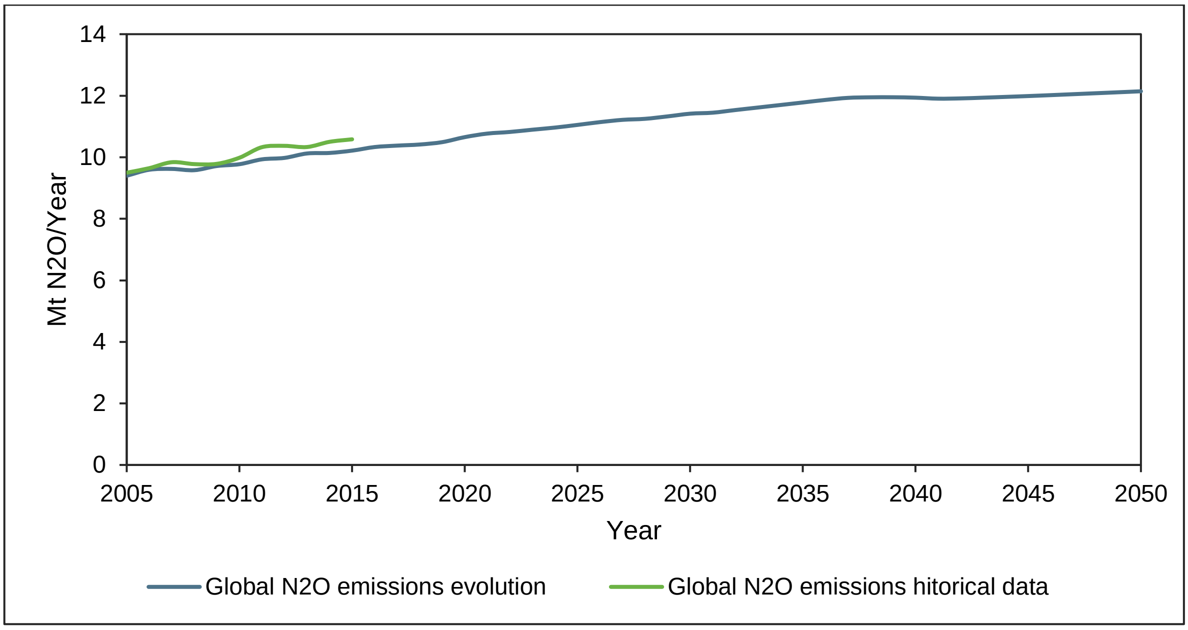

Figure 69: Global N2O emissions evolution in the Baseline scenario.

In the case of CO_2 emissions, in a basic scenario, they continue to increase steadily until around 2040. After that, the amount of CO_2 emissions remains constants. In the case of methane and nitrous oxide emissions the same happens.

- **CO_2 CONCENTRATION**

In the case of CO_2 concentration (Figure 70), the evolution is also growing as in the case of CO_2 emissions. Due to the complex dynamics and time lags that the carbon cycle has the effect of the evolution at the last years (more constant in the case of emissions), it is not appreciable in the concentration and the last one keep growing to the inertia.

In addition, for validation purposes, the value of the historic CO_2 concentration (until 2022) is compared with historic observations from NOAA Mauna Loa. It is possible to check that the model is able to represent historic values of CO_2 concentration.

It is important to note that in this BAU scenario where past trends are continuing in the future without additional climate policies, the 400 pm were surpassed in 2015 which was considered a "climate milestone". However, this concentration keeps growing in the baseline scenario of WILIAM, which shows that the 450 ppm will be reached before 2050. 450 ppm is another important value for which scientists estimate that 2ºC will occur taking into account the accumulation of GHGs and the time necessary to see the effect in terms of temperature in the following years. Finally, we can see that in 2050 the value will surpass 500 ppm of concentration, which put us in even a more negative scenarios, where we could even reach temperature of more than 3 degrees. This probes the urgent need for real action, and urgent additional climate policies, as past trends, or climate-mitigation efforts and not enough.

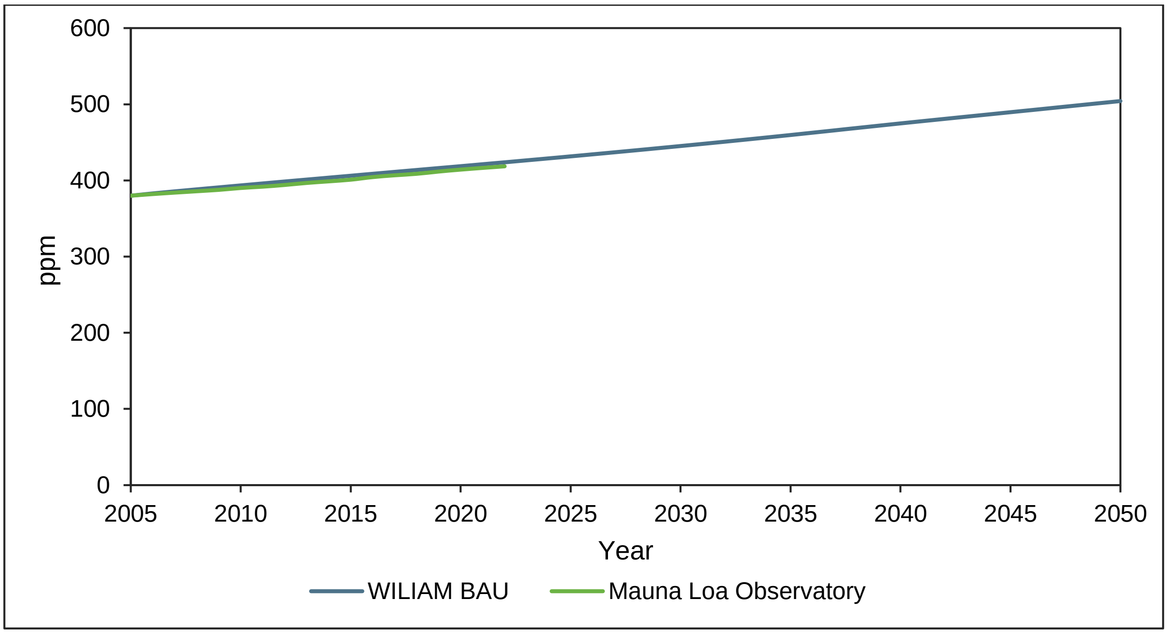

Figure 70: Global CO2 concentration in the baseline scenario.

- **GLOBAL TEMPERATURE CHANGE**

In the case of global temperature change the evolution is also keeping a growing trend in the BAU scenario as shown in Figure 71. In particular, in relation to the Paris Agreement Climate goals for 2050 the temperature nearly reach the limit of 2ºC of temperature change, and in 2033 the limit of 1,5 degrees is also surpassed.

The data is compared with historic observations (year 2022) (adjusted to preindustrial reference as WILIAM output) from:

- NASA (GISS Surface Temperature Analysis (GISTEMP v4)). [2]
- HadCRUT5 Data (Met Office Hadley Centre observations datasets). [3]

[2] GISS Surface Temperature Analysis (GISTEMP v4) https://data.giss.nasa.gov/gistemp/
[3] Met Office Hadley Centre observations datasets https://www.metoffice.gov.uk/hadobs/hadcrut5/

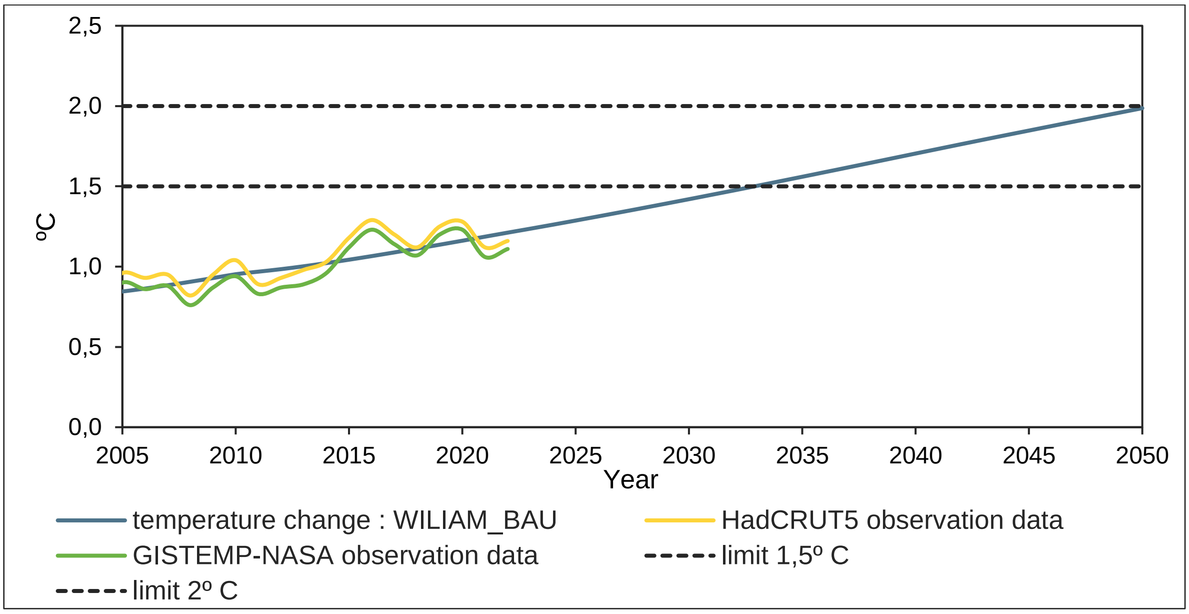

Figure 71: Global mean temperature change (land and ocean) in the baseline scenario.

- **PROBABILITY OF AMOC'S WEAKENING**

The probability of the Atlantic Meridional Overturning Circulation (AMOC) weakening (Figure 72) is a tipping point that can impact the northern hemisphere climate. This tipping point depends on the global temperature and modelled for the baseline scenario, increases steeply as the global temperature continues to increase. Consequently, it is expected that the probability of the AMOC's weakening, that can cause impacts in the climate, will be 18% in 2050, a value based on (Castellana et al., 2019; Liu et al., 2023).

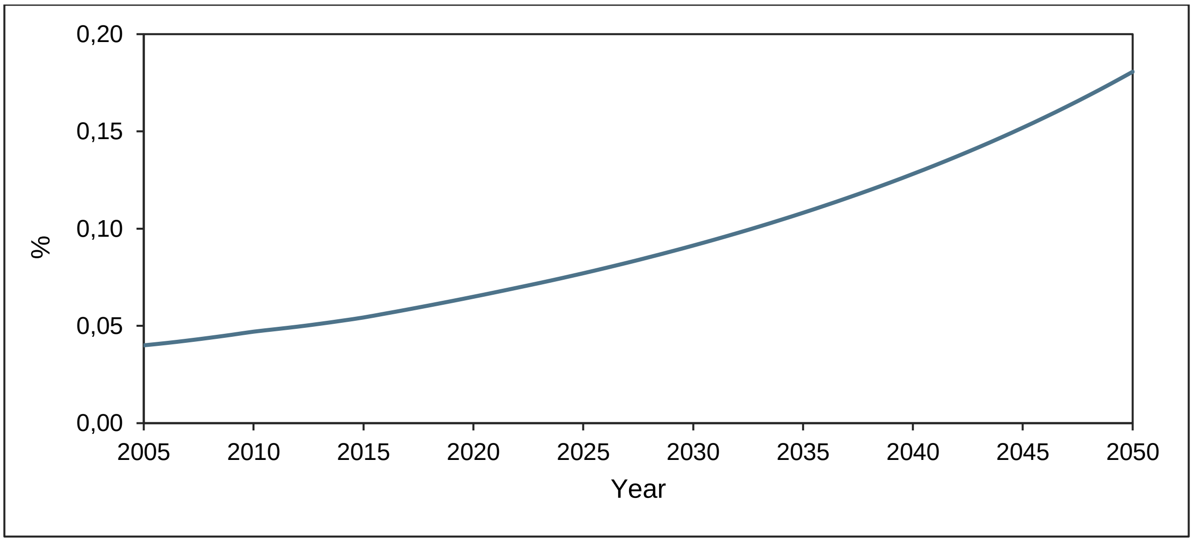

Figure 72: Probability of AMOC's weakening (%).

- **OCEAN ACIDIFICATION**

In the case of the global average pH in the ocean (Figure 73), which is a direct climate impact modelled in WILIAM climate module, it is possible to see how it decreases (more acid) which has impacts on the organisms living in the ocean system, as coral reefs, and other marine ecosystems.

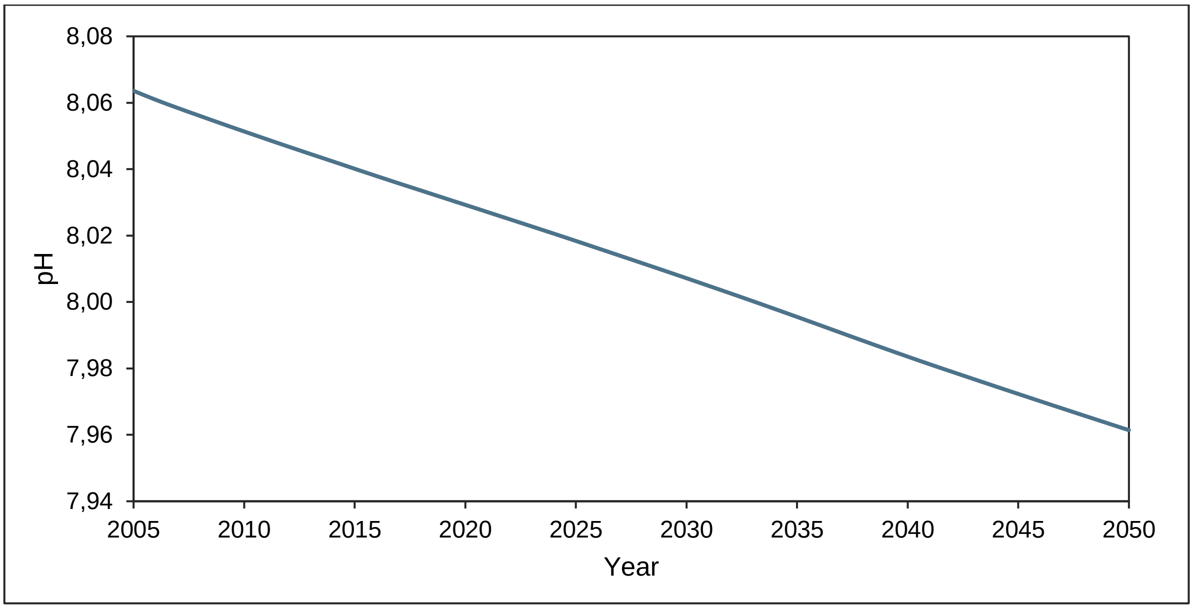

Figure 73: pH ocean evolution in the baseline scenario.

- **SEA LEVEL RISE**

In the case of sea level rise (Figure 74), another direct impact from temperature increase, also can be seen how it grows continuously. The sea level rise value is with respect to the year 2000 (as in C-ROADS). This can have important indirect effect on land use, as part of the area could be flooded.

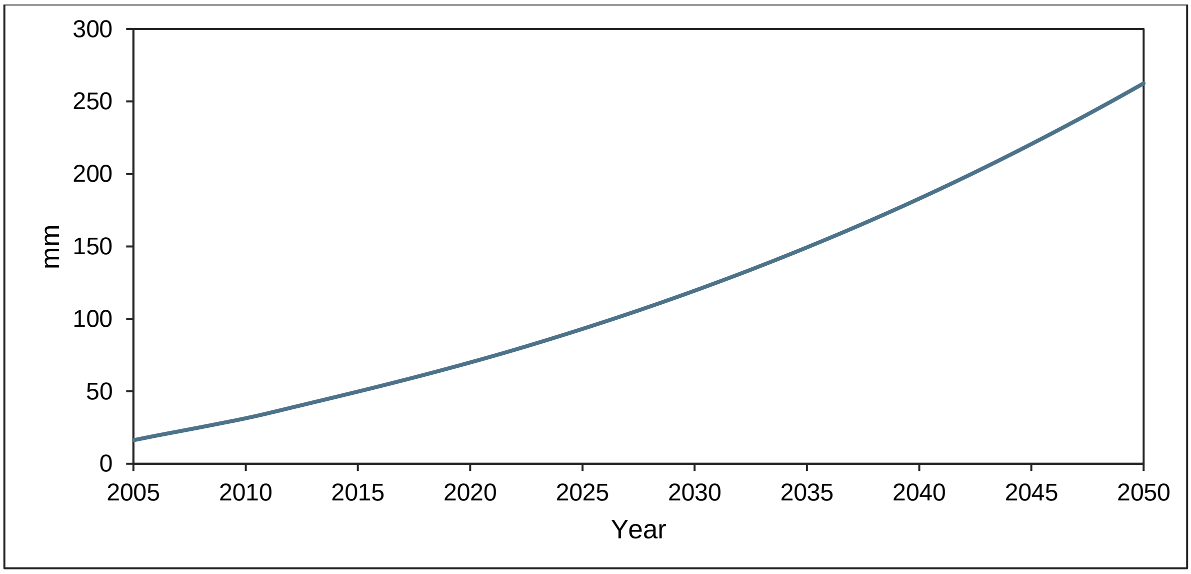

Figure 74: Global Sea Level Rise in the baseline scenario.

- **DISTRIBUTION OF TEMPERATURE CHANGE AMONG REGIONS**

Finally, in this last result it is possible to see in Figure 75 the distribution of global temperature change among WILIAM regions.

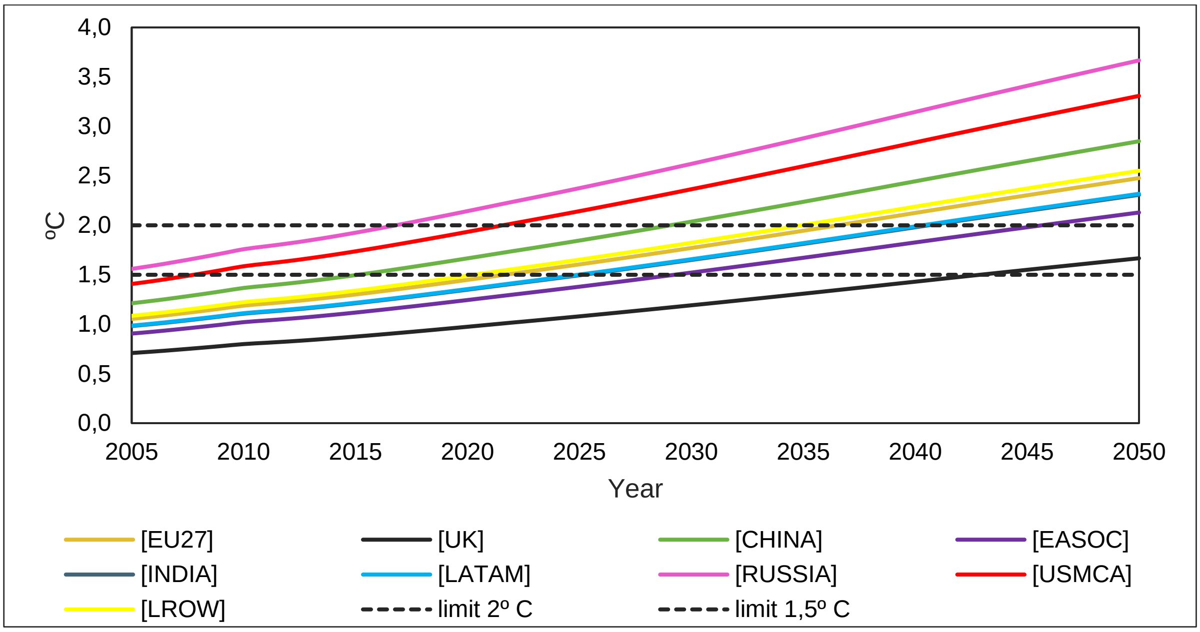

Figure 75: Temperature change in the 9 WILIAM regions in the baseline scenario.

The differences regarding the higher average value of temperature change (most of them are above 2ºC in 2050) with respect to the global value which reaches 1,99 in 2050 is due to the fact that total global mean temperature is the average between land and ocean, while in the case of WILIAM regions the temperature calculation is focused in "land". This shows the contrasts between land and ocean when responding to temperature change. This is because land warm up faster than the ocean due to difference system dynamics.[4]

The region that increases most its average temperature in Russia (3,67 in 2050), followed by USMCA. In contract, UK is the only region that does not reach the 2ºC limit before 2050 (1,67 ºC).

[4] https://www.carbonbrief.org/guest-post-why-does-land-warm-up-faster-than-the-oceans/

5. ASSESSMENT OF CRITICAL FEATURES MISSING FROM WILIAM MODEL

The WILIAM model v1.1 is in a very advanced stage of development, and it is hence possible to obtain partial results of some dimensions, features and interlinks which are reliable and informative (cf. D8.4 for the most relevant cases identified for developing Policy Recommendations). But there are still some critical features not fully developed or validated which prevent us from using the whole model to explore long-term decarbonisation pathways within planetary boundaries since without them, implausible results are obtained. In this section, we aim at describing which are the most critical features missing from the v1.1 of the WILIAM model, also taking into consideration the GA. These critical features are structured in 2 types: (1) missing features within each module, and (2) missing inter-module links. The importance of each critical feature identified is briefly described, as well as the status with relation to its implementation. Hence, minor improvements or corrections are not listed here for the sake of synthesis of the most important elements. Still, there is a certain degree of subjectivity for some features between “critical features” and “nice-things-to-have”. The relative importance of the identified features will be assessed complementing literature review with the first steps of implementation to prioritize the most relevant features.

5.1. MISSING CRITICAL FEATURES BY MODULE

A list of critical missing features by module has been created (including justification on why is so relevant for the model to be workable), together with an assessment of its current status.

5.1.1. DEMOGRAPHY

Table 4: Critical missing features in Demography module.

Critical missing feature. Justification	Status
1. Endogenizing life expectancy at birth. Currently, life expectancy at birth is a driver of mortality rates, calculated throughout exponential relationships. However, without a complete integration of life tables mortality is misrepresented (e.g., life expectancy at birth should be an output).	A literature review about the demographic approaches for world models has been done without clear solutions. It is needed to consider again the data available and test methods to select the best option.
2. Migration flows. The shares of migration flows are constant assumptions over time.	There are few literature proposing methods to estimate migration flows and the disaggregation of this phenomena into different factors seems to be complex due to social and material reasons.
3. Endogenize fertility. Fertility is one of the main determinants of population growth.	A literature review is pending to select the dependent terms of fertility.
4. Endogenous household types of evolution. For those countries where 60 household types are modelled, the current approach assumes exogenous parameters of linear relationships with evolutions independent among households’ categories.	A state-space approach has been tested but data seems to be not enough to validate the method.

5.1.2. SOCIETY

Table 5: Critical missing features in Society module.

Critical missing feature. Justification	Status
1. Health. The concept of health has not been developed in the project, including a healthcare system and feedback to demographic variables.	Specific literature has been identified to start a module of the healthcare system.
2. Education. The approach present in WILIAM has not been validated in the historical period and it just contain an economic driver, i.e., the public expenditure on education. Private expenditures should also be considered.	A literature review to expand the module is pending.
3. Governance and Social Movements. There is no module about social and political movements. The role of disruptive and synergic efforts to modify the rules of a society is not represented neither the dynamic of policy implementations nor government expenditures.	A literature review to expand the module is pending.

5.1.3. ECONOMY

Table 6: Critical missing features in Economy module.

Critical missing feature. Justification	Status
1. Lack of robustness. The version 1.1 of the module does not pass the robustness test of insensitivity to TIME STEP. Issues with delays.	Ongoing work
2. Wage curves and unemployment. Improve relationships between wage curves and labour productivity to avoid situations of negative unemployment.	Ongoing work
3. Comprehensive definition of policies and hypotheses as entry points to the module to perform scenarios. It is currently difficult to parametrize a scenario of the economy module, requiring pre-treatment of inputs requiring high expert-knowledge. It is critical for the usability of the model to improve this.	Ongoing work
4. Labour productivity. Better integration of Labour productivity within the modelling.	Ongoing work
5. Improvements in investment modelling. Link GFCF with government investment, and introduce capital constraints to production	Very advanced work, still not validated.

5.1.4. FINANCE

Table 7: Critical missing features in Finance module.

Critical missing feature. Justification	Status
1. Add financial accounts of firms. Difficulties in making the financial accounts compatible with the input-output table have prevented the addition of the financial accounts of firms.	Ongoing work.
2. Complete the stock-flow consistent structure. To complete the stock-flow consistent structure it is necessary to add the financial accounts of the companies. At the moment only the financial accounts of households (divided into different types of households) and the financial accounts of governments are in the model.	Ongoing work.

5.1.5. ENERGY

Table 8: Critical missing features in Energy module.

Critical missing feature. Justification	Status
1. No possibility to apply energy policies in households. Household's buildings represent very high shares of energy demand. Without policies in this sector, it is not possible to design meaningful mitigation scenarios for a full economy.	Ongoing work.
3. Robust energy variability implementation. Renewables with more potential (solar & wind) are not dispatchable sources of energy and introduce variability which needs to be dealt so they can reach high shares of demand in the system.	The current version represents a first approximation with several methodological drawbacks which makes it not totally reliable. Currently working on new results to address identified shortcomings.
4. Dupont method (Dupont et al., 2018) **substantially overestimates wind potential** since it considers that all the wind in the atmospheric boundary layer (ABL) could be captured by windmills (de Castro et al., 2011).	Ongoing recalculations.
5. EROI feedback is missing. This is issue is the same than the lack of feedback from energy investments into GFCF into the economy investment module. If the EROI of the system changes, then amount of gross energy required to satisfy the same level of net energy must increase. In scenarios of fast transition to RES this is very relevant feedback (Capellán-Pérez et al., 2019b).	MEDEAS approach (Capellán-Pérez et al., 2019b) could be replicated.
6. Avoid discontinuities, unrealistic strong leaps when changing the allocation priorities for capacity expansion in 2020.	Under discussion.

5.1.6. MATERIALS

Table 9: Critical missing features in Materials module.

Critical missing feature. Justification	Status
1. Decoupling of Gas and Oil price. In the current model version, the price of oil is tightly linked to the natural gas price, due to co extraction, overlap of infrastructure and substitution in consumption. This reality is likely to change in future due to different policies and regulation for different fossil fuel types, geopolitics, emerging electrical transportation, differing applications. Changes in the model are needed to calculate the gas price independently from the oil price.	Ongoing work
2. Set recycling policies. Implementation of the recycling policies in the metal modules for Fe, Al, Ni and Cu. Give the user the possibility to set EOL- Recycling targets. Further optimize the recycling modelled in the Fe and Ni model.	Ongoing work
3. No variation of energy requirements and price. When declining ore grade for fossil fuels the energy requirements should rise, beside the rising energy requirements also the price to extract these resources is expected rise with lower qualities available. Not represented in the moment.	Ongoing work
4. No link between WORLD7 and MEDEAS bottom-up approach. In the moment four metals and the 3 fossil fuels are coupled to the economy module, while also a wide range of other metals are available and modelled with the MEDEAS bottom-up approach. Optimally there is a way to connect both approaches and find a way to integrate the MEDEAS bottom-up approach with the economy module and the WORLD7 modules.	Under discussion
5. Linking energy intensity for materials extraction to the energy intensities. the energy intensities for mining or extracting materials will rise due to lower and lower ore qualities being extracted. Currently the energy intensity development is calculated in the materials model, but the feedback needs to be closed.	Ongoing work

5.1.7. LAND AND WATER

Table 10: Critical missing features in Land and Water module.

Critical missing feature. Justification	Status
1. Adjustment of some limits. Limits of land use changes, maximum limits (forest expansion, cropland, etc.), average values of policies (afforestation, biodiversity protection, etc.), maximum yield potential of industrial agriculture, and extraction limits for forests.	On progress.
2. Feedback about land products shortage into available diet. Incorporation of this feedback by considering specific factors for each food item and aligning with the Agrofood matrix.	Ongoing work.
3. Links between land and water. Implementation of changes in irrigated land due to water availability by region and link the water stress and irrigated cropland.	Right now, the module is prepared to work without separating irrigated and rainfed crops.
4. Livestock management and reduction of food waste policies.	Not yet implemented.
5. Carbon capture of regenerative techniques. Particularly within grasslands and croplands.	Ongoing calculation.
6. Climate change impacts on Land. Implementation of changes of non-productive land uses due to climate change.	Right now, the changes are constants.

5.1.8. CLIMATE

Table 11: Critical missing features in Climate module.

Critical missing feature. Justification	Status
1. Climate change impacts on forests.	Ongoing calculations
2. Climate change impacts on crop yields.	Ongoing calculations

5.2. MISSING CRITICAL INTER-MODULE LINKS

5.2.1. ENERGY-ECONOMY

Currently, there is no direct link from energy to economy. The only link is indirect through the prices of fossil fuels (oil, gas and coal) in the materials module. But these links are also not fully validated, see below.

Table 12: Critical missing links between Energy and Economy modules.

Critical missing links. Justification	Status
1. A matrix evolution depending on energy transformation. Without this link, the economic structure does not reflect change in the structure of the generation of energy.	Concept and equations defined. Adaptations made in economy module (e.g., creation of a specific sector for HYDROGEN SUPPLY). Issues with 9-35 regions. Agreement reached to start testing with the REGIONS_8_I vector (to avoid the issue with EU aggregated/disaggregated).
2. Endogenize GFCF of the energy sectors with the investments from the energy module.	Concept defined and equations set. Issues with 9-35 regions and with the compatibility of the

Without this link, the investments in the economy module are independent from the investments for the energy transition, which is a wrong assumption given the state-of-the-art.	modelling of climate change impacts on capacity stock in the economy module.
3. A matrix evolution depending on energy intensities Without this there would be an inconsistency between monetary and physical flows.	Under discussion.

5.2.2. ECONOMY-FINANCE-ENERGY

Table 13: Critical missing links between Economy, Finance, and Energy modules.

Critical missing links. Justification	Status
1. Limit purchase of private vehicles with household disposable income. Without this link, households can buy new vehicles without any link to their real budget.	Concept defined, entry point in the bottom-up passenger module defined. Ongoing work.

5.2.3. MATERIALS-ECONOMY-ENERGY

Table 14: Critical missing links between Materials, Economy, and Energy modules.

Critical missing links. Justification	Status
1. Material price feedbacks. materials price feedbacks for Gas, Coal , Al, Fe, Cu and Ni need to be validated and checked. Implementation of filters for the price reaction are necessary if scarcity accurse to the exponential shape of the function, scarcity can lead to an overreaction of the price signal.	Ongoing work
2. Validation of the primary energy demand. The primary energy demand for naturals gas needs to be calibrated and validated to match the historical data	Ongoing work
3. Oil-demand calibration. The problem with oil-demand being not correct anymore after the changes in economy and transport model. New calibration is needed.	Ongoing work

5.2.4. LAND AND WATER-ENERGY-ECONOMY

Table 15: Critical missing links between Land and Water, Energy and Economy modules.

Critical missing links. Justification	Status
1. The shift towards regenerative agriculture. This could lead to a reduction in fertilizer demand and an increase in labour demand.	Not yet implemented in WILIAM
2. The effect of peak oil in agriculture.	Discussion to integrate through oil and gas prices. Not yet implemented in WILIAM

5.2.5. SOCIETY-LAND AND WATER

Table 16: Critical missing links between Society and Land and Water modules

Critical missing links. Justification	Status
1. Diets and nutrition. A relevant dimension of health is diets and nutrition, which have been implemented in WILIAM but without feedback to society and economic (e.g., productivity) variables.	Ongoing calculations
2. Water quality affecting society variables.	Not yet implemented in WILIAM

5.2.6. SOCIETY-ECONOMY

Table 17: Critical missing links between Society and Economy modules.

Critical missing links. Justification	Status
1. Link between health and labour productivity.	Not yet implemented in WILIAM

5.2.7. DEMOGRAPHY-ECONOMY

Table 18: Critical missing links between Demography and Economy modules.

Critical missing links. Justification	Status
1. Economic conditions in households affecting demographic variables.	Not yet implemented in WILIAM

5.2.8. TRANSVERSAL TOPICS

Table 19: Critical missing of certain transversal topics.

Critical missing links. Justification	Status
1. Introduce CO2 prices consistently across modules. CO2 price is a conventional policy of the Green Growth and Green Deal, and it is necessary to perform modifications in economy and energy modules to comprehensively implement its potential impacts (energy intensities, bottom-up transport, energy transformation, etc).	Partially implemented in WILIAM. Ongoing work
2. Deal with different regionalization in different modules. Some modules are split at 9 and other at 35 regions. The different lies into the disaggregation or not of the 27 EU Member States. This creates issues during interlinkages.	Under discussion.

CONCLUSIONS

This deliverable reports the work of WILIAM model development accomplished within WP9 during LOCOMOTION project.

The WILIAM model has been developed in a collaborative distributed (Gitlab) and sequential way, from modules to full model, and from simpler to more complex structures. It is structured in eight modules (Demography, Society, Economy, Finance, Energy, Materials, Land and Water and Climate), to allow for flexibly testing, validating, improving, and expanding each module without impairing the robustness of the model as a whole. The joint development of an IAM simulation model between various research groups requires a significant effort in technical coordination. The adoption of common rules and procedures for modelling and programming are essential for the effectiveness of work. During the process of developing the model, the Python version and user interfaces (including Explorer, Analyzer, and Simplified Analyzer applications) for the WILIAM model have also been developed and created.

Due to the difficulties to achieve all the challenges and ambitions initially proposed in the project in the planned time, the European Commission requested to limit the expectations and scope that the WILIAM model to a level that can be realistically achieve by the end of this project. That's why, at the time of writing this deliverable, WILIAM is not a fully functional model yet. Hence, these deliverable reports preliminary results from the most updated version of WILIAM (v1.1) including those validated functionalities. The preliminary results show here show that all modules are in a very advanced stage of development, some of them even are considered to be finalized. Many inter-module links are already operational. As a result, it is possible to obtain partial results of some dimensions and features which are reliable and informative (cf. D8.4 for further details). However, the fact that some central modules are still not fully validated, and some key interlinks are missing prevents from using the whole model for obtaining sensitive results and robust policy recommendations.

This deliverable serves to exemplify the importance (1) of designing scenarios with policies to comprehensively cover all relevant dimensions and (2) of using integrated modelling tools, such as WILIAM, that are able to capture such complex feedbacks, in order to not arrive at wrong conclusions. The tested scenarios show how a selective implementation of policies leads to rebound effects and perverse dynamics given the interconnections between the different economic sectors and countries.

An assessment of the critical features missing, including its status, is also reported in order to guide model development until the end of the project. And a further work will be directed to solve pending issues (cf. section 5) and develop scenarios in coordination with the rest of modules of WILIAM.

REFERENCES

Abramo, L., Cecchini, S., & Morales, B. (2019). *Programas Sociales, Superación de la Pobreza e Inclusión Laboral: Aprendizajes desde América Latina y el Caribe* (Book of CEPAL).

Banerjee, A. V, Hanna, R., Kreindler, G. E., & Olken, B. A. (2017). Debunking the Stereotype of the Lazy Welfare Recipient: Evidence from Cash Transfer Programs. *The World Bank Research Observer*, *32*(2), 155–184. https://doi.org/10.1093/wbro/lkx002

Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics. *System Dynamics Review*, *12*(3), 183–210. https://doi.org/https://doi.org/10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Capellán-Pérez, I., de Blas, I., Nieto, J., de Castro, C., Miguel, L. J., Carpintero, Ó., Mediavilla, M., Lobejón, L. F., Ferreras-Alonso, N., Rodrigo, P., Frechoso, F., & Álvarez-Antelo, D. (2020). MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints. *Energy & Environmental Science*, *13*(3), 986–1017. https://doi.org/10.1039/C9EE02627D

Capellán-Pérez, I., de Castro, C., & Miguel González, L. J. (2019a). Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies. *Energy Strategy Reviews*, *26*, 100399. https://doi.org/https://doi.org/10.1016/j.esr.2019.100399

Capellán-Pérez, I., de Castro, C., & Miguel González, L. J. (2019b). Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies. *Energy Strategy Reviews*, *26*, 100399. https://doi.org/https://doi.org/10.1016/j.esr.2019.100399

Castellana, D., Baars, S., Wubs, F. W., & Dijkstra, H. A. (2019). Transition Probabilities of Noise-induced Transitions of the Atlantic Ocean Circulation. *Scientific Reports*, *9*(1), 20284. https://doi.org/10.1038/s41598-019-56435-6

Cesarini, D., Lindqvist, E., Notowidigdo, M. J., & Östling, R. (2017). The Effect of Wealth on Individual and Household Labor Supply: Evidence from Swedish Lotteries. *American Economic Review*, *107*(12), 3917–3946. https://doi.org/10.1257/aer.20151589

Cieplinski, A., D'Alessandro, S., & Guarnieri, P. (2021). Environmental impacts of productivity-led working time reduction. *Ecological Economics*, *179*, 106822. https://doi.org/https://doi.org/10.1016/j.ecolecon.2020.106822

de Blas Sanz, I., Capellán-Pérez, I., Álvarez Antelo, D., Miguel, L. J., Crespo, Y., Campos, J., Bartolomé, L., Samsó, R., Martín, E., Neumann, M., Markovska, N., Duic, N., Arto, I., Kratena, K., Tomás, M., Rueda, M., Llases, L., Parrado, G., Cieplinski, A., … Sverdrup, H. (2022a). *Deliverable 9.2: Interim synthesis of the model, selected results and scenario analysis*.

de Blas Sanz, I., Capellán-Pérez, I., Álvarez Antelo, D., Miguel, L. J., Crespo, Y., Campos, J., Bartolomé, L., Samsó, R., Martín, E., Neumann, M., Markovska, N., Duic, N., Arto, I., Kratena, K., Tomás, M., Rueda, M., Llases, L., Parrado, G., Cieplinski, A., … Sverdrup, H. (2022b). *Deliverable 9.2: Interim synthesis of the model, selected results and scenario analysis*.

de Castro, C., Mediavilla, M., Miguel, L. J., & Frechoso, F. (2011). Global wind power potential: Physical and technological limits. *Energy Policy*, *39*(10), 6677–6682. https://doi.org/https://doi.org/10.1016/j.enpol.2011.06.027

de Hoop, J., & Rosati, F. C. (2014). Cash Transfers and Child Labor. *World Bank Research Observer*, *29*(2), 202–234. https://doi.org/10.1093/wbro/lku003

Dupont, E., Koppelaar, R., & Jeanmart, H. (2018). Global available wind energy with physical and energy return on investment constraints. *Applied Energy*, *209*, 322–338. https://doi.org/https://doi.org/10.1016/j.apenergy.2017.09.085

Hardt, L., & O'Neill, D. W. (2017). Ecological Macroeconomic Models: Assessing Current Developments. *Ecological Economics*, *134*, 198–211. https://doi.org/https://doi.org/10.1016/j.ecolecon.2016.12.027

Kangas, O., Jauhiainen, S., Simanainen, M., & Ylikännö, M. (2019). *The basic income experiment 2017–2018 in Finland : Preliminary results*.

Kassouf, A. L., & de Oliveira, P. (2012). Impact Evaluation of the Brazilian Non-Contributory Pension Program Benefício De Prestação Continuada (BPC) on Family Welfare. *Partnership for Economic Policy Working*.

Laherrère, J., & Hall, C. A. S. (2018). *Hubbert linearization: a "new" and explicit method to estimate petroleum reserves and its application to U.S*.

Laherrère, J., Hall, C. A. S., & Bentley, R. (2022). How much oil remains for the world to produce? Comparing assessment methods, and separating fact from fiction. *Current Research in Environmental Sustainability*, *4*, 100174. https://doi.org/https://doi.org/10.1016/j.crsust.2022.100174

Liu, W., Fedorov, A. V, Xie, S.-P., & Hu, S. (2023). Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Science Advances*, *6*(26), eaaz4876. https://doi.org/10.1126/sciadv.aaz4876

Marx, A., & Peeters, H. (2008). An unconditional basic income and labor supply: Results from a pilot study of lottery winners. *The Journal of Socio-Economics*, *37*(4), 1636–1659. https://doi.org/https://doi.org/10.1016/j.socec.2007.08.007

Matondi, P. B., Havnevik, K., Beyene, A. , Mutopo, P., Beyene, A., Haaland, H., Boamah, F., Widengård, M., & Skarstein, R. (2011). *Biofuels, Land Grabbing and Food Security in Africa*.

Mohr, S. H., Wang, J., Ellem, G., Ward, J., & Giurco, D. (2015). Projection of world fossil fuels by country. *Fuel*, *141*, 120–135. https://doi.org/https://doi.org/10.1016/j.fuel.2014.10.030

Painter, A. (2016). A universal basic income: the answer to poverty, insecurity, and health inequality? *BMJ*, *355*, i6473. https://doi.org/10.1136/bmj.i6473

Picchio, M., Suetens, S., & van Ours, J. C. (2018). Labour Supply Effects of Winning a Lottery. *The Economic Journal*, *128*(611), 1700–1729. https://doi.org/https://doi.org/10.1111/ecoj.12465

Piketty, T. (2014). *Capital in the 21st Century.* (Harvard University). Harvard University Press.

Piketty, T., Saez, E., & Zucman, G. (2013). *Rethinking capital and wealth taxation*.

Pulido-Sánchez, D., Capellán-Pérez, I., de Castro, C., & Frechoso, F. (2022). Material and energy requirements of transport electrification. *Energy & Environmental Science*, *15*(12), 4872–4910. https://doi.org/10.1039/D2EE00802E

Samsó, R., Ramos, I., Ferreras, N., Lifi, M., Mediavilla, M., LLases, L., de Blas Sanz, I., Capellán-Pérez, I., Parrado-Hernado, G., Calleja, M., Markovska, N., Arto, I., Calheiros, T., Papagianni, S., Van Alen, O., & Eggler, L. (2023). *Deliverable 11.2: Python translation and e-Handbook for model sharing and transparency*.

Scrieciu, S., Rezai, A., & Mechler, R. (2013). On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. *WIREs Energy and Environment*, *2*(3), 251–268. https://doi.org/https://doi.org/10.1002/wene.57

Simpson, W., Mason, G., & Godwin, R. (2017). The Manitoba Basic Annual Income Experiment: Lessons Learned 40 Years Later. *Canadian Public Policy*, *43*(1), 85–104. https://EconPapers.repec.org/RePEc:cpp:issued:v:43:y:2017:i:1:p:85-104

Sterman, J. D. (2000). *Business dynamics: systems thinking and modeling for a complex world*.

Wright, E. O. (2016). *Unconditional basic income*.