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Research Dissertation

A Macroeconomic View of the Water-Energy-Food (WEF) Nexus Implications Under a Changing Climate

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Abstract (EN)

This thesis studies the most relevant dynamics relative to the Water-Energy-Food (WEF) Nexus, using an innovative modelling approach, and advancing the state of the art of Computable General Equilibrium (CGE) models. It begins with a critical review of the CGE literature, finding that CGEs have specific advantages in representing the Nexus, though they still need improvements, particularly in addressing the Water-Energy link. Thus, it proposes a method to explicitly model water uses for both sectors of the Nexus. Then, this framework is applied to assess the implications of Nexus water withdrawal pathways under two climate scenarios, which highlights that a) water projections will have regionally differentiated, but globally negative, GDP impacts b) a resource distribution/coordination mechanism generally improves the macroeconomic conditions, though it does not eliminate the benefits of reducing climate change c) the GDP damages are particularly reduced when it leads to a low carbon/low water energy mix. All in all, this thesis evaluates Nexus implications in a "limits to growth" perspective, enhancing the ability of CGEs to assess in which conditions sustainable development paths will be possible under climate change.

Abstract (IT)

Questa tesi studia le maggiori dinamiche del Nexus Acqua-Energia-Cibo (WEF), utilizzando un innovativo approccio modellistico e progredendo lo stato dell'arte dei modelli Computazionali di Equilibrio Economico Generale (CGE). Essa inizia con una revisione critica della letteratura CGE, sottolineando che essi presentano vantaggi specifici nella rappresentazione del Nexus, sebbene necessitino ancora di miglioramenti, in particolare per quanto riguarda il legame Acqua-Energia. Pertanto, propone un metodo per modellizzare esplicitamente gli usi dell'acqua per entrambi i settori del Nexus. Quindi applica questo quadro alla valutazione delle implicazioni dei percorsi di uso idrici del Nexus in due scenari climatici, evidenziando che a) le tendenze indriche avranno impatti differenziati a livello regionale, ma globalmente negativi sul PIL b) un meccanismo di distribuzione/coordinamento delle risorse migliora in generale le condizioni macroeconomiche, anche se non elimina i benefici della riduzione dei cambiamenti climatici c) i danni sul PIL sono particolarmente ridotti quando si arriva a un mix energetico a basso contenuto di carbonio/basso contenuto di acqua. Nel complesso, questa tesi valuta le implicazioni dei Nexus in una prospettiva di "limiti alla crescita", migliorando la capacità dei CGE di valutare in quali condizioni saranno possibili percorsi di sviluppo sostenibile in presenza di cambiamenti climatici.

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Executive Summary

This dissertation aims to address the repercussions of relevant social, economic, and climatic dynamics regarding the Water-Energy-Food (WEF) Nexus on macroeconomic growth, developing an innovative modelling approach and advancing the current state of the art of Computable General Equilibrium (CGE) models. In particular, it targets the following research questions:

- What is the relationship between the WEF Nexus and economic growth?
- How relevant is a detailed modelling of the Nexus in methodological tools like CGEs to address this issue?
- What is the influence of climate change on the Nexus, economic growth, and their relationship ?
- What could be an effective strategy to mitigate the (potential) limits to growth induced by the Nexus-Climate conundrum?

The conceptual background underpinning this work is the idea that growth depends on finite resources and that the satisfaction of basic human needs must be guaranteed for all [1], [2]. In particular, this dissertation focuses on the issues of water, energy, and food provision, which are three basic needs with strong interconnections with the environment, climate change, economic growth and between the three basic needs themselves (the WEF).

Methodologically, the thesis relies on Computable General Equilibrium (CGE) models. CGEs can be particularly suitable for analysing the Nexus, as they are intrinsically built to track interdependencies and transmission effects across sectors and countries. Furthermore, their advantages in addressing the Nexus reside in the following features: 1) their capacity to quantify the macroeconomic impact of structural changes (e.g. a change in factor productivity) or policy

interventions 2) their ability to assess the magnitude and direction of shocks propagation in complex circumstances (e.g. global scale economic issues) 3) their proficiency in accounting for macro-economic trends over the long run and 4) their ability to provide a full representation of the economy while maintaining a relative simplicity, i.e. lowering the risks of complexity pitfalls due to excessive data requirements, which, instead, is often an issue in models such as in System Dynamic models [3]–[7].

The first chapter of the dissertation critically reviews the CGE literature about the WEF, analysing their structure, pros, cons, and possible paths for improvement in reference to this topic. Despite the specific advantages that CGEs can offer to the study of this issue, still many aspects, mostly related to the representation of water as a production factor for the energy sector, are missing or not incorporated with enough realism. Indeed, on one side, water for agricultural uses has been extensively represented in this literature, also in consideration of the importance of distinguishing irrigated and rainfed production. Irrigated agriculture is currently responsible for around 40% of the total agricultural output [8]–[10] with increasing land being shifted to this type of production and it being generally associated with higher yields with respect to rainfed, e.g. [11]. Thus, irrigated agriculture will be a crucial sector to ensure food security under the expected future population, development, and nutritional trends [11], [12][1]. Furthermore, the land and water requirements of irrigated agriculture will strongly influence the pressures on the hydrological, land and climatic planetary boundaries [2], [13]–[15], with irrigated agriculture being also strongly affected by the latter, e.g. [16]–[18], as climate change will shape both future yields and water availability required for this production. Additionally, irrigated agriculture is the main user of water, being it responsible for around 70% of the total global withdrawals [19]. Nevertheless, even if

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[1] Nevertheless, also the rainfed agricultural sector still holds a role in the discussion [45]–[47]

associated with lower withdrawals than irrigated agriculture, the energy sector is also strongly interconnected with water uses, and accounts for around another 15% of the totality of global water withdrawals [20]. Like for (irrigated) agriculture, (strong) dependency of energy from the water resource is significant in several stages of production of all types of energy. For example, primary oil and gas use water for drilling, well completion, and hydraulic fracturing; for injection into the reservoir in secondary and enhanced oil recovery; for oil sands mining and in-situ recovery; and for upgrading and refining oil and gas into products. Primary coal uses water for cutting and dust suppression in mining and hauling; for washing to improve coal quality; for re-vegetation of surface mines; and for long-distance transport via coal slurry. Thermal power generation sources such as fossil fuels and nuclear power use water for boiler feed, i.e. the water used to produce steam or hot water, for cooling; for steam condensing; and for pollutant scrubbing using emissions-control equipment [20]. Solar power generation is generally associated with a low level of water withdrawal, even though the specific technology and cooling system implemented can significantly increase its water requirement. Concentrating solar power CSP technologies based on parabolic trough, solar tower and Fresnel technologies can indeed have water needs comparable to fossil fuel-based and nuclear power plants using the same cooling system, which is one of the highest water-dependent types of energy-related production [20], [21]. As such, water withdrawals for energy are not a negligible element, though it is never addressed in its entirety within the current CGE literature. To be noted, the current level of availability of data on water withdrawals for energy uses limits the regional detail achieved in this thesis. The only countries not in regional aggregation throughout the chapters of this dissertation are China and India, though this matches the importance of these two countries from an agricultural perspective, as they together account for more than half of the irrigated area in developing countries [22].

The second chapter, therefore, stems from the gaps previously highlighted and suggests a procedure to explicitly represent water uses for both the irrigated agriculture and the energy sectors in the "Intertemporal Computable Equilibrium System" (ICES) CGE model of the Euro-Mediterranean Center on Climate Change (CMCC) [23], [24]. Accordingly, it modifies the production function and implements a coherent expansion of the base data to properly represent the additional economic value, relying on [23]–[28] as methodological guidelines. More specifically, it introduces the economic value of water in the production structure on the basis of physical water withdrawals. Indeed, withdrawals describes the amount of water abstracted from the environment to enable sectoral production of irrigated agriculture and energy [25] and identify a more correct indicator of water uses for production than water consumption, since the latter represent the portion of water that evaporates due to production, i.e. the environmental damage related to sectoral production. To be noted, at the moment, the available data on freshwater withdrawals do not allow to differentiate between water types, e.g. groundwater, or production technique e.g. desalination or wastewater treatment. As such, water is introduced as an undifferentiated production factor, as in [7], [23]–[25], [27], although we recognise the relevance of issues mentioned in the modelling literature [29]–[34] about other water types, quality, and production technologies. The expanded model framework that includes the Water-Energy link is then tested with systematic static and dynamic simulations. The main findings of these tests are: a) including water as a production factor for the energy sector can lead to increased macroeconomic losses in context of water scarcity, since, in this situation, two sectors rather than one, irrigated agriculture, are dependent on a scarce endowment b) this result, however, is not confirmed if water can be freely allocated between sectors, i.e. if there is an efficient distribution mechanism between firms of the same region (water mobility between regions is not possible in our model) c) water competition and mobility trigger specific international specialization effects, driven by the relative water intensity of regional agriculture and energy productions. Indeed, when the water supply is constrained, countries with more water-intensive energy sectors, such as OECD[2] Europe, OECD America, and China, tend to shift water towards irrigated agriculture production. Hence, they specialise away from energy, preferring to import this good from the neighbours. The opposite occurs in countries with less water-intensive energy sectors. Thus, by allowing mobility, the regions redistribute the resource towards the sector in which is more efficient for them to specialise in d) In a dynamic setting, Gross Domestic Product (GDP) growth expectations are significantly affected by the presence (or absence) of the Water-Energy link, even in in scenarios that do not feature water scarcity issues.

The third chapter investigates the macroeconomic implications of future trends of water availability under a changing climate exploiting the methodology developed in the second chapter and proposing some further modelling refinements. More in detail, the third chapter: a) improves the representation of the energy sector, disaggregating it into eight sub-sectors b) associates emission values with different energy types and calibrates the emissions scenarios through a carbon tax module c) introduces explicitly climate change, specified according to two Representative Concentration Pathways (RCPs) in the 2050 horizon, RCP 2.6 and 6.0, based on [35] and [36]–[38] d) implements an innovative endogenous water calibration mechanism to have a more realistic representation of future water withdrawal paths. In particular, the water withdrawals are initially calibrated by setting the socioeconomic projections of GDP, energy, and population for the Shared Socioeconomic Pathway (SSP) 2 as drivers [39]–[41], and then an assessment of the climatic impact on the water resource is performed against it.

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[2] Organization for Economic Co-operation and Development (OECD)

Within this framework, the first assessment concerns a water availability analysis i.e. compares the socio-economic trends of water demanded with the runoff available in the regions (from Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) data), for RCP 6.0 and 2.6, i.e. the "Availability" scenario.

Then, an additional analysis is implemented, integrating the availability issue with the trends of actual water withdrawals at fixed social factors for irrigated agriculture reported in the ISIMIP repository. Indeed, this database shows that the actual withdrawals for agriculture, even without considering the influence of social dynamics such as land use changes, are associated with significant variations. In particular, they differ for distinct RCP due to issues such as surface temperature, land evaporation etc, which instead do not affect energy or industrial production, e.g. the functioning of turbines. To specifically address this issue shaping the withdrawal trends, the "Overall Climate" impact scenario was also developed. Both climate scenarios were run for twelve combinations of hydro-climatic models and a multimodal median. In the 2050 horizon, only Middle East appears to be constrained. The level of constraint of water scarcity and the impact of climate change, though, are significantly influenced by the adopted time and temporal scales. Indeed, water scarcity problems are likely to be widespread but localized to small sub-regional and sub-country levels, which are usually averaged out in large geopolitical blocs such as the ones generally considered in the CGE literature. For what concerns the time scale, the hydro/climatic projections were smoothed to yearly time series, which removes the influences of seasonality and interannual trends, and, consequently, the possibility of assessing the implications of potential peaks of scarcity issues and relative economic impacts. Future research will need to increase the regional resolution of the analysis and improve their ability to account for undetected feedback.

The scenario analyses highlighted the following results: a) the Middle East is always the worst impacted region (i.e. expected water scarcity/significant resource constraint is the stronger driver of GDP losses) b) additional climate impact on irrigated agriculture can have positive or negative effects, with significant variance across regions c) RCP 6.0 has more intense impacts and shows more variability than RCP 2.6 d) At a global level, both RCPs have negative GDP impacts, with RCP 6.0 having stronger negative effects.

Moreover, the paper evaluates the consequences of water mobility across sectors, i.e. a coordination mechanism between water-using sectors enabling the distribution of the (scarce) resource towards the most economically efficient allocation. Under water mobility, the negative macroeconomic impacts are reduced, and the positive ones are incremented. These effects are particularly relevant in OECD Europe, OECD America, Latin America, and India, with India and OECD Europe shifting from negative to positive macroeconomic impacts. Furthermore, it is shown that mobility generally redistributes water towards agriculture and water efficient renewables, and away from the water-intensive fossil and nuclear energy production. As such, a water mobility between sectors can favour the decarbonization process. To be noted, these positive effects on the macroeconomic impacts are nevertheless not enough to reduce the levels of the losses of a "water efficient" RCP 6.0 to the one of an RCP 2.6 i.e. a scenario with high climate change, even under efficiency-driven policies, is still associated with higher losses than a low climate change scenario. This strengthens and highlights the well-established need to aim for low climate change pathways [42]–[44].

All in all, the dissertation improves the current state of the art in Nexus modelling, evaluating its implications in a "limits to growth" perspective, improving upon CGE modelling literature and enabling a richer evaluation of the conditions that would ensure a more sustainable development in a climate-changing future.

With reference to the research questions presented in the first paragraph, it is shown that:

- The WEF can trigger significant macroeconomic losses otherwise undetected, especially in the presence of water constraint/scarcity.
- An explicit representation of WEF Nexus interconnections within CGEs has significant repercussions on the impact assessments and policy recommendations they can provide.
- Climate change will have substantial impacts on the WEF dynamics, on economic growth, and on their feedback.
- An efficient use of water (water management arrangements) has the potential to mitigate these losses, and, under certain conditions, can act as a growth accelerator However this is not sufficient to reduce the losses experienced in high climate change scenarios to the level of those that can characterize a low climate change scenario.

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Critical Reflections on Water-Energy-Food Nexus in Computable General Equilibrium Models: A Systematic Literature Review[3]

Abstract: The paper analyses how Computable General Equilibrium (CGE) models address the Water-Energy-Food Nexus (WEF), discussing their design, relevance, and possible improvements. This is crucial in the evaluation of their potential in understanding the reciprocal dependencies between Nexus elements and the expected macroeconomic, demographic, and climatic pressures that will act on them. General equilibrium models result to be particularly useful devices to this end, as they are specifically built to track interdependencies and transmission effects across sectors and countries. Nevertheless, the review showed that most of the literature still lacks a proper representation of the competing water uses across sectors, particularly, the ones related to the energy sector. As such, it highlights this issue as a crucial future research objective.

Keywords: Water-Energy-Food Nexus; Computable General Equilibrium model; Economic Modelling

1. Introduction

The Water-Energy-Food (WEF) Nexus is a topic that gained exponential attention in the recent history of the academic and political environments. Indeed, since 2011, the year in which Hoff and the World Economic Forum introduced the concept [1], [2], the Nexus gained more and more influence in both these arenas. In particular, its importance derives from the fact that water, energy, and food are three fundamental human needs and, as such, are critical factors for the assessment of potential pathways of social and well-being development [3]. Furthermore, understanding the interconnections between these elements is a critical issue in light of the increasing macroeconomic,

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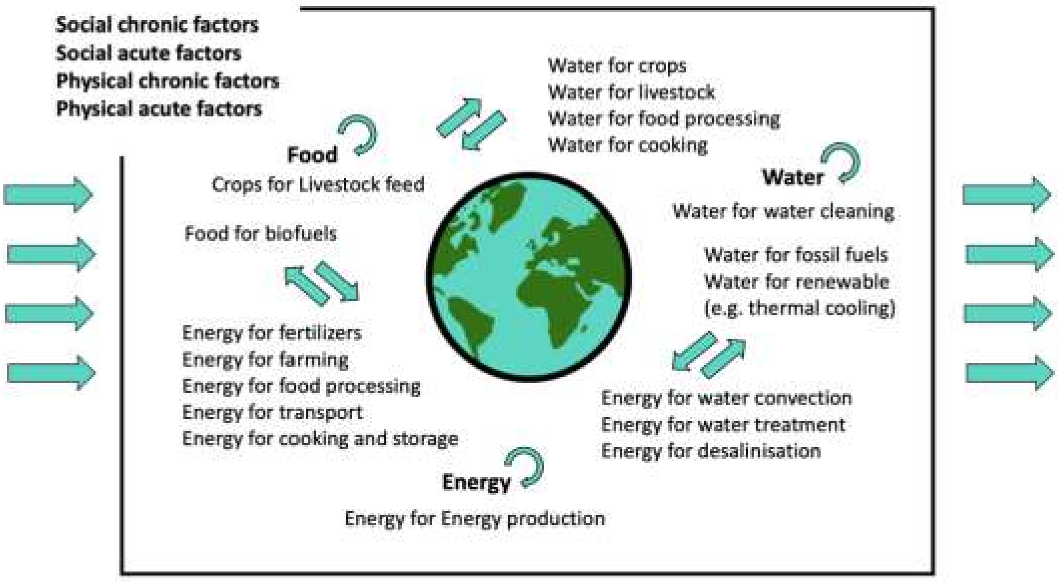
Contributions: Conceptualization E.B, F.B.; Methodology E.B.; Writing- Original draft preparation E.B.; Supervision F.B., Writing – Reviewing and Editing F.B., E.B.

demographic and climatic pressures expected to act on them in the short- and mid-term future [4]–[9].

Though the WEF Nexus is a multifaced concept, it is primarily marked by two ideas. The first is the notion of constraint and limitations. Indeed, all the items of the Nexus are nature-based and, therefore, connected to risks of resource exhaustion and overexploitation [10]–[14], and to general security issues [15]–[17]. The second essential foundation of the Nexus is the idea of interconnections and linkages. This concept defines the very basis of the Nexus, which is mainly built upon the finding that, historically, the single-sectoral perspectives on resource management adopted by the policymakers have turned out to be ineffective and/or inefficient [18]–[21]. Furthermore, recent literature points out that the single-sectoral approach has often led to declines in well-being and unsustainable development strategies [18], [22] which could have been avoided by adopting an integrated perspective. Implementing a systemic thinking approach, indeed, has shown to be an effective method to achieve a better understanding of issues such as general trends, the pressures on the use of resources, and to better assess the direct and cascading effects of different policies [23]. The relevance of interconnections within the Nexus is particularly evident by looking at the schematic structure of the concept, as shown in Figure 1. These interconnections fall mainly under two categories. First, there are the direct interconnections: water is used for food in agricultural production, food processing, management of livestock, and cooking and in energy production i.e. for electricity and fuel extraction. Biofuels are agricultural products that can function as an energy source. Energy is consumed to produce food through the use of fertilizers, food processing, transport, cooking, and storage and to extract, distribute, and process water (i.e. desalinization, water convection, and water treatment) [24], [25]. Among the direct connections, it is worth noticing that all the Nexus components also entail a degree of self-consumption (e.g. fodder for livestock or energy for energy production).

Figure 1. Conceptual Representation of the WEF Nexus Structure - Elements and links (based on [10], [24], [25]).



Then, there are the external elements or indirect drivers of the Nexus [10], which can be furtherly classified according to their type and temporal dimension. The four main categories of indirect drivers are: the chronic social factors (user behaviours, population growth, economic conditions, urbanization); the acute social factors (sabotage, riots/wars, politics, technical innovation); the chronic physical factors (climate change, resource depletion, infrastructures, land use) and the acute physical factors (pollution incidents, extreme weather events, natural hazards).

All these issues are important for the Nexus and should be incorporated in any model aiming to realistically represent the processes, trends and feedback involved in it. Therefore, this review explicitly focuses on analysing the strategies and methods for integrating the Nexus into Computable General Equilibrium models. In particular, it aims to inquire about the explicit presence of all the three Nexus elements in the models, as this issue is fundamental, for example, to properly capture resource competition. Indeed, competition for e.g. a scarce water resource and its implications for economic growth will become increasingly relevant in a context of climate change, which is expected to exacerbate resource needs, scarcity, and competition issues.

More in detail, the paper is structured as follows: Section 2 presents a justification of the research question; Section 3 introduces the criteria of literature selection; Section 4 discusses the state of the art of Nexus modelling in CGE; Section 5 discusses possible improvements to overcome the gaps identified; Section 6 draws a general conclusion.

2. Rationale of the Review: CGE models and their role in the literature

Being the WEF relationships intrinsically multifaceted, they have been modelled in several ways [5], [26]–[31]. In general, the choice of the modelling approach depends upon specific factors, i.e. the research scale, objectives and level of interdependency that the study wants to consider [10]. While there are tools that can be easily adapted to different spatial scales (e.g. integrated indexes, statistics, or system dynamics), aggregated methods such as econometric analysis or macro-economic approaches (e.g. CGEs) are associated with wider spatial scales. Conversely, more micro-oriented methods such as agent-based models usually apply to smaller-scale questions, also in consideration of their significant data requirement. For what concerns the research objectives, if the aim is to analyse the impact of a policy developed at a national level or the effects on trade patterns, a macro approach such as General Equilibrium (GE), macro-econometric (ME) or System Dynamic (SD)[4] can be more appropriate. On the other hand, if the objective is to analyse the emergence of consumption patterns,

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[4] Computable general equilibrium identifies models that are a) solved numerically – computable – b) concern the whole economy – general – and c) are based on the idea of equilibrium, which is the optimization of the agent's behaviour equating demand and supply in a macroeconomically balanced framework [168]. System dynamic models are complexity-oriented tools that aim to address nonlinear behaviour of complex systems, utilizing concepts such as stocks, flows, and feedback [169].

a more micro approach such as agent-based modelling or micro-econometric analysis is generally considered to be a more appropriate fit.

Among the different modelling techniques, this review focuses on CGE models. The justification of this choice stems from the fact that these instruments present many features that are potentially useful for a Nexus analysis, such as its ability to capture input-output linkages between sectors and countries; its effectiveness in representing impacts of technical changes (e.g. changing the productivity of a factor) or policy interventions; and its ability to account for macro-economic feedbacks [32], [33]. As such, CGEs can provide an aggregated, or top-down representation of the economy while maintaining a relative simplicity of interpretation and, to some extent, avoiding the complexity pitfalls e.g. CGEs are less data intensive with respect to other approaches such as system dynamic modelling. In particular, as tools that can assess the propagation, magnitude, and direction of disturbances on the overall economy [34], [35] CGEs are advantaged to address the Nexus issue as they can be easily adapted to address the different elements of the Nexus and to discuss resource competition across different sectors and countries [36], [37]. Finally, CGEs are used by and familiar to many institutions for impact and policy analysis. Their popularity and acceptance among policy making is another factor that suggests the necessity to improve their ability of conducting Nexus analysis rather than building from scratch brand new policy evaluation tools.

Nevertheless, it is important to recognise that CGEs also have some limitations, as several authors extensively stated [38]–[41]. In particular:

a) CGEs are normative and optimisation-based tools. Their theoretical underpinning, aiming toward optimisation, can lead, while trying to facilitate mathematical tractability, to the exclusion of phenomena like increasing returns and self-reinforcing feedback.
b) These models generally consider the actors as rational and “homogeneous” (i.e. representative agents), even though distinguishing the characteristics of

different agents would be an important feature in discussing the potential impacts of specific feedback and relationships.

c) While their usual level of aggregation provides a full-economy overview of the consequence of a shock, it generally implies that they are not able to account for local structures or intra-sectoral intricacies [29], [42].
d) CGE models are heavily dependent on calibration data. Indeed, their parameterization is based on observations of the economic system at a given time. Accordingly, they can lose predictive power as their simulations are pushed too far from the starting point. Moreover, they are rarely tested against their predictive power to check for the consistency of their projections [34].
e) CGEs have difficulties in adapting to different spatial and temporal scales. As such, generally do not perceive the economic phenomena that take place at the sub-national and intra-annual scale, since these models generally work at (multi)country-yearly level [43].
f) CGEs have difficulties in properly modelling technological changes [40], [44]. Usually, technological shifts are represented in CGEs by altering the Constant Elasticity of Substitution (CES) functions [45], [46] and/or the exogenous productivity factors. On the one hand, this simplifies the mathematical and computational structure of the model. On the other, in this framework, technological shifts are extremely simplified, and generally not accounted for with high detail.

To sum up, the main criticism against CGEs is that they are based on unrealistic and idealized economic assumptions [34], [47], [48]. This can be a potentially problematic issue in developing a Nexus-oriented analysis. Nevertheless, Computable General Equilibrium (CGE) models are fundamental instruments in the economic literature [49] and can be considered useful tools to address this issue [50]. Moreover, they are advantaged in detecting impacts and feedback between sectors and on the whole economy, which perfectly fits in with the character of a Nexus investigation.

Hence this review aims to present how the Nexus is represented in CGE models, evaluating the state of the art and, then, highlighting a possible line of research to overcome the eventual shortcomings identified.

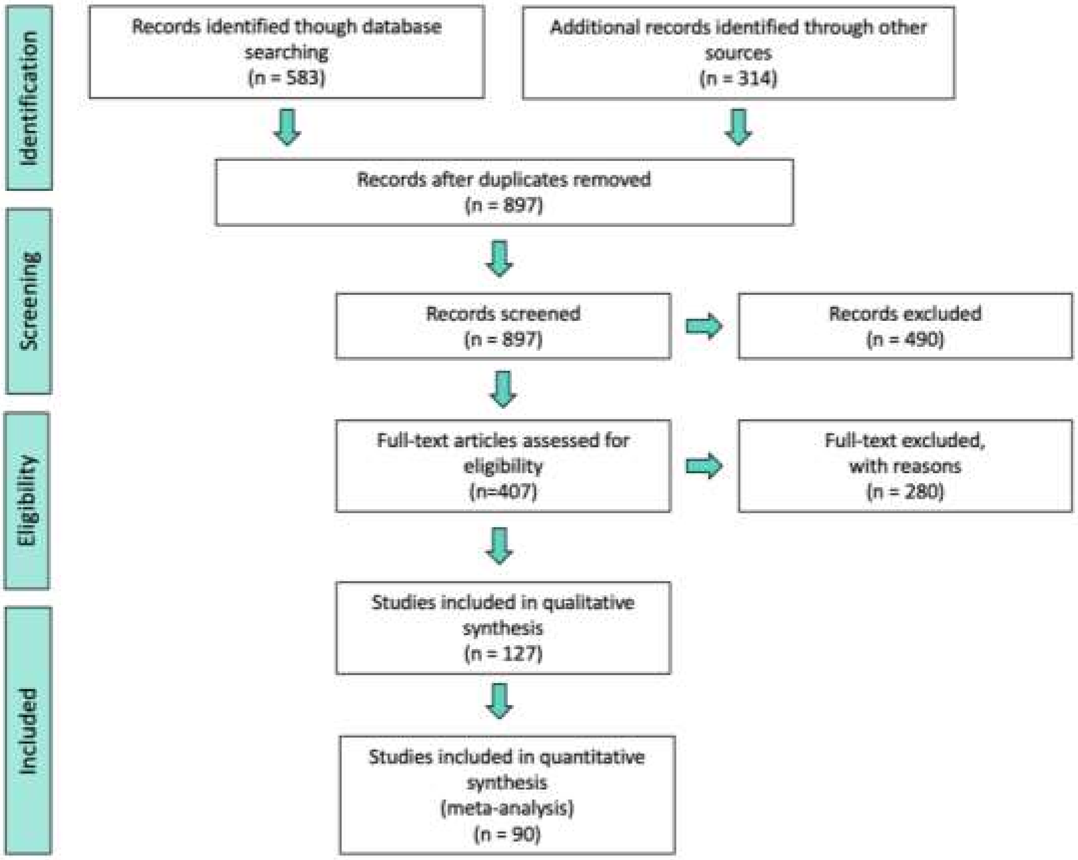
3. Methodology of the Review Process

The review started conducting a general assessment of the concept of Nexus, Nexus modelling and, specifically, the role of CGEs within the Nexus literature. The collection of publications has been developed systematically by following the steps illustrated in Figure 2.

The first screening was conducted using Water AND Energy AND Food AND Nexus AND CGE as keywords in the Elsevier Scopus, Elsevier ScienceDirect, and Web of Science databases. This step produced respectively 4, 103, and 5 articles. Then, the papers not directly involving CGE modelling were removed, and a complementary screening was performed through a Google Scholar Citation tracing procedure (forward and backwards).

Then, a further search has been conducted focusing on CGE modelling and the three sub-components of the Nexus. The research process was therefore re-run using the keyword combinations (Food AND Energy AND CGE), (Food AND Water AND CGE), and (Water AND Energy AND CGE), originating, respectively, 43, 37 and 71 papers on Scopus (title abstract and keyword restriction), 17, 11, 40 on ScienceDirect (title abstract and keyword restriction), and 78, 67, 114 on Web of Science (filtered for topic). After the second process of Google Scholar Citation tracing (forward and backwards) and the cleaning of the double-counted references, the overall review identified a total of 583 papers. Reviews of Nexus modelling, conceptual discussion of the framework, historical development of the concept and resource modelling with CGEs were also collected, adding a total of 314 papers to the screening. After abstract and keyword screening and the selection of the articles relevant to the Nexus and/or (at least partially) to CGE modelling, a total of 407 articles were used for textual analysis. With the irrelevant papers discarded, the review proceeded to a qualitative analysis of the WEF in CGEs, utilizing 127 studies. Of these, 90 of them were used for quantitative analysis.

Figure 2. Methodological steps of the systematic review process, based on the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)* structure - Moher et al. (2009)



4. Results: WEF Nexus and CGE Modelling

4.1. First Link: Water-Energy in CGEs

Water is crucial in energy production [52], with different intensity of dependency for different sources of generation [52], [53]. All uses should be accounted for to guarantee proper modelling of the energy-water link. Table 1 shows that only four studies directly integrate water as a factor of production of the energy sector in a CGE: [54]–[57].

Table 1. Relevant features of studies on the Water-Energy link (In Chronological Order)

Paper	Year	Pure/ Hybrid [5]	Spatial resolution[6]			Water as Endowment
			Sub- National	National	Global	
[58]	2016	P		China		N
[33]	2018	P		China		N
[53]	2018	H			X	N
[59]	2018	H	Urban catchment (China)			N
[60]	2018	P		China		N
[61]	2019	H		China		N
[57]	2020	P		Global-Morocco		Y
[54]	2020	H		Portugal		Y
[56]	2020	P		China		Y
[62]	2021	P		China		N (but as sector)
[55]	2021	P		China		Y

Indeed, the majority of the literature accounts for this factor "externally", e.g. creating a link with hydrological models (but, generally, without back feeding); quantifying the changes in water demand proportionally to the expected changes in energy production, or using the fictitious instrument of "pricing through

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[5] Pure models identify models that only consist of a CGE, while the Hybrid label defines models that mix CGEs and other models, e.g. Integrated Assessment Models (IAMs).

[6] When the National aggregation is labelled as "Global-" followed by a National or Sub-national label it means that the global model was aggregated focusing on a specific Nation/Sub-Nation vs. the rest of the world and analysed prioritising the specific region.

taxation" [33], [53], [58], [61]. The latter, in particular, is a method that sets water fees proportionally to the sectorial water withdrawal in order to account for the different water costs [60]. Only two studies in the review explicitly addressed water uses for cooling [53], [58]. None of the studies accounts explicitly for all the Nexus elements or water competition implications. Finally, with the only exception of Zhou et al. [53], all the studies are at the "country–level", particularly focusing on China. As such, the literature shows a lack of global analyses about this issue.

All in all, this section highlights how the explicit representation of the water-energy link in CGEs is not well-developed and therefore it suggests the need of setting this issue as a priority in the future research agenda.

4.2. Second Link: Energy-Food in CGEs

The Energy-Food link is complex and multifaceted. Nevertheless, this label has been generally reduced to the biofuel issue [7]. CGEs focused on biofuels for two main reasons: a) their potentiality, even if strongly debated and generally controversial, in contributing to the reduction of GHG emission [63], b) their implications in terms of food security agricultural and food price volatility. The latter, in particular, has gained significant attention after the 2008's food prices crisis, where biofuels played a critical role [64]. Nevertheless, issues such as their relationship with biodiversity and potential economic losses, gains, and competition problems relative to water are investigated with significantly lower frequency within this literature (Table 2).

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[7] Indeed, the Energy-Food interconnection would be much broader than the biofuel issue. The agri-food sector uses around 30% of global energy, of which 70% is directly used for crop production, even without considering transport or processing [170] or the role of fertilizers [171], which are highly energy-intensive inputs. The representation of this issue is nevertheless considered and modelled minimally, i.e. as standard sectoral exchanges in CGE models, and generally not explicitly considered in Nexus terms.

Table 2. Selected literature on Biofuels using CGEs (In Chronological Order)

Paper	Year	Spatial resolution	Objective	Water as Endowment
[65]	2008	China	GTAP-BIO to assess food price crisis of 2008	N
[66]	2009	China (village)	Effect of off-farm employment on consumption of biomass	N
[67]	2009	Brazil	Structural adjustment to Fuel ethanol demand	N
[68]	2010	Thailand	Impact of biofuel consumption on household income	N
[63]	2010	Global	Impact of biofuels on land-use change, food supply and prices, and the overall economy	N
[69]	2010	Mozambique	Growth and income impacts of investments in biofuels	N
[70]	2011	Germany	Impact biofuel targets on food production and land allocation up to 2020	N
[71]	2011	Global	Interdependencies between energy, bioenergy, and food prices	N
[72]	2012	Thailand	Country self-sufficiency and energy security	N
[73]	2012	Global-Sri Lanka	Oil-food prices impact on poverty	N
[74]	2013	Thailand	biofuels in promoting energy self-sufficiency and security	N
[75]	2014	China	non-grain fuel ethanol on food price	N
[76]	2014	India	Food-Biofuels trade-off in India	N
[77]	2015	Iran	Food and energy subsidy	N
[78]	2017	China	Policy for non-grain bioethanol	N

[79]	2018	Brazil	Mitigation policies' impact on Land-Biofuels	N
[80]	2019	China	Effect of biofuel expansion on food security	N
[81]	2019	Global-EU	Biomass pathways impact in EU	N
[82]	2019	USA-Virginia	Land impact bioenergy production	N
[83]	2019	Thailand	Scenarios for bioethanol production evaluation	N
[84]	2019	Mozambique	Biofuels impact assessment	N
[57], [85]–[91]	2012-2020	Global	Multiple Objective (GTAP– Purdue's University and GTAP-Based studies)	Y (N depending on the version)
[92]	2020	Global-Ghana	Biofuels impacts on food security	N
[93]	2020	Global	Biomass socio-environmental-macroeconomic impacts through biochemicals	N
[94]	2021	Scotland	Macroeconomic impacts of offshore wind energy and seafood production	N
[95]	2021	Global-Germany	Bio-economy/biofuels pathways to 2050	N
[96]	2021	Global-Thailand	Biofuel Subsidy impact in Thailand	N

Analysing the table's results emerges that the role of water, though potentially critical, has been explicitly addressed just by very few contributions. The first is Ge, Lei and Tokunaga [75], which addressed water costs in their input-output table of the non-grain fuel ethanol sector. Nevertheless, they did not aim to investigate water uses *per se*, as their inquiry concerned the implications of expanding ethanol production in terms of food security and land use. The second, still from Ge and Lei [78], presents an improved framework, as it models water as an economic sector and enriches its representation of the interactions between water and the other economic sectors, even though it still does not account explicitly for the role of water as a factor of production. Similarly, Kaenchan et al. [83] address water requirements from a statistical point of view, define a water demand function and develop a scenario analysis on the sustainability of bioethanol production in Thailand. Nevertheless, none of these studies explicitly represent the water input in the firms' production function. The only framework which successfully implements it is the GTAP-W-BIO model [57], [85]–[87], an extension of the Global Trade Analysis Project (GTAP) model. GTAP, initiated in 1997 [97], is a framework that, in time, developed several improvements that enhanced its ability to address Nexus connections. As such, it included a detailed energy sector representation through GTAP-E [98], [99] and GTAP-P [100], accounted for biofuels in GTAP-BIO [85], [101], provided the possibility of disaggregating into agro-ecological zones (AEZ) and, thus, a better perspective on land uses and relative trade-offs (GTAP-BIO-AEZ) [101], [102]; addressed the link between energy and GHG emissions in GTAP-E and GTAP-BIO-ADV [103]. Finally, particularly relevant for this survey, it introduced water among the endowments (primary production factors) in GTAP-W-BIO [86]. GTAP-W-BIO, therefore, could have a lot of potential in Nexus analysis, as it is equipped to address biofuels, it explicitly uses water as a production factor and deals with several Nexus adjacent issues such as irrigation-induced land use changes (via biofuels) [102], the implications of crop switching, and the effects of technological changes (e.g. introduction of irrigation) [87].

Nevertheless, the only paper in this review that focuses explicitly on an overall Nexus perspective, i.e. the economic impacts and trade-offs between energy, food, and water is Qu et al. [94], which is not adopting a GTAP framework. Furthermore, even if it openly addresses the Nexus perspective, still lacks the explicit representation of the third element of the WEF, and, as such, still does not achieve a complete perspective on this topic.

4.3. Third Link: Water-Food in CGEs

The link between water and food is generally well-recognized and highly significant.[8] Within this literature sub-section, CGEs generally focus on the analysis of issues such as the socio-economic impacts on the agricultural sector [29], the implications of water policies on agriculture [104], [105], and fluctuation in agricultural prices due to water shocks. Seldomly, it addresses the implications of technological shifts e.g. [106].

This section of the literature shows that there are mainly two approaches for the implementation of water into a CGE model: to introduce it "indirectly"/"externally", or to include it as an explicit production factor (see Table 3).

A typical "indirect" approach to water modelling is to use land productivity changes as a proxy for the variations in water supply, on account of their role in determining the final demand, supply, and price of the agricultural products. Dudu, Ferrari, and Sartori [37] enhanced this approach, proposing the implementation of a CES Shifter (i.e. a total factor productivity calibrated with specific sectorial detail), to have a better representation of the specific behaviour of the sectorial production functions. This would allow representing with higher

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[8] Water influences agricultural production both directly (i.e. as input) and indirectly (i.e. technological issues such as ineffective water drainage can lead to decreases in the level of land salinization or to waterlogging, which can lower crop yields) [172], [173]. Their relationship is also quantitatively significant, as agriculture uses roughly 70% of total water withdrawals [174] and accounts for around 86% of the world's freshwater resource consumption [172], [175]. The Water-Food link has also had a significant relationship with climate change, with multiplier dynamics acting on both sides [152]. Temperature variations and extreme events are expected to influence future crop productivity [7], [176], [177] and water availability [178]–[181], with water scarcity increasingly pressuring countries to rely on trade in order to ensure food security [174]. Moreover, climate change will be particularly important for rainfed crops, which nowadays account for 80% of the cultivated land and 60% of the world's food supply [182], [183], even though irrigation practices are expanding [184]. Climate change will therefore be a critical driver of food production and water management issues [174].

precision the consequences of water availability impacts. Changes in agricultural or land productivity have also been used as proxies of fictional costs for water, in an attempt to solve the issue of the zero price "curse" that generally affects water in CGEs (see [107] and [108]).

Table 3. Water-Food and CGEs literature (In Chronological Order)

Paper	Year	Spatial resolution			Pure/ Hybrid	Water as Endow.	Water Endow. for non-agric.
		Sub-national	National	Global			
[109]	2000	Rural Nevada			H	N	Y (No energy)
[110]	2004	Balearic Island			P	Y	N
[111]	2004	Murray-Darling Basin - Australia			P	Y	N
[112]	2004			X	P	Y	N
[107]	2005		Australia		P	N	N
[113]	2006	Queensland - Global			H	N	N
[108]	2007		S. Africa		P	N	N
[114]	2008		S. Africa		P	Y	N
[115]	2010		Australia		P	Y	N
[116]	2013			X	H	N	N
[117]	2014		China		P	Y	Y(as intermediate)
[118]	2015	China (Heihe River Basin)			H	Y	Y
[119]	2015	China (Multi-prov.)			P	Y	N
[120]	2016			X	H	N	N
[121]	2016	Israel			P	Y	Y (No energy)
[122]	2016		Malawi, Mozambique		H	N	N
[123]	2016		China		P	Y	N
[124]	2016		Global-S.Asia		H	N	N

[125]	2016		Australia		P	N	N
[126]	2016		Global-Italy		H	N	N
[127]	2016			X	P	Y	Y (No energy)
[128]	2017		China		P	Y	N
[129]	2017			X	H	N	N
[36]	2017			X	P	Y	N
[130], [131]	2017			X	H	N	N
[132]	2017		Netherl.		P	Y	Y (No energy)
[29]	2017	East Nile Basin			H	N	N
[133]	2018			X	P	N	N
[134]	2018			X	H	N	N
[135]	2018		Malawi		H	N	N
[136]	2018			X	P	Y	Y
[137]	2018	Heihe River Basin (China)			H	Y	Y (No energy)
[138]	2019		Global-Spain		H	N	N
[139]	2019	Global-Nile Riv. Basin			H	Y	N
[140], [141]	2020		Sudan		H	Y	Y (as intermediate)
[142]	2020		Spain		P	Y	N
[57], [86], [104], [143]	2007 - 2020			X	P	Y	Y (No energy)
[144]	2021				H	N	N
[145]	2021				P	Y	Y(no energy)
[146]	2021			X	H	N	N
[147]	2021		Global-Ethiopia		P	N	N

The models that introduce the endowments “directly” in the model generally define water as a production factor, which can then be exchanged with a certain degree of substitution with the other resources i.e. with no (Leontief functions as in [114], [143]), or partial substitution (Constant Elasticity of Substitution (CES) [104], [112]). This method highlights the necessity of water in the production of water-dependent goods. Nevertheless, it is also associated with specific issues, such as the problem of assigning a price and economic value to the water resource. One system to address these matters (dealing with agriculture) is to disentangle the economic value of water from the one attributed to land, i.e. calculating its value from the differential between the prices of irrigated and non-irrigated agricultural goods.

Interestingly, this review highlights a significant increase in the second, i.e. explicit type of water representation, since shortly after the introduction of the Nexus concept, not only for agricultural but also for non-agricultural sectors. Nevertheless, their volume is still limited [122], [134], [137] and in general addresses non-agricultural water uses only in an aggregated way [57], [121], [132], [148]–[150]. A partial exception is the RESCU-WATER model from Nechifor and Winning [136], which, starting from the GTAP-E structure [98] and GTAP-P [100], also addresses some energy sector water uses.

Be noted, independently from the type of water modelling, CGEs dealing with water are often coupled with physical-based hydrologic models (e.g. [29]) to increase the consistency and dependability of their simulations. Nevertheless, this practice is generally associated with several limitations, such as the difficulty in testing the convergence of the models' outputs [151] and the merging of heterogeneous spatial and temporal scales [152] across different models. Accordingly, the improvement of the existent coupling strategies emerges as one of the key issues for the future of this research field [29], [134], [137].

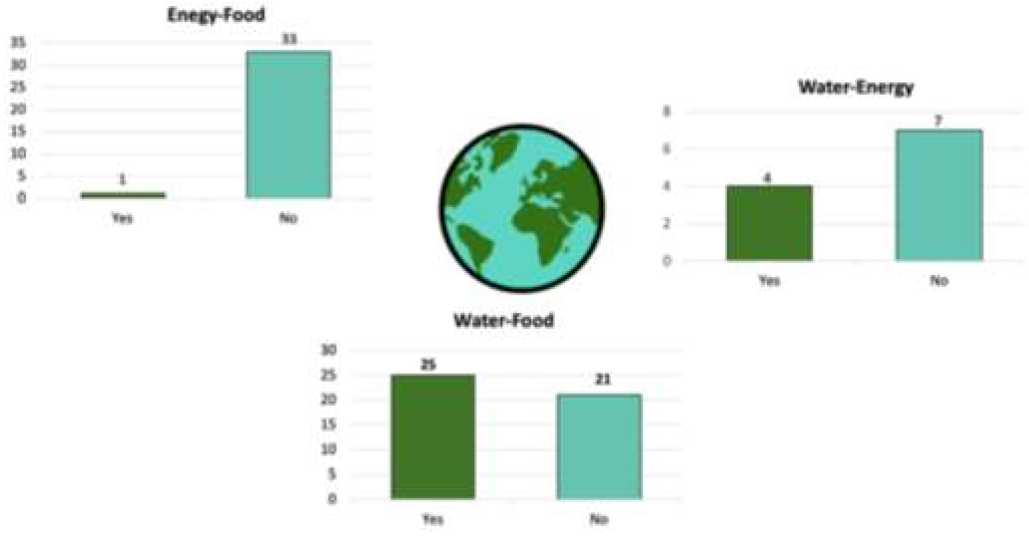
5. Discussion: Challenges and Possible improvements in CGE's Nexus modelling

The review highlighted how there are still significant difficulties in modelling all the interdependencies associated with the Nexus. Indeed, within this survey, only one paper [57] showed to have the potentiality to address all the Nexus links in their entirety, though still showing some necessary refinements in the Water-Energy link. Indeed, the most problematic dimension in addressing the Nexus appears to be the one associated with the water representation (Figure

3). In this review, only one-third of the studies addressed water as an explicit production factor, with most of them focusing on the water-agriculture relationship and not acknowledging the other sectors. The relationship between water as an input and energy, instead, has been addressed only by four studies, which were also still associated with specific shortcomings in their spatial dimension and the detail of the representation of the energy sector (Table 3).

Thus, this survey emphasizes how the Water-Energy Nexus is an underrepresented Nexus link and stresses the necessity for improvements in the explicit introduction of water in CGEs in general, and particularly concerning the energy sector.

Figure 3. Statistics (n. of papers) with explicit water endowment representation in CGEs - Results of the literature review process[9].



Additionally, the review identified the following water modelling issues:

a) Water pricing. Water, in general, is an almost-free public good, with virtually no price. In a standard CGE with CES demand functions, this would imply infinite consumption [37]. Moreover, even when it is possible to identify a price structure for water, it is typically sector-

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[9] [57] is reported in both the Energy-Food and Water-Food, as this framework is built explicitly to address both issues (i.e. GTAP-W-BIO).

specific and unlikely to be responsive to competitive market mechanisms, since, for example, the water resource is generally allocated by institutions and following political considerations outside market forces [153]. This is an obvious problem for models such as CGE, which are based on market transactions.

b) Data availability [154]. There is a shortage of explicit information on the uses of water and the availability of water types (e.g. surface water or groundwater, distribution through irrigation or rainfall) across sectors. This inevitably leads to weaknesses in model calibration, which results in lower model reliability.

c) Spatial and time scale issues in water modelling ([137], [155]–[157]). Water is often a transboundary resource, while the typical scale of investigation for CGE models is at the country scale. Concerning the temporal framework, crops vary on a seasonal basis, water availability and flows change hourly, whereas economic analyses with CGEs generally refer to annual periods [43]. Baum et al. [45], for instance, stress this problem in their study about salinity variations in water use for agricultural production in Israel. Indeed, their factors varied according to different space-time scales (e.g. field-national level), creating an imbalance in regional crop profitability and a sub-optimal allocation of land and water between cultivations and sub-regions.

d) The economic modelling of water (and environmental/ecological variables in general) opens to potential violations of thermodynamics. This issue has been raised since shortly after the introduction of these laws, e.g. [158] and extensively discussed in the Ecological Economics literature [159]–[162], though its implementation in the CGE literature e.g. [163] is not mainstream. Nevertheless, making sure that the translation of physical units (e.g., m3) of water to monetary values is correct is fundamental and specific control mechanisms should be developed in every model to ensure it.

Some suggestions and specific improvements are provided in the literature about how to address the current shortcoming and develop possible improvements in water modelling in CGEs [44].

The first is to account for potential losses due to changes in evapotranspiration [10]. This may be done in either by: a) an econometric manner, based on existent data about how water availability is impacted by different plants/technologies, or b) as in Mekonnen and Hoekstra [164], where it is computed endogenously by using the Penman-Monteith equation[11].

Another specific issue that merits further attention is the 'buffering time' of groundwater. This element, which affects the capacity of the environment to recharge its water reserves, could significantly affect the calculation of water availability and should be carefully considered in order to obtain a more realistic representation of the water flows [165].

As mentioned, it would be valuable to explicitly introduce consumption feedback between water and energy. Hertel and Liu [44], propose to move from grouping water only with land in production functions to nesting it also with capital [166]. In this manner, and by estimating the cost of capital and water, as well as their substitution, it would be possible to achieve a more appropriate water modelling.

Concerning the water-biofuel modelling, an possible improvement could reside in CGEs systematically representing competition issues for irrigation water in an explicit way [86], [104]. This would allow addressing with further

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[10] Evapotranspiration is the quantity of water that passes from land and plants to the atmosphere, therefore not going to contribute directly to groundwater recharge. It is an important factor contributing to water availability reduction.

[11] The Penman-Monteith Equation is the standard method used by the United Nations Food and Agriculture Organization to model evapotranspiration. It is based on (daily) mean temperature, wind speed, humidity, and solar radiation.

detail the issue of competition between food crops and biofuels, also through water uses. This procedure, however, is not standard practice in the literature.

A further, central, under-investigated topic is the dynamics of water for residential uses. In most cases, this issue is neglected because of the relatively low share of water involved, but, in practice, it has profound welfare implications. Nevertheless, this investigation is linked with several data availability issues, particularly in developing countries, which are generally affected by the joint presence of formal and informal water uses that can mask or distort effective water quantities and pricing.

Another factor to be considered in addressing household water consumption is the heterogeneity of agents. Different household classes, whether rich/poor or rural/urban, have very distinct water consumption patterns, which may be exacerbated by the unfolding of demographic, socio-economic and environmental changes. Accordingly, it would be crucial to introduce this factor when addressing the Nexus.

A final development could be the incorporation of the trade-offs between environmental quality and water uses, which in the specific context of Nexus would translate into the inclusion of environmental factors in the production/demand function of different water users, included in the household utility function [167].

6. Conclusions

CGEs models are tools utilised to describe the behaviours of rational economic agents, institutions, and markets, as well as the relationships between them. Their design allows to synchronously identify interdependencies between sectors and the detection and quantification of the implications of eventual shocks on the full economy. Hence, they may be appropriate tools to handle a complex issue such as the WEF Nexus, that inherently concerns multiple sectors and flows.

That said, it seems that there are not many CGEs that can fully address the Nexus, which limits the realism and soundness of both the modelling results and relative policy advice.

One of the biggest barriers concerns the explicit modelling of the water resource and its competitive uses across sectors and agents. This is mainly determined by the challenge of representing economically a zero-price resource such as water and providing consistent access to reliable data on water uses.

Thus, this review highlights some priorities for the research agenda, such as: a) improving the quality of data on water uses and prices in different countries and sectors; b) including water as a specific input for sectors other than agriculture, starting with energy; c) account for household water use and d) generally try to expand the analysis to multi-country/global level.

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Towards Full Implementation of the Water-Energy-Food Nexus in Computable General Equilibrium Modelling: Methods and Macroeconomic implications[12]

Abstract: This paper contributes to the advancement of Computable General Equilibrium (CGE) modelling in dealing with the water-energy-food (WEF) nexus. As such, it suggests a method to explicitly represent additional components of the WEF in a CGE model, particularly introducing water as an input for both the energy sector and irrigated agriculture, along with their competition for the resource. Different modelling frameworks are developed and examined by calculating regional GDP, sectoral production, and price reactions to hypothetical water shortage scenarios. This approach allows the determination of the role of the data and modelling structure e.g. the structure of the production function, the degree of water substitution with other endowments, water mobility between sectors and the intensity of the sectoral water uses, in determining the outcomes. Lastly, the paper develops a dynamic scenario analysis, demonstrating that a better representation of the Nexus can significantly influence the projections of macroeconomic trends and their implications at a regional level.

Keywords: Computable General Equilibrium, Water-Energy-Food Nexus, Water-Energy Nexus, Economic modelling

1. Introduction

Since its introduction in 2011 by Hoff [1] and the World Economic Forum [2], the Water-Energy-Food (WEF) Nexus (hereafter, the Nexus) has gained increasing consideration [3], [4]. As a result, the Nexus-based notions of recognizing the sectoral and production interlinkages as well as the importance of adopting a holistic view in addressing all the economic relations, are now widely recognized in the welfare and environmental economics literature [5]–

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[12] This chapter is based on a paper, co-authored with Professor Francesco Bosello, Dr. Gabriele Standardi and Dr. Ramon E. Key Hernandez, which has been submitted to Economic Systems Research and is undergoing the second round of revision.

Contributions: Conceptualization E.B, F.B.; Methodology E.B.; Formal Analysis E.B., Validation E.B., G.S., R.H. Writing- Original draft preparation E.B.; Supervision F.B., Writing – Reviewing and Editing E.B., F.B., G.S., R.H.

[10]. Of the several quantitative methods available for analysing the Nexus, Computable General Equilibrium (CGE) models have several specific advantages. Indeed, they are inherently constructed to account for input-output linkages between sectors and countries, macroeconomic feedback and higher-order consequences of eventual economic and policy shocks [11]–[14]. Hence, these models may be particularly suitable to be applied to the Nexus investigation [14]–[22]. However, the representation of all the different junctions of the Nexus in such models is not equally well developed. For example, while modelling of the water-food linkage using water as a primary input for agricultural production is fairly well established [22]–[29], water use by firms, energy producers, and households and the consequent water competition issues are only rarely addressed [16]. Even the most well-developed CGEs used for the analyses of Nexus-related issues (e.g. [30], [31]) do not take into account the Nexus in its entirety. Indeed, they generally lack the explicit representation of at least some linking mechanism, particularly the ones related to water for energy production, and the consequent macroeconomic implications due to sectorial water competition.

Within this context, this paper (a) suggests a methodology to represent the Water-Energy (WE) link in a CGE model, and thus accounting for water uses by both irrigated agriculture and the energy sectors (b) implements the possibility to accounts for the water competition between them (c) examines the implication of these changes in an enriched, although simplified, Nexus perspective. The chosen CGE to carry out this procedure is ICES (Intertemporal Computable Equilibrium System) [32], [33][13]. ICES is a recursive-dynamic, multi-sector, multi-country CGE, calibrated on the GTAP (Global Trade Analysis Project) 9 database [34], that gathers data about domestic and international exchanges on the base

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[13] The complete bibliography, including a full description of the structure and the studies developed through ICES is available at https://www.icesmodel.org/

year 2011. As usual in a CGE framework, sectorial supply is developed by representative firms following the objective of minimizing the production costs under a specific technological constraint (i.e. a specific elasticity of substitution between factors of production within the production function) with given input prices i.e. the existence of markets with perfect competition. The standard ICES structure is based on four primary factors: labour, land, capital, and natural resources. This work introduces water as an additional endowment for both energy and irrigated agricultural production. As such, the procedure implies structural modifications of the ICES production function and an adequate expansion of the original database. This process allows for the investigation of economic patterns that are generally poorly investigated: the impact of Nexus uses and competition-induced water stress on growth: the emergence of comparative advantage-driven specialization in national-sectorial production due to water availability variations; potential issues of energy and food security due to water scarcity i.e. increasing dependency on imported instead of domestic production [35].

Even if, in reality, water uses would involve more actors than just energy and agriculture, this paper focuses specifically on the WEF Nexus and does not account for other industries or household uses. Whilst it may seem restrictive to focus only on these two firms, the aim of the paper is primarily methodological and specifically concerns to address the competition consequences induced by the Nexus. Furthermore, it still captures the main drivers of water withdrawal patterns and relative competition, since energy and agriculture account for roughly 85% of the totality of global water withdrawals [36], [37]. Additionally, the proposed methodological process could be easily generalized to include the other actors, even though this objective will be momentarily left for future analyses. All in all, the overall procedure of introducing water as an explicit primary factor for both irrigated agriculture and energy requires to steps, i.e. a proper adjustment of the production function and an appropriate expansion of the database. A detailed description of these two processes is conveyed in the Materials and Methods section hereafter. Thus, Section 2 describes the material and methods, Section 3 discusses the results and Section 4 presents the discussion and the main conclusions.

2. Materials and Methods

2.1. Database Modifications

The ICES model is calibrated on the GTAP database (version 9) which includes a total of 140 countries and 76 sectors [34]. However, due to data availability and consistency purposes[14], in this paper the basic database is aggregated into five macro-economic sectors (irrigated agriculture, rainfed agriculture[15], industry, energy production and services) and ten macro-regions (OECD Europe, OECD America, OECD Asia-Oceania, Other Europe and Eurasia, China, India, Other Asia, Latin America and Caribbean, Africa, and Middle East)[16]. The structure and value-added for the agricultural sector have already been addressed in the GTAP literature [38], [39], and are introduced in ICES accordingly[17]. On the other hand, to associate water with energy requires assigning an economic value to regional energy water uses, which has not been

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[14] That is, concerning the possibility of finding withdrawal data on the energy sector that would be consistent with the variable used to build water uses for agriculture in the literature. As such the regional aggregation is adapted to the coarser of the two data regional resolutions, i.e. the IEA one [37].

[15] Irrigated and Rainfed agriculture are aggregating the same agricultural goods (e.g. wheat, paddy rice, etc.) originally included in the GTAP database of Version 9 [34], just differentiated according to production method, i.e. divided by proportion of land type (rainfed or irrigated) and water uses as in GTAP-W [38], [39].

[16] OECD refers to the Organization for Economic Co-operation and Development (OECD). Table 1 and Table 2 of the Supplementary Information report the detailed regional and sectoral aggregation of the Database.

[17] The value of water is build starting from the (regional and sectorial specific) value added for total Land in the original GTAP database. Then, this value is split proportionally to rainfed and irrigated agriculture production and yield difference for specific region. Thus, the value of the water endowment is extracted from the Land value added for irrigated agriculture on the basis of the production and productivity differences between irrigated and rainfed agriculture for specific region [38].

explicitly addressed in the GTAP/CGE literature. Thus, its development starts with retrieving the data on the physical quantities of water used by the energy sector. The chosen indicator is km^3 of water withdrawal[18] reported by the International Energy Agency (IEA) [37] i.e. the withdrawals associated with the production of both primary energies and electricity generation. Indeed, primary oil and gas use water for drilling, well completion and hydraulic fracturing, for injection into the reservoir in secondary and enhanced oil recovery, for oil sands mining and in-situ recovery, and for upgrading and refining oil and gas into products. Primary coal uses water for cutting and dust suppression in mining and hauling, for washing to improve coal quality, for re-vegetation of surface mines and for long-distance transport via coal slurry. Thermal power generation sources such as fossil fuels and nuclear power use water for boiler feed, i.e. the water used to generate steam or hot water, for cooling for steam condensing, and for pollutant scrubbing using emissions-control equipment. All in all, renewables such as wind, solar and geothermal have the lower water withdrawal requirement (i.e. around a mean of 10^2 litres per Megawatt-hour (MWh) followed by primary coal oil and gas (in different order depending on the specific production method e.g. conventional gas has lower requirement then refined oil but gas-to-liquids has higher withdrawals) for a mean of 10^4 litres per MWh. The highest withdrawals are associated with fossils electricity and nuclear power, also differentiated by production methods (in general cooling towers have lower

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[18] This measure accurately describes the amount of water abstracted from the environment to enable sectoral production. It thus differs from water consumption, which represents the portion of water that evaporates due to production, i.e. the environmental damage related to sectoral production. Moreover, in this context, agriculture and energy are considered as self-abstracting [31], i.e. retrieve directly the raw material. In this stage of the research, no distinction is made between different types of water or available water 'production' technologies, such as desalination or wastewater treatment, i.e. water is regarded as an undifferentiated production factor based on withdrawals, although the importance of improvements in this direction is recognised.

withdrawals than cooling ponds, and both have lower levels of withdrawals with respect to once-though technologies) spanning from 10^4 MWh up to 10^6 litres per MWh.

The water withdrawal requirements of all these activities are then aggregated and associated with our overall energy sector in ICES using the following approach. The physical data are used to build a proportional economic value for water. Due to the existence of the price-accounting system, the model needs to specify the water values at "market prices" (VFM), at "agent prices" (EVFA) and at "agent prices along the supply chain" (EVOA). Their difference resides in taxation values that can be imposed at each stage of the transaction: the tax on the primary input that can be paid from the firms (in sector j and region r) accounts for the difference between EVOA and VFM, while the tax on the supply of the inputs that may be paid from the households (which by construction are the owners of the endowments in the model) account for the difference between VFM and EVFA. Because of the scarcity of information on both water taxation and prices, the values for the regional energy sectors are drawn from [38][19], i.e. the water prices estimated for agriculture are transferred to energy. Indeed, given the lack of better information, we hypothesize that regional technological/infrastructural costs, sources of supply, availability risks and overall costs are comparable among different actors in the same region. After computation, the value added of water for energy has been extracted from the relative sectorial capital value, as suggested in [40] (amounts in percentage displayed in Figure 1 and economic value in Figure 3). The proposed procedure aligns with the methodological suggestions of [38], [41] and [30], [39], [40], [42] concerning the introduction of water as a production factor in a CGE.

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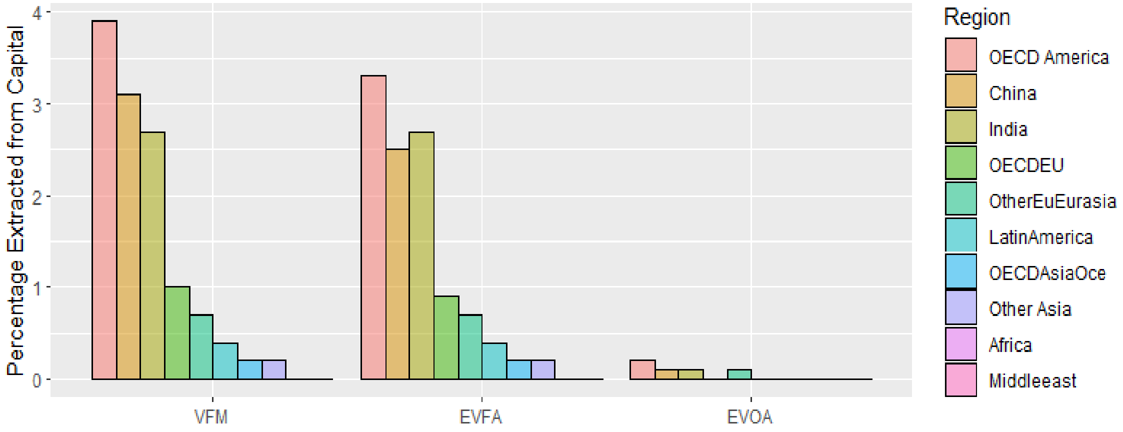
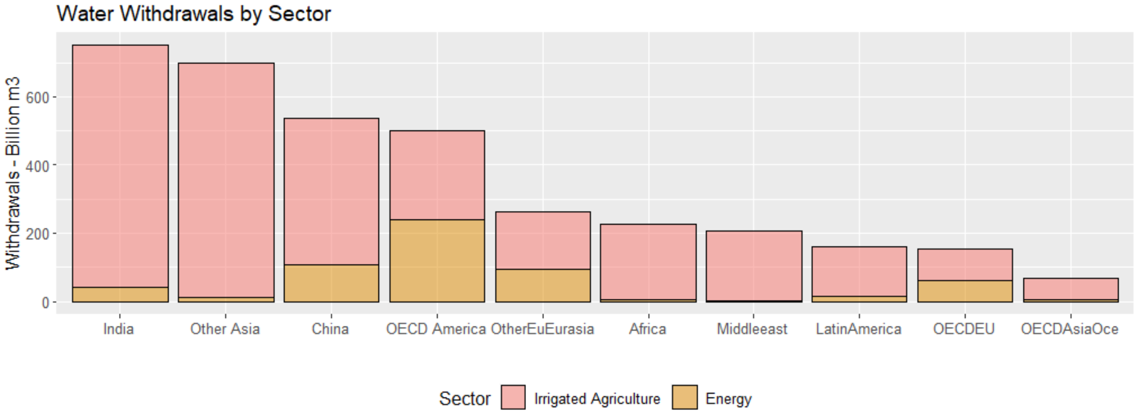
[19] Their procedure consisted of first computing the value of VFM by deduction through the value of irrigated agriculture, rainfed agriculture and the regional amount of land in the different regions. Then, EVFA and EVOA were computed by applying the irrigated agriculture land tax rates to irrigated agriculture water endowment.

Figure 1. Percentage of (Capital) Value added redirected from Capital to Water.



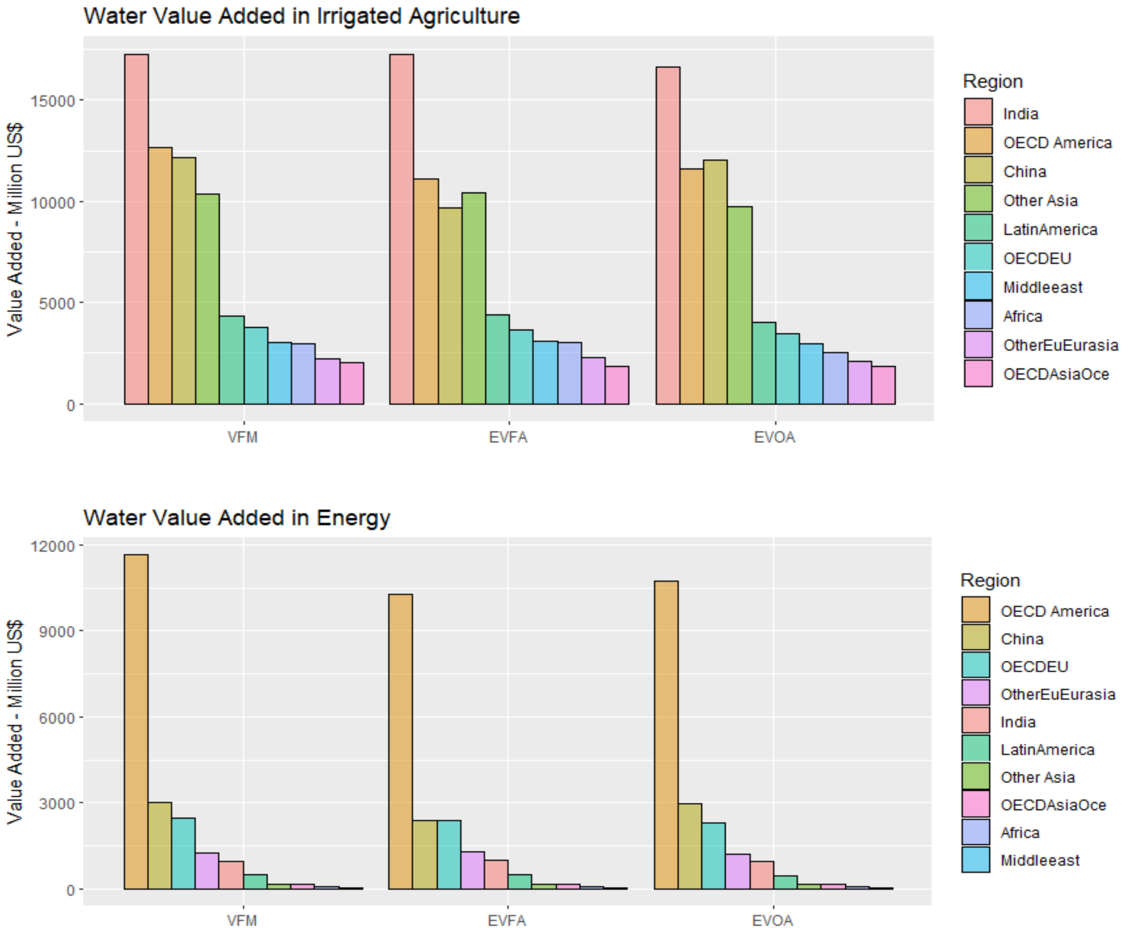
The values produced through this method are coherent with the technological dependence on water in the energy sector of the different regions. Indeed, the more water-intensive energy sectors are in OECD America, China and India and OECD Europe, while the water value-added share in Africa, and the Middle East, is almost negligible. To be noted, though irrigated agriculture is the main driver of withdrawals, comparable levels of regional value added can be found also in water for energy in water-intensive energy regions such as OECD Europe and OECD America, which sets energy as an additional crucial variable in this context (Figure 3). Furthermore, energy and agriculture together account for roughly 85% of the totality of global water withdrawals [36], [37], with agriculture accounting for roughly 70% and energy for around 15% of the total physical amount, even though the relative shares of withdrawal levels by sector are differentiated at regional level (Figure 2).

Figure 2. Water used in Agricultural and Energy Production in Base Year (2011)



The physical values in Figure 2 are reflected in the amount of final amount of value added associated with the water endowment in these two sectors (Figure 3).

Figure 3. Water Value added in Energy and Irrigated Agriculture, in base year (2011)



These values acquire specific importance when contextualised in a basic needs and environmental perspective. Indeed, irrigated agriculture is crucial in terms of share of agricultural production, thus water is a production factor directly related to around 40% of the total agricultural output [43]–[45], with the area for irrigated agriculture being under continuous expansion, and this sector being associated with generally higher yields with respect to rainfed agriculture, e.g. [46]. Accordingly, withdrawals-dependent agriculture and water withdrawals will be crucial in light of the future demographic, macroeconomic and nutritional trends [46], [47] and their expected trends [20]. Furthermore, the land and water requirements of irrigated agriculture will strongly influence the pressures on the hydrological, land and climatic planetary boundaries [48]–[50] while also being strongly affected by the latter, e.g. [51]–[53] which will shape both future yields and water availability required for this production. On the other hand, energy production is critically also linked with water withdrawals, and its requirements and impacts on and from the water endowment will also be strongly influenced by the expected trends in population growth, development, and climate change.

2.2. Production Structure Modifications

Concerning the production function, two different specifications have been tested. The first replicates the basic structure existing in ICES adding water in the same configuration as the other endowments i.e., water is introduced in the same nest of the other primary factors of production as shown in Figure 4. This is the simplest possible specification, that is, there is just one parameter (the elasticity of substitution) that governs the substitutability in production across all primary factors of production, including water. The elasticity of substitution is kept the same as the original model calibration.

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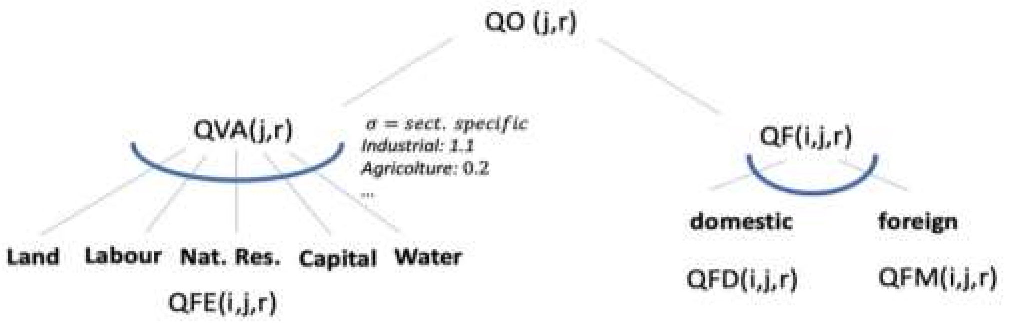
[20] Nevertheless, also the rainfed agricultural sector still holds a role in the discussion [45]–[47]

Figure 4. ICES's Production Function – CES

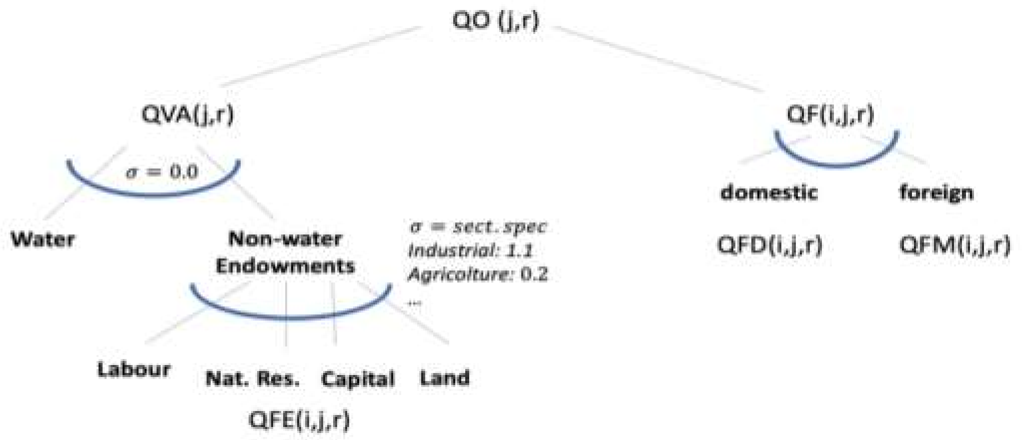


Note: QO Production in sector j and region r; QVA Value Added of sector j in region r; QFE use of endowment i in sector j of region r; QF intermediate input i used by sector j of region r; QFD domestic intermediate, QFM imported intermediate input.

In addition, we investigated a more elaborate specification consisting of a Quasi-Leontief nest linking water and the other primary inputs, i.e. assuming almost perfect complementarity (or very low substitutability) between water and the other endowments [23], [45], [46], [54], [55]. This implies a two-tiered structure: in the first, water is disentangled from the bundle of the other primary factors; the second defines the substitution across the remaining production factors, i.e. capital, land, natural resources, and labour (Figure 5). Therefore, this case is specified as under an almost zero substitution between water and the other endowments, as suggested by most of the literature. The main benefit of this technical framework is the introduction of an additional metric to specify the substitution of water in the production function, differentiating it from the one of the other factors of production. As such, this configuration is advantaged by the modelling flexibility of this structure, which facilitates an eventual modification of the substitution values and the incorporation of new information when available.

Nevertheless, while this second setting has more detail and is closer to the assumptions set in the literature, the first structure has some significant technical advantages and can be considered a valuable reference. Indeed, it is less disruptive of the original structure of the model, and, most importantly, it is associated with less challenging computational needs. This is crucial since, in general, assuming an (almost) zero elasticity of substitution leads to the emergence of issues of mathematical intractability in the solutions and relative challenges in scenarios building perspective (see section 2.4). As such, both structures are investigated.

Figure 5. ICES's Production Function – Quasi-Leontief



Note: QO Production in sector j and region r; QVA Value Added of sector j in region r; QFE use of endowment i in sector j of region r; QF intermediate input i used by sector j of region r; QFD domestic intermediate, QFM imported intermediate input.

2.3. Endowment inter-sectorial mobility

Primary factors (land, capital, labour, water, and natural resources, within this model) can be perfectly or imperfectly mobile across sectors. The latter are generally defined as "sluggish". When imperfectly mobile, the degree of sluggishness is driven by the value of a determined elasticity in a constant elasticity of transformation (CET) function. In general, within the standard GTAP (and ICES) model, it is assumed that labour and capital are perfectly mobile, whilst land and natural resources are sluggish, i.e., can be relocated between sectors, but with significant friction.

In this exercise, we examined several specifications, addressing scenarios in which both land and water are sluggish, perfectly mobile and a combination of the two. This decision about water comes from the fact that, in general, water mobility between irrigated agriculture and energy production can be easily justifiable, but only under the assumption of absence of institutional or regulatory constraints and assuming an explicit and stable willingness to cooperate/coordinate between actors. As such, both cases can have their validity.

Concerning the land sluggishness assumption, instead, it was relaxed and tested in both specifications due to the nature of our experiments. Indeed, the scenarios were based on shocks constraining water withdrawals, i.e., affecting/increasing prices only for irrigated agriculture and not for rainfed.

As such, we expect them to trigger shifts from irrigated to rainfed and not vice versa, which could be rationally justifiable. The constraints in shifting land from one type of agriculture to the other, indeed, are generally due to the high investment costs that are required to implement irrigation systems, which should rightfully be considered a major constraint in the shift from rainfed to irrigated. On the other hand, irrigated land could easily become rainfed. As such, this justifies our interest in also investigating the mobile land case, even if the standard practice in CGE is to have that factor as sluggish.

Nevertheless, the results do not identify significant differences according to the land mobility assumption. Hence, for sake of compactness, Section 3 presents only the results relative to sluggish land, i.e., the ones following the standard literature assumption.

2.4 Experiments' design

The behaviour of all the versions of the modified model was examined under two types of tests, i.e. a set of static and a set of dynamic simulations. The firsts were specified as a set of comparative static exercises addressing globally uniform reductions of the water supply, from 10% to 50%[21], for a total of 120 simulations. These experiments were employed to evaluate how the different model specifications reacted to the introduction of water as an input for the energy sector; the sensitivity of the results with respect to the production structure (the 'original' constant elasticity of substitution (CES) versus the 'Quasi-Leontief') and the role of water mobility between sectors. Table 1 provides a summary of the various model specifications and their main features.

Table 1. Model specifications

Version	Water input to irr. agriculture	Water input to energy and irr. agriculture	CES Prod. function (Fig.1)	Quasi-Leontief Prod. function (Fig.2)	Water as "sluggish" factor of prod.	Water as perfectly mobile factor of prod.
CES_Onesec_SlugW	X		X		X	
CES_Twosec_MobW		X	X			X
CES_Twosec_SlugW		X	X		X	
Quasi-Leontief Onesec_SlugW	X			X	X	
Quasi-Leontief Twosec_MobW		X		X		X
Quasi-Leontief Twosec_SlugW		X		X	X	

The second round of analyses, i.e. the dynamic one, tested the behaviour of the models focusing specifically on the role of water competition across agriculture and energy (the Water-Energy-Food Nexus). To this end, these simulations were carried out under the assumption of Shared Socio-Economic Pathways (SSPs) [58]–[60] for the socioeconomic component, perfect water mobility between water-using sectors (i.e. energy and irrigated agriculture) and almost zero substitutability among water and the other endowments (the Quasi-Leontief case). This configuration was chosen because of its increased realism and

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[21] Larger negative shocks were incompatible with the models' simulation capacity in some of the specifications (i.e., Quasi-Leontief-based).

its capability of highlighting possible competition/specialization issues. More in detail, the exercise is carried out as follows: first, the ICES model where water is used only by irrigated agriculture is calibrated to match the GDP and population growth trends in the different SSPs [61], [62]. This process generates a vector of changes in total factor productivity, which are the parameters allowed to vary in order to reproduce the targeted rates of regional GDP growth. Then, these productivities are set as fixed in the model where water is a factor of production for both energy and irrigated agriculture. In this context, the GDP growth is allowed to fluctuate, together with sectoral production, prices, etc, under the influence of the previously missing energy-water link and the related water competition. Therefore, the difference between the original growth rates and the second growth rates will provide a sense of the relevance of the explicit existence of the Water-Energy link in the model, as well as consequent potential issues of Energy-Food competition for water. This set of analyses concerns, overall, 5 baselines (i.e., one for each SSP) and 5 scenarios.

3. Results

3.1. Macroeconomic and sectoral impacts of water scarcity

The addition of water as a factor of production for the energy sector, if the inter-sectoral mobility of water is not allowed, increases the negative effect on GDP of water supply restrictions (Table 2 and Table 3). This is not unexpected since, in this case, an additional sector is negatively affected by shortages of one of its inputs. GDP losses, though, are reduced when sectorial water mobility is enabled. As such, this preliminary stage suggests that the existence of an institutionalised "water market"[22] which guarantees/regulates access to water for

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[22] The presence of an institutionalised water market must be intended as a hypothetical platform that allows exchange of information/coordination between actors and the possibility to allocate the resource between different sectors maximising economic efficiency.

the different users might be a strategic factor in adapting to water scarcity and mitigating its overall negative impacts. Furthermore, the assumption on the parameter of substitution between factors appears to be one of the main drivers of GDP impacts. For instance, in response to a 50% reduction in water supply, overall GDP impacts range from -0.39% to -0.42% in the CES specification and from -16.02% to -18.63% with the Quasi-Leontief. Thus, this highlights the necessity of very a careful evaluation of the calibration process and of the choice of the elasticity parameter. Another interesting result is that the GDP response to water supply reductions is non-linear, with losses increasing exponentially after a 30% water reduction (see Table 2). This means that, although depending on the current model calibration and the definition of economic relationships within the model's structure, a 30% water shortage might be a threshold under which water scarcity is still "manageable". Nevertheless, it also signals the risks and damages associated with constraints of water availability beyond this level.

Table 2. Impacts of homogeneous water shocks on Global GDP–Static Scenarios

Model Description	**-10%**	**-20%**	**-30%**	**-40%**	**-50%**
CES_Onesec_SlugW	-0.01	-0.04	-0.08	-0.16	-0.39
CES_Twosec_MobW	-0.02	-0.04	-0.08	-0.16	-0.32
CES_Twosec_SlugW	-0.02	-0.04	-0.09	-0.18	-0.42
Quasi-Leontief_Onesec_SlugW	-0.04	-0.56	-3.09	-8.22	-16.02
Quasi-Leontief_Twosec_MobW	-0.05	-0.4	-1.72	-5.02	-10.67
Quasi-Leontief_Twosec_SlugW	-0.05	-0.63	-3.44	-9.08	-18.63

Table 3. Real Regional GDP Impacts (% change) across model specifications – Static Scenarios

10%	**OECD Europe**	**OECD America**	**OECD Asia-Oceania**	**Other Europe and Eurasia**	**Other Asia**	**China**	**India**	**Middle East**	**Africa**	**Latin America**
CES_Onesec_SlugW	0.00	-0.01	0.00	-0.01	-0.05	-0.02	-0.14	-0.02	-0.02	-0.01
CES_Twosec_MobW	-0.01	-0.02	0.00	-0.01	-0.05	-0.02	-0.14	-0.02	-0.02	-0.01
CES_Twosec_SlugW	-0.01	-0.02	-0.01	-0.01	-0.05	-0.02	-0.15	-0.02	-0.02	-0.01
Quasi-Leontief Onesec_SlugW	-0.01	-0.02	-0.02	-0.06	-0.13	-0.07	-0.43	-0.07	-0.10	-0.03
Quasi-Leontief Twosec_MobW	-0.03	-0.06	-0.01	0.05	-0.12	-0.09	-0.41	-0.02	-0.05	-0.02
Quasi-Leontief Twosec_SlugW	-0.02	-0.05	-0.02	-0.05	-0.13	-0.09	-0.43	-0.04	-0.07	-0.03

50%	OECD Europe	OECD America	OECD Asia-Oceania	Other Europe and Eurasia	Other Asia	China	India	Middle East	Africa	Latin America
CES_Onesec_SlugW	-0.09	-0.20	-0.14	-0.33	-1.34	-0.53	-4.31	-0.53	-0.70	-0.36
CES_Twosec_MobW	-0.08	-0.23	-0.08	-0.20	-1.10	-0.39	-3.54	-0.35	-0.44	-0.24
CES_Twosec_SlugW	-0.11	-0.27	-0.14	-0.35	-1.34	-0.56	-4.37	-0.51	-0.68	-0.37
Quasi-Leontief Onesec_SlugW	-7.83	-11.91	-10.96	-13.40	-29.03	-35.03	-35.33	-22.66	-28.44	-21.08
Quasi-Leontief Twosec_MobW	-5.60	-8.11	-4.96	-6.85	-15.62	-29.54	-32.38	-7.31	-13.45	-11.56
Quasi-Leontief Twosec_SlugW	-10.23	-14.65	-15.53	-20.12	-31.40	-35.46	-36.24	-25.32	-31.14	-22.19

As illustrated in Table 4, irrigated agricultural prices increase substantially in all specifications, particularly in the Quasi-Leontief context. Concerning the energy prices, instead, they decrease when water is not a factor of production for the energy sector, while tend to increase when the WE Link is "active". In the first case, energy prices are merely moving in accordance with the declining macroeconomic trends (GDP). In the second case, water scarcity becomes the stronger driver. Notably, when water is mobile in the Quasi-Leontief's specification, the increases in energy prices are greatest in OECD Europe, OECD America, and China. This is consistent with the relocation of water from energy to irrigated agriculture implicit in Table 5, which reveals a much greater reduction in energy production than in irrigated agriculture within these areas. Indeed, these regions are associated with water-intensive energy sectors and, consequently, have an incentive to import energy from other regions, whose energy sector is less water-dependent, and, as such, have a comparative advantage in this regard. To be noted, in this framework rainfed agriculture is not directly affected by water withdrawal scarcity shocks. However, this sector is strongly related to irrigated agriculture and the implicit possibility of inputs shifts between them. Nevertheless, the responses of the prices and production of rainfed agriculture are mostly negative, especially in the Quasi-Leontief. Therefore, they appear to be mainly driven by the macroeconomic and demand negative trends rather than by substitution effects with irrigated agriculture.

Furtherly analysing the production shifts, two types of regional responses can be detected when water is used by both sectors. In OECD Europe, OECD America, China, and India the energy sector is less affected when water is sluggish (Table 5). Therefore, contrarily to the effect on GDP (Table 3),which are negative, in these regions the effect on energy is positive due to the sluggishness that prevents the redirection of the water resource towards agriculture. For instance, taking the Quasi-Leontief specification as an example, this issue emerges with particular significance in OECD Europe and OECD America, where, in the most water-restricted scenario, energy production impacts are -89% and -92% respectively with perfectly mobile water, instead of -34% and -38% with sluggish water. The opposite occurs for irrigated agriculture, e.g. in OECD Europe production declines are over 40% in the sluggish case instead of around 10% in the mobile scenario. Production behaviours are mirrored by similar trends in imports (Table 6). For instance, energy imports in OECD Europe and OECD America increase by 116% and 261% with mobile water, instead of 31% and 33% when water is sluggish. The regions that feature less water-intense energy sectors, show opposite trends. These patterns, therefore, confirm the hypothesis about the role of water intensity in the regional energy sectors.

In this regard, it is interesting to note the performance of large energy producers such as Other Asia and Latin America. Indeed, these regions, under conditions of sectoral water mobility, tend to find convenient to specialise in energy production and channel (or retain) the scarce water supply there. The Other Asia region, in particular, becomes a major hub in the supply of energy. Water scarcity, thus, has the potential to act as a driver of specialisation towards energy production for less water-intensive energy producers.

Table 4. Prices Impacts (% change) of systematic water shocks for different specifications – Static Scenarios

Irr. Agri	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	2.5	110.7	4.7	178.9	2.4	118.7	4.1	130.6	6.7	226.4	3.1	122.9	8.0	305.6	2.5	96.5	2.3	104.6	4.3	170.0	4.1	156.5
CES_Twosec_MobW	1.7	39.1	3.2	65.5	2.1	61.1	3.2	60.3	6.4	157.7	2.5	58.8	7.4	228.0	2.4	59.5	2.2	56.8	3.6	81.0	3.5	86.8
CES_Twosec_SlugW	2.5	110.5	4.7	178.7	2.4	118.3	4.1	130.3	6.7	225.5	3.1	122.7	8.0	305.0	2.5	96.4	2.3	104.5	4.3	169.6	4.1	156.1
Q-Leontief_Onesec_SlugW	51.6	9009.0	60.7	9810.3	52.5	8071.3	50.9	7647.2	64.0	4248.7	54.8	3918.6	68.8	4064.2	44.5	4688.4	49.8	6649.9	60.7	8884.7	55.8	6699.2
Q-Leontief_Twosec_MobW	38.3	3477.1	45.4	3319.4	41.7	5018.7	42.2	4958.3	54.6	2430.4	43.9	2635.5	63.4	2075.8	36.5	2987.0	39.7	3574.7	47.8	5110.6	45.4	3558.7
Q-Leontief_Twosec_SlugW	51.4	8590.1	60.7	9049.5	52.4	7382.2	50.6	6201.4	63.7	4004.1	55.1	3779.7	70.0	3790.3	44.2	4722.4	49.6	6498.8	60.5	8481.9	55.8	6250.0

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	0.0	-1.0	0.0	-1.3	0.0	-1.5	0.0	-1.6	-0.1	-4.6	-0.1	-2.7	-0.5	-14.4	-0.1	-2.7	-0.1	-2.4	-0.1	-2.0	-0.1	-3.4
CES_Twosec_MobW	0.1	1.8	0.3	4.1	0.0	0.4	0.1	1.1	0.0	-1.2	0.2	2.1	-0.1	-6.3	0.1	0.5	0.1	1.0	0.1	1.3	0.1	0.5
CES_Twosec_SlugW	0.1	-0.2	0.2	0.7	0.0	-1.0	0.0	-0.8	-0.1	-3.9	0.1	-1.5	-0.3	-12.7	0.0	-1.9	0.0	-1.5	0.1	-1.1	0.0	-2.4
Q-Leontief_Onesec_SlugW	-0.4	-45.3	-0.4	-57.1	-0.6	-60.3	-0.6	-52.4	-1.4	-66.8	-1.1	-53.6	-3.4	-42.7	-0.9	-64.5	-0.9	-64.3	-0.7	-64.4	-1.0	-57.1
Q-Leontief_Twosec_MobW	2.3	204.9	3.8	346.9	0.8	34.9	1.4	60.2	0.4	33.3	2.4	162.8	-0.6	45.7	1.2	52.6	1.5	57.5	1.6	55.8	1.5	105.5
Q-Leontief_Twosec_SlugW	1.2	190.6	2.3	198.8	0.3	157.4	0.9	179.2	-0.1	146.8	1.1	109.4	0.1	87.9	0.5	158.9	0.7	171.6	1.0	173.3	0.8	157.4

Rainfed Agr.	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	0.0	0.4	0.0	0.6	0.3	6.3	0.0	-0.1	-0.1	-4.4	0.0	-0.2	-0.4	-13.6	0.0	0.0	0.0	-1.0	0.0	-0.3	0.0	-1.2
CES_Twosec_MobW	0.0	0.5	0.0	0.7	0.2	3.3	0.0	0.1	-0.1	-3.7	0.0	0.0	-0.4	-11.6	0.1	0.3	0.0	-0.3	0.0	-0.1	0.0	-1.1
CES_Twosec_SlugW	0.0	0.4	0.0	0.5	0.3	6.3	0.0	-0.1	-0.1	-4.5	0.0	-0.3	-0.4	-13.9	0.1	0.3	0.0	-0.7	0.0	-0.3	0.0	-1.2
Q-Leontief_Onesec_SlugW	-0.2	-26.6	-0.4	-38.9	0.2	-13.0	-0.4	-40.0	-2.3	-58.5	-1.3	-71.4	-4.2	4.0	-0.8	-52.4	-1.2	-39.1	-0.5	-43.5	-1.1	-37.9
Q-Leontief_Twosec_MobW	-0.1	-16.6	-0.5	-24.5	0.1	-16.2	-0.3	-31.8	-2.2	-56.0	-1.2	-73.4	-4.5	-34.1	0.0	8.0	-0.5	-24.1	-0.3	-37.3	-0.9	-30.6
Q-Leontief_Twosec_SlugW	-0.2	-30.5	-0.6	-46.4	0.2	-18.6	-0.5	-56.0	-2.4	-56.8	-1.4	-66.5	-4.9	7.4	-0.3	-43.7	-0.9	-40.4	-0.5	-43.3	-1.1	-39.5

Table 5. Regional production Output impacts (% change in real terms) across model specifications – Static Scenarios

Irrigated Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	1.11	9.03	-1.17	-14.51	1.22	11.44	-1.59	-13.77	-1.20	-17.06	0.13	0.69	-1.25	-19.42	0.39	3.71	0.88	10.87	-0.44	-8.57	-0.2	-3.8
CES_Twosec_MobW	1.18	17.61	-0.24	2.41	0.80	5.84	-1.09	-7.76	-1.33	-18.90	0.08	0.45	-1.22	-18.59	0.04	-3.62	0.37	0.95	-0.85	-11.86	-0.2	-3.3
CES_Twosec_SlugW	1.11	9.01	-1.15	-14.49	1.21	11.40	-1.59	-13.79	-1.21	-17.08	0.13	0.69	-1.24	-19.41	0.36	3.58	0.85	10.74	-0.45	-8.60	-0.2	-3.8
Q-Leontief_Onesec_SlugW	0.03	-42.04	-3.59	-44.85	0.76	-41.78	-3.53	-44.38	-4.24	-45.18	-1.01	-42.76	-4.79	-45.76	-0.80	-42.31	0.27	-41.73	-2.71	-44.13	-2.0	-43.5
Q-Leontief_Twosec_MobW	1.86	-9.88	-1.10	-0.31	0.28	-47.87	-5.22	-63.16	-4.62	-47.54	-0.88	-31.43	-5.15	-44.97	-1.44	-43.22	-0.46	-43.82	-3.46	-52.09	-2.0	-38.4
Q-Leontief_Twosec_SlugW	0.03	-42.04	-3.58	-44.85	0.76	-41.77	-3.53	-44.36	-4.25	-45.18	-0.99	-42.76	-4.73	-45.76	-0.87	-42.30	0.22	-41.73	-2.72	-44.13	-2.0	-43.5

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	-0.09	-2.83	-0.06	-2.02	-0.15	-4.61	-0.03	-1.19	0.26	8.57	-0.02	-0.23	0.64	23.05	-0.02	-0.53	-0.01	0.32	-0.04	-1.15	0.0	1.9
CES_Twosec_MobW	-0.10	-2.51	-0.45	-6.80	0.05	-0.56	0.01	-0.12	0.39	8.13	-0.19	-3.32	0.24	10.40	0.07	1.06	0.12	2.01	0.08	0.82	0.0	0.9
CES_Twosec_SlugW	-0.10	-2.87	-0.34	-4.39	-0.02	-3.50	-0.01	-0.99	0.35	9.29	-0.11	-1.03	0.48	20.15	0.04	-0.03	0.07	1.04	0.04	-0.41	0.0	1.7
Q-Leontief_Onesec_SlugW	-0.83	-58.11	-0.74	-23.99	-1.20	-28.28	-0.38	-28.13	2.06	-8.66	0.36	-72.45	4.93	-69.37	0.14	35.00	0.83	90.51	-0.35	38.38	0.5	-12.5
Q-Leontief_Twosec_MobW	-2.88	-89.94	-5.00	-92.32	1.14	64.00	0.64	6.12	3.94	135.73	-2.32	-87.68	2.92	-53.67	1.28	35.25	2.31	75.69	1.45	52.99	0.3	4.6
Q-Leontief_Twosec_SlugW	-1.42	-34.47	-3.35	-38.54	0.55	-28.09	-0.14	-32.32	2.85	-28.25	-1.21	-36.33	0.09	-37.60	0.99	-16.01	1.94	-22.57	0.29	-31.14	0.1	-30.5

Rainfed Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	-0.03	-1.39	-0.05	-2.63	-0.30	-8.48	0.02	-0.26	-0.04	-0.52	-0.04	-1.10	-0.03	-0.06	-0.07	-2.33	-0.04	-0.93	-0.01	-0.69	-0.1	-1.8
CES_Twosec_MobW	-0.04	-1.14	-0.05	-2.27	-0.25	-4.94	-0.01	-0.59	-0.04	-0.04	-0.03	-0.72	-0.01	0.38	-0.15	-2.45	-0.04	-0.64	-0.02	-0.49	-0.1	-1.3
CES_Twosec_SlugW	-0.04	-1.41	-0.02	-2.34	-0.31	-8.55	0.01	-0.37	-0.05	-0.57	-0.04	-1.08	-0.02	0.02	-0.14	-2.93	-0.05	-1.03	-0.03	-0.89	-0.1	-1.9
Q-Leontief_Onesec_SlugW	-0.73	-33.14	-1.03	-29.77	-1.57	-56.40	-0.20	-2.39	0.37	-24.60	0.14	0.94	0.47	-49.48	-0.53	-23.23	-0.03	-24.77	-0.54	-35.39	-0.4	-27.8
Q-Leontief_Twosec_MobW	-0.51	-36.28	-0.41	-38.10	-1.47	-47.12	-0.51	-18.92	0.27	-10.38	0.24	60.07	0.67	-43.30	-1.88	-69.06	-0.25	-17.42	-0.84	-24.95	-0.5	-24.5
Q-Leontief_Twosec_SlugW	-0.71	-31.28	-0.67	-16.24	-1.74	-55.59	-0.31	20.16	0.30	-32.03	0.22	-23.78	0.80	-52.65	-1.64	-39.51	-0.20	-16.64	-0.78	-38.10	-0.5	-28.6

Table 6. Import impacts (% change in real terms) across model specifications – Static Scenario

Irrigated Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Model Description	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	-0.95	-2.74	2.34	41.95	-3.24	-19.4	2.84	32.69	5.97	110.6	-2.27	-21	11.4	313.8	-1.56	-12.41	-3.01	-24.4	0.86	21.88	1.23	44.11
CES_Twosec_MobW	-1.05	-9.97	1.13	16.65	-1.68	4.58	2.04	23.39	6.69	163.1	-1.38	-5.29	12	519.9	-0.63	4.96	-1.42	-0.16	1.89	36.35	1.75	75.36
CES_Twosec_SlugW	-0.95	-2.75	2.33	42.07	-3.23	-19.5	2.81	32.26	5.94	109.8	-2.26	-20.9	11.3	313	-1.52	-12.51	-2.98	-24.5	0.87	21.63	1.23	43.86
Q-Leontief_Onesec_SlugW	2.35	50.55	19.43	79.39	0.98	93.82	10.75	74.56	17.23	-72.4	3.81	-87	27.9	-79.87	-3.4	-49.9	-3.05	-62	12.44	-12.88	8.85	-6.57
Q-Leontief_Twosec_MobW	0.43	13.72	14.75	45.39	3.05	193.4	11.81	84.57	19.16	-55	5.66	-45.8	45.3	-82.58	-1.85	-19.36	-1.7	-35.9	13.19	130.26	10.98	22.87
Q-Leontief_Twosec_SlugW	2.36	51.22	19.62	68.53	0.61	72.57	10.26	-11.05	16.39	-72.3	4.44	-85	30.8	-82.09	-3.85	-39.07	-3.62	-52.6	12.11	-7.84	8.91	-15.76

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Model Description	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	0.05	1.88	0.05	2.03	0.01	0.53	0.01	0.57	-0.27	-8.18	-0.03	-1.21	-0.73	-26.96	-0.04	-0.89	-0.09	-2.77	-0.03	-0.79	-0.11	-3.58
CES_Twosec_MobW	0.04	1.35	0.45	7.38	-0.04	-0.4	-0.04	-0.47	-0.3	-6.13	0.25	4.36	-0.4	-15.47	-0.08	-1.16	-0.07	-1.1	-0.02	-0.18	-0.02	-1.18
CES_Twosec_SlugW	0.04	1.83	0.34	4.68	-0.03	0.12	-0.02	0.25	-0.3	-8.36	0.1	0.02	-0.61	-25.23	-0.07	-1.12	-0.09	-2.79	-0.04	-0.88	-0.07	-3.15
Q-Leontief_Onesec_SlugW	0.55	83.96	0.66	42.18	0.12	-7.39	0.17	89.98	-2.11	-81.2	-0.77	-29.6	-4.88	-62.77	-0.22	-15.65	-0.94	-74.9	-0.16	-48.18	-0.76	-10.35
Q-Leontief_Twosec_MobW	1.41	116.5	5.52	261.9	-0.58	-5.56	-0.6	-8.25	-2.54	-60.2	3.71	81.81	-3.11	-64.48	-0.95	-14.7	-0.83	-49.4	-0.49	-15.71	0.15	24.19
Q-Leontief_Twosec_SlugW	0.74	31.43	3.52	33.37	-0.45	-16.4	-0.19	-25.68	-2.25	-75.8	1.8	-76.8	-1.05	-87.11	-0.71	-36.23	-1.06	-68.3	-0.08	-34.03	0.03	-35.55

Rainfed Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Model Description	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)	(-10%)	(-50%)
CES_Onesec_SlugW	0.02	1.19	0.04	1.74	0.22	5.65	-0.01	1.61	-0.24	-8.15	0.03	1.07	-0.97	-30.68	-0.03	-0.47	-0.1	-3.46	-0.04	-1.27	-0.11	-3.28
CES_Twosec_MobW	0.03	0.94	0.05	1.7	0.15	2.73	-0.04	0.46	-0.27	-6.52	0.03	1.06	-1.04	-26.58	-0.04	-0.65	-0.05	-1.79	-0.06	-1.06	-0.12	-2.97
CES_Twosec_SlugW	0.02	1.18	0.03	1.66	0.21	5.63	-0.04	1.31	-0.25	-8.17	0.03	1.05	-1.04	-31.18	-0.03	-0.44	-0.06	-3.07	-0.04	-1.23	-0.12	-3.33
Q-Leontief_Onesec_SlugW	0.47	35.35	0.33	12.5	0.64	34.92	0.54	37.35	-3.05	-64.4	-1.12	-89.3	-7.53	291	-0.7	-49.44	-2	-35	-0.24	-34.87	-1.27	13.8
Q-Leontief_Twosec_MobW	0.46	45.59	0.27	46.87	0.44	32.87	-0.26	12.66	-2.97	-51.7	-0.89	-89.2	-8.58	11.68	-0.49	24.75	-0.76	3.07	-0.17	-17.9	-1.29	1.87
Q-Leontief_Twosec_SlugW	0.49	35.65	0.26	-8.22	0.6	23.88	0.08	-44.23	-3.06	-64.7	-1.12	-82.8	-9.17	278.6	-0.6	-28.21	-1.34	-16.5	-0.17	-28.9	-1.4	6.45

To be noted, these results lead to the general conclusion that water scarcity seems to be a more concerning issue for agriculture rather than for the energy sector. Indeed, it highlights the potential emergence of food security issues, as well as spikes in agricultural prices and declines in agricultural output in all the regions, particularly when water availability is reduced by more than 30%. Furthermore, these issues can be exacerbated in developing regions like Africa and Other Asian countries, due to water competition between agriculture and the energy sector. This said, regional reductions in energy production are far from negligible and may lead to an increased dependence on imported energy commodities in regions such as the EU, which is already a heavy net energy importer, amplifying the concerns about energy security in these areas.

3.2 Water competition under water scarcity

After investigating the macroeconomic and sectoral implications of water scarcity, this section focuses on the dynamics triggered by sectorial water demand. In light of the general agreement within the literature concerning the limited substitutability between water and other production factors [23], [31], [43], we chose to conduct this examination only under Quasi-Leontief.

From the results emerge that, if water is sluggish, the sectoral water demand strictly follows the water supply trends (Table 7). This, though, is not the case when water is mobile, as the sectoral demand for water is shaped by the inter-sectoral reallocation of the resource and regional production specialisation.

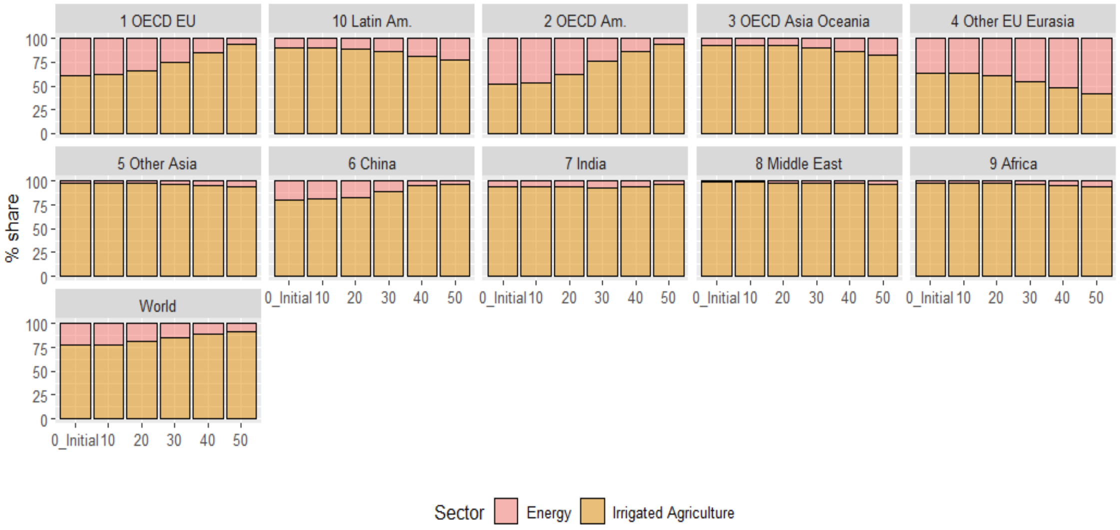
Considering the 50% reduction in water supply, regions such as OECD Asia-Oceania, Other Asia, Africa, and Latin America are highlighted, since they are increasing energy production and, consequently, the demand for water from this sector. Therefore, there, irrigated agriculture decreases its water demand, and the resource is shifted away from it.

Table 7. Sectoral water demand (% change) – Static Scenarios

	Irrigated Agriculture				Energy			
	With water mobility across sectors		"Sluggish" across sectors		With water mobility across sectors		"Sluggish" water sectors	
Water supply reduction (Scenarios)	10%	50%	10%	50%	10%	50%	10%	50%
1 OECD Europe	-7.59	-22.21	-10	-50	-13.66	-92.30	-10	-50
2 OECD America	-7.15	-9.57	-10	-50	-13.09	-93.74	-10	-50
3 OECD Asia-Oceania	-9.89	-55.22	-10	-50	-11.39	16.35	-10	-50
4 Other Europe and Eurasia	-11.21	-66.88	-10	-50	-7.85	-20.06	-10	-50
5 Other Asia	-10.08	-52.14	-10	-50	-4.70	84.05	-10	-50
6 China	-9.37	-40.10	-10	-50	-12.58	-90.33	-10	-50
7 India	-10.24	-49.27	-10	-50	-5.69	-62.88	-10	-50
8 Middle East	-10.01	-50.73	-10	-50	-9.36	-0.53	-10	-50
9 Africa	-10.01	-51.76	-10	-50	-9.35	27.83	-10	-50
10 Latin America	-10.21	-57.11	-10	-50	-8.10	13.51	-10	-50

Figure 6 shows the variations in the proportion of water used by the individual sectors in the respective regions. Globally, the quota of total water directed towards agricultural uses increases. Thus, this hints that water uses are less compressible for agriculture with respect to the energy sector and suggests that water scarcity may be a more significant issue for food rather than for energy security. However, there are considerable regional differences in this matter. The regions that specialise in energy production such as OECD Asia-Oceania, Other Europe and Eurasia, Other Asia, Middle East, and Latin America show an increased share of water in that sector. Therefore, this might suggest a relatively higher sensitivity of these regions about energy security issues, especially if fluctuations in water withdrawals are expected in the future e.g. under the influence of climate-changing scenarios.

Figure 6. % Share of water used by sector in different scenarios (Mobile Water)



3.3 Modelling implications in a dynamic setting

This section discusses the implications of implementing the water-energy link in a dynamic context, i.e. under SSP2 assumptions (the results relative to the other SSPs are provided in the Supplementary Information). Figure 7 illustrates that, upon the introduction of water competition between agriculture and energy, the regions characterised by more water-intensive energy sectors fail to meet the multi-decade cumulative GDP growth targets associated with SSP2 when using their initially calibrated total factor productivity. As such, OECD Europe and OECD America exhibit a cumulative GDP that is about 5 per cent below the target, while India displays a GDP contraction of 5.6 per cent. In contrast, regions like Other Asia and Africa exhibit trends above the target. Economic growth requires energy and energy requires water. Thus, when the water dependency is explicitly modelled, countries with a water-intensive energy sector experience relatively higher production costs with respect to the other regions. Consequently, they adapt by lowering their production/demand for this good domestically, and their ability to support growth. On the contrary, in countries with energy sectors with low water intensity, water is relatively abundant, thus they have the possibility of producing and exporting more, experiencing more growth.

These results, albeit purely explorative, validate the hypothesis about the relevance of explicitly introducing multisectoral water uses and competition between sectors. Nexus analysis can indeed highlight tensions in the achievement of certain development goals that would otherwise remain undetected. Furthermore, it signals the potential relevance of including a Nexus perspective in the quantitative assessment of sustainability, planetary boundaries, and economic growth scenarios, as well as in the analysis of energy and climate policies.

Figure 7. Difference in GDP % output change of model with and without Water-Energy link, 2011–2050 – Dynamic simulations of socio-economic pathway (SSP2)[23]

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[23] The colors (which match the intensity of the impacts) were assigned connecting each country to the relative ICES region, e.g. Algeria is not present in the Database, Italy is associated to OECD Europe etc. As such, the color and intensity of impact is exactly the same across the ICES regions and it is not to be intended as results at the singular country level except for the two countries disaggregated in the regional aggregation reported in Table 1 of the Supplementary Information: China and India.

4. Discussion and conclusion

This work suggests a methodology to incorporate the water-energy-food nexus in a CGE framework. Hence, it enriches a CGE model with a water input for both irrigated agriculture and energy production. Subsequently, it tests the proposed approach and the relative model responses by performing some illustrative simulations of exogenous water supply reduction and some dynamic scenario analyses.

These tests reveal that the inclusion of water as an input for energy production significantly affects the impacts of eventual water supply restrictions, which become more damaging than when water is used only by the agricultural sector. Nevertheless, the negative aggregate impacts are reduced when water competition/redistribution is allowed, or, in other words, when water is mobile between the two sectors. This specification, which mimics a perfectly efficient institutional water market, allows for the most efficient use of water between sectors and mitigates the negative impacts of water scarcity.

Furthermore, water competition leads to the emergence of interesting international specialisation effects, driven by the relative water intensity of regional water-dependent productions. As such, those with more water-intensive energy sectors tend to redirect water towards irrigated agriculture and to relatively specialise in food production. The converse holds for countries with less water-intensive energy sectors. In particular, similar behaviours emerge in Other Asia, which responds to water scarcity by becoming a hub for energy production, and in OECD countries, which react by expanding their irrigated agricultural production. Water competition, therefore, appears to exacerbate the negative impacts of water scarcity on agricultural production in energy-specialised regions, raising concerns about food security in these areas. Likewise, it increases the concerns about energy security in the regions specialising in agricultural production. The first trends generally emerge in developing areas like Asian (except China) and African countries, while the second is relatively concentrated in developed areas such as the EU and the US.

Additionally, the dynamic simulations reveal that, in general, developed regions can potentially expect lower growth as a result of the energy-food competition over the water resource in a context where both water links are explicitly considered. Developing regions, on the other hand, may generally expect higher levels of GDP growth. Nevertheless, the latter outcome does not guarantee the absence of disadvantages. Indeed, higher growth does not preclude the potential emergence of energy and food security issues generated through water competition, particularly if the higher GDP growth was induced by a significant specialization in the production and trade of one of these goods.

Given the methodological purpose of the paper, these results are mainly used to test the performance of the modified model and to evaluate its sensitivity to different parameterisations. Accordingly, they demonstrated that the degree of substitutability of water with the other inputs and the mobility of water between sectors are the most important drivers of the model's responses. As such, at this stage, we placed less emphasis on the realism of the scenarios and relative responses, though we are conscious of the complexities of real life. For instance, we acknowledge that regulatory and institutional constraints are significantly more relevant in the practice of allocating water between sectors under scarcity than any consideration of pure economic efficiency. Indeed, under resource constraints, could be infeasible and inconvenient (morally or politically) to reduce domestic or agricultural uses over a certain threshold, regardless of its efficiency from a merely economic point of view. Likewise, international specialisation, which, in our framework, is solely driven by comparative advantages, would be generally expected to be mediated also by geopolitical strategies. For example, it is arduous to believe that the EU, which is already dealing with energy insecurity and import-dependency issues, would deliberately exacerbate these patterns in order to respond to water scarcity pressures, even though this might be an economically efficient option.

Furthermore, it is necessary to recognise other simplifications in our analysis. The most noteworthy among them are:

a) The representation of the energy sector. Currently, it does not distinguish between different technologies for energy production and is therefore unable to capture instances such as the water specificities of fossils vis a vis renewable or other energy sources.
b) The scale of the analysis. These simulations were developed on the basis of rather large geopolitical blocs. Consequently, they are unable to capture the sub-regional responses to water scarcity, and thus fail in revealing eventual local hotspots (e.g. at the sub-national or river basin level) that could be potentially at risk of energetic or agricultural insecurity.
c) The specification of water types and water generation technologies. These analyses were limited to considering water as an undifferentiated factor of production. As such, they did not differentiate with respect to the availability and regeneration patterns of freshwater vs. groundwater. Similarly, the possibility of compensating for water scarcity with unconventional water production technologies, such as desalination or wastewater treatment, was not taken into consideration.

Still, the enhanced Nexus analysis allowed by our improved framework highlights trends that are usually overlooked by current macroeconomic analyses. Furthermore, it highlights that neglecting these factors can lead to distorted scenario projections and biased policy recommendations. This work is therefore a preliminary step towards a comprehensive Nexus analysis that paves the way for numerous research developments. More specifically, the possible steps forward will require addressing the limitations of this work, and incorporating the political dimension, investigating, for instance, whether climate change mitigation strategies may be more or less effective and/or costly in the presence of sectoral competition over water.

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Supplementary Information Chapter 2

Section A. Regional and Sectorial

Table A1. Regional Aggregation

Region Name	Countries
OECD Europe	Austria; Belgium; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Luxembourg; Netherlands; Poland; Portugal; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Switzerland; Norway; Rest of European Free Trade Association; Israel; Turkey
OECD America	Canada; United States of America; Mexico, Rest of North America; Chile
OECD Asia-Oceania	Australia; New Zealand; Rest of Oceania; Japan; Korea, Republic of
Other Europe and Eurasia	Cyprus; Latvia, Lithuania, Malta; Albania; Bulgaria; Belarus; Croatia; Romania; Russian Federation; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyzstan, Rest of Former Soviet Union; Armenia, Azerbaijan; Georgia
Other Asia	Mongolia; Rest of East Asia, Brunei Darussalam; Cambodia; Indonesia; Lao PDR; Malaysia; Philippines; Singapore; Thailand; Viet Nam; Rest of Southeast Asia; Bangladesh; Nepal; Pakistan; Sri Lanka; Rest of South Asia
China	China, Hong Kong, Special Administrative Region of China; Taiwan
India	India
Middle East	Bahrain; Iran, Islamic Republic of; Jordan; Kuwait; Oman; Qatar; Saudi Arabia; United Arab Emirates; Rest of Western Asia
Africa	Egypt; Morocco, Tunisia; Rest of North Africa; Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Nigeria; Senegal; Togo; Rest of Western Africa; Rest of Central Africa; South Central Africa; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mozambique; Rwanda; Tanzania, United Republic of; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Namibia; South Africa; Rest of South African Customs Union
Latin America	Argentina; Bolivia; Brazil; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela (Bolivarian Republic of); Rest of South America; Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Rest of Caribbean

Table A2. Sectoral Aggregation

Sector Name	Sectors
Irrigated Agriculture	Irrigated: Paddy rice, Wheat, Cereals; Veg and Fruit; Oil seeds; Cane and Beet; Fibers crops; Other Crops
Rainfed Agriculture	Rainfed: Paddy rice, Wheat, Cereals; Veg and Fruit; Oil seeds; Cane and Beet; Fibers crops; Other Crops
Industries	Cattle; Other Animal Products; Raw milk; Wool; Forestry; Fishing; Other Mining Extraction; Cattle Meat; Other Meat; Vegetable Oils; Milk: dairy products; Processed Rice; Sugar and Molasses; Other Food; Beverages and Tobacco Products; Manufacture of textiles; Manufacture of wearing apparel; Manufacture of leather and related products; Lumber; Paper Products and Publishing; Chemical, rubber, plastic products; Mineral products nec; Ferrous metals; Metals nec; Metal products; Motor vehicles and parts; Transport equipment nec; Electronic equipment; Machinery and equipment nec; Manufactures nec;
Energy	Coal: mining and agglomeration of hard coal, lignite and peat; Oil: extraction of crude petroleum, service activities incidental to oil and gas extraction excluding surveying (part); Petroleum and Coke; Gas: extraction of natural gas, service activities incidental to oil and gas extraction excluding surveying (part), distributed gas; Transmission and Distribution of Electricity; Nuclear Base Load; Coal Base load; Gas Base load; Oil Base load; Gas Peak load; Oil Peak load; Wind Base load; Other Base load; Solar peak load; Hydropower Base load, Hydro peak load
Services	Water: collection, purification, and distribution; Construction: building houses factories offices and roads; Trade; Other transport; Water transport; Air transport; Communications; Other financial intermediation; Insurance; other business services, Dwellings, imputed rents of houses occupied by owners

Section B. GDP, output and prices and import impacts of systematic homogeneous water shocks on different model specifications.

B1. GDP impacts.

	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America	
Model Description	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**	**Min (-10%)**	**Max (-50%)**
CES_Onesec_SlugLa_SlugW	0.00	-0.09	-0.01	-0.20	0.00	-0.14	-0.01	-0.33	-0.05	-1.34	-0.02	-0.53	-0.14	-4.31	-0.02	-0.53	-0.02	-0.70	-0.01	-0.36
CES_Onesec_MobLa_SlugW	0.00	-0.09	-0.01	-0.20	-0.01	-0.14	-0.01	-0.32	-0.05	-1.32	-0.02	-0.52	-0.14	-4.24	-0.02	-0.52	-0.02	-0.69	-0.01	-0.36
CES_Twosec_MobLa_MobW	-0.01	-0.08	-0.02	-0.23	0.00	-0.09	-0.01	-0.20	-0.05	-1.09	-0.02	-0.39	-0.14	-3.50	-0.02	-0.35	-0.02	-0.43	-0.01	-0.24
CES_Twosec_SlugLa_MobW	-0.01	-0.08	-0.02	-0.23	0.00	-0.08	-0.01	-0.20	-0.05	-1.10	-0.02	-0.39	-0.14	-3.54	-0.02	-0.35	-0.02	-0.44	-0.01	-0.24
CES_Twosec_MobLa_SlugW	-0.01	-0.11	-0.02	-0.27	-0.01	-0.14	-0.01	-0.34	-0.05	-1.32	-0.02	-0.56	-0.14	-4.29	-0.02	-0.50	-0.02	-0.67	-0.01	-0.36
CES_Twosec_SlugLa_SlugW	-0.01	-0.11	-0.02	-0.27	-0.01	-0.14	-0.01	-0.35	-0.05	-1.34	-0.02	-0.56	-0.15	-4.37	-0.02	-0.51	-0.02	-0.68	-0.01	-0.37
Q-Leontief_Onesec_MobLa_SlugW	-0.01	-7.84	-0.02	-11.91	-0.02	-10.96	-0.06	-13.40	-0.13	-29.01	-0.07	-35.01	-0.43	-35.32	-0.07	-22.65	-0.10	-28.43	-0.03	-21.08
Q-Leontief_Onesec_SlugLa_SlugW	-0.01	-7.83	-0.02	-11.91	-0.02	-10.96	-0.06	-13.40	-0.13	-29.03	-0.07	-35.03	-0.43	-35.33	-0.07	-22.66	-0.10	-28.44	-0.03	-21.08
Q-Leontief_Twosec_MobLa_MobW	-0.03	-5.60	-0.06	-8.11	-0.01	-4.95	0.05	-6.83	-0.12	-15.60	-0.09	-29.53	-0.41	-32.37	-0.02	-7.30	-0.05	-13.44	-0.02	-11.56
Q-Leontief_Twosec_SlugLa_MobW	-0.03	-5.60	-0.06	-8.11	-0.01	-4.96	0.05	-6.85	-0.12	-15.62	-0.09	-29.54	-0.41	-32.38	-0.02	-7.31	-0.05	-13.45	-0.02	-11.56
Q-Leontief_Twosec_MobLa_SlugW	-0.02	-10.23	-0.05	-14.65	-0.02	-15.54	-0.05	-20.12	-0.13	-31.38	-0.09	-35.44	-0.43	-36.23	-0.04	-25.31	-0.07	-31.12	-0.03	-22.20
Q-Leontief_Twosec_SlugLa_SlugW	-0.02	-10.23	-0.05	-14.65	-0.02	-15.53	-0.05	-20.12	-0.13	-31.40	-0.09	-35.46	-0.43	-36.24	-0.04	-25.32	-0.07	-31.14	-0.03	-22.19

B2. Output impacts.

Irr. Agri	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	1.11	9.03	-1.17	-14.51	1.22	11.44	-1.59	-13.77	-1.20	-17.06	0.13	0.69	-1.25	-19.42	0.39	3.71	0.88	10.87	-0.44	-8.57	-0.2	-3.8
CES_Onesec_MobLa_SlugW	1.10	8.81	-1.21	-14.54	1.30	12.64	-1.65	-13.87	-1.16	-16.79	0.15	1.03	-1.21	-19.16	0.36	3.44	0.87	10.65	-0.44	-8.55	-0.2	-3.6
CES_Twosec_MobLa_MobW	1.18	17.39	-0.25	2.39	0.86	6.63	-1.14	-7.95	-1.30	-18.74	0.09	0.66	-1.18	-18.34	0.02	-3.83	0.36	0.73	-0.87	-12.02	-0.2	-3.3
CES_Twosec_SlugLa_MobW	1.18	17.61	-0.24	2.41	0.80	5.84	-1.09	-7.76	-1.33	-18.90	0.08	0.45	-1.22	-18.59	0.04	-3.62	0.37	0.95	-0.85	-11.86	-0.2	-3.3
CES_Twosec_MobLa_SlugW	1.10	8.78	-1.19	-14.52	1.29	12.60	-1.65	-13.89	-1.17	-16.81	0.15	1.03	-1.20	-19.15	0.33	3.30	0.84	10.52	-0.45	-8.58	-0.2	-3.7
CES_Twosec_SlugLa_SlugW	1.11	9.01	-1.15	-14.49	1.21	11.40	-1.59	-13.79	-1.21	-17.08	0.13	0.69	-1.24	-19.41	0.36	3.58	0.85	10.74	-0.45	-8.60	-0.2	-3.8
Q-Leontief_Onesec_MobLa_SlugW	0.03	-42.04	-3.59	-44.85	0.80	-41.78	-3.54	-44.38	-4.26	-45.18	-1.00	-42.76	-4.80	-45.76	-0.80	-42.31	0.27	-41.73	-2.71	-44.13	-2.0	-43.5
Q-Leontief_Onesec_SlugLa_SlugW	0.03	-42.04	-3.59	-44.85	0.76	-41.78	-3.53	-44.38	-4.24	-45.18	-1.01	-42.76	-4.79	-45.76	-0.80	-42.31	0.27	-41.73	-2.71	-44.13	-2.0	-43.5
Q-Leontief_Twosec_MobLa_MobW	1.88	-9.88	-1.09	-0.30	0.31	-47.87	-5.27	-63.18	-4.64	-47.54	-0.86	-31.43	-5.17	-44.97	-1.45	-43.22	-0.46	-43.82	-3.47	-52.09	-2.0	-38.4
Q-Leontief_Twosec_SlugLa_MobW	1.86	-9.88	-1.10	-0.31	0.28	-47.87	-5.22	-63.16	-4.62	-47.54	-0.88	-31.43	-5.15	-44.97	-1.44	-43.22	-0.46	-43.82	-3.46	-52.09	-2.0	-38.4
Q-Leontief_Twosec_MobLa_SlugW	0.03	-42.04	-3.58	-44.85	0.79	-41.77	-3.54	-44.36	-4.27	-45.18	-0.97	-42.76	-4.74	-45.76	-0.87	-42.30	0.22	-41.73	-2.72	-44.13	-2.0	-43.5
Q-Leontief_Twosec_SlugLa_SlugW	0.03	-42.04	-3.58	-44.85	0.76	-41.77	-3.53	-44.36	-4.25	-45.18	-0.99	-42.76	-4.73	-45.76	-0.87	-42.30	0.22	-41.73	-2.72	-44.13	-2.0	-43.5

Energy	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	-0.09	-2.83	-0.06	-2.02	-0.15	-4.61	-0.03	-1.19	0.26	8.57	-0.02	-0.23	0.64	23.05	-0.02	-0.53	-0.01	0.32	-0.04	-1.15	0.0	1.9
CES_Onesec_MobLa_SlugW	-0.09	-2.72	-0.06	-1.92	-0.15	-4.49	-0.03	-1.13	0.25	8.12	-0.02	-0.35	0.61	22.23	-0.02	-0.51	-0.01	0.31	-0.04	-1.09	0.0	1.8
CES_Twosec_MobLa_MobW	-0.10	-2.46	-0.45	-6.72	0.05	-0.53	0.01	-0.10	0.38	7.90	-0.20	-3.33	0.22	9.91	0.08	1.06	0.12	2.00	0.08	0.85	0.0	0.9
CES_Twosec_SlugLa_MobW	-0.10	-2.51	-0.45	-6.80	0.05	-0.56	0.01	-0.12	0.39	8.13	-0.19	-3.32	0.24	10.40	0.07	1.06	0.12	2.01	0.08	0.82	0.0	0.9
CES_Twosec_MobLa_SlugW	-0.10	-2.76	-0.34	-4.30	-0.02	-3.38	-0.01	-0.94	0.34	8.85	-0.11	-1.15	0.46	19.39	0.04	0.00	0.07	1.03	0.04	-0.35	0.0	1.6
CES_Twosec_SlugLa_SlugW	-0.10	-2.87	-0.34	-4.39	-0.02	-3.50	-0.01	-0.99	0.35	9.29	-0.11	-1.03	0.48	20.15	0.04	-0.03	0.07	1.04	0.04	-0.41	0.0	1.7
Q-Leontief_Onesec_MobLa_SlugW	-0.83	-58.08	-0.73	-23.94	-1.20	-28.24	-0.38	-28.09	2.04	-8.85	0.35	-72.46	4.90	-69.37	0.14	35.01	0.83	90.47	-0.34	38.29	0.5	-12.5
Q-Leontief_Onesec_SlugLa_SlugW	-0.83	-58.11	-0.74	-23.99	-1.20	-28.28	-0.38	-28.13	2.06	-8.66	0.36	-72.45	4.93	-69.37	0.14	35.00	0.83	90.51	-0.35	38.38	0.5	-12.5
Q-Leontief_Twosec_MobLa_MobW	-2.88	-89.94	-5.00	-92.33	1.14	64.12	0.65	6.16	3.93	135.69	-2.33	-87.66	2.91	-53.68	1.28	35.25	2.31	75.65	1.46	53.03	0.3	4.6
Q-Leontief_Twosec_SlugLa_MobW	-2.88	-89.94	-5.00	-92.32	1.14	64.00	0.64	6.12	3.94	135.73	-2.32	-87.68	2.92	-53.67	1.28	35.25	2.31	75.69	1.45	52.99	0.3	4.6
Q-Leontief_Twosec_MobLa_SlugW	-1.42	-34.47	-3.34	-38.54	0.55	-28.09	-0.14	-32.32	2.83	-28.25	-1.21	-36.33	0.08	-37.60	0.98	-16.01	1.94	-22.57	0.30	-31.14	0.1	-30.5
Q-Leontief_Twosec_SlugLa_SlugW	-1.42	-34.47	-3.35	-38.54	0.55	-28.09	-0.14	-32.32	2.85	-28.25	-1.21	-36.33	0.09	-37.60	0.99	-16.01	1.94	-22.57	0.29	-31.14	0.1	-30.5

Rainfed	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	-0.03	-1.39	-0.05	-2.63	-0.30	-8.48	0.02	-0.26	-0.04	-0.52	-0.04	-1.10	-0.03	-0.06	-0.07	-2.33	-0.04	-0.93	-0.01	-0.69	-0.1	-1.8
CES_Onesec_MobLa_SlugW	-0.03	-1.45	-0.05	-2.89	-0.33	-8.80	0.02	-0.32	-0.04	-0.24	-0.04	-0.98	-0.02	0.58	-0.06	-2.15	-0.04	-0.94	-0.01	-0.69	-0.1	-1.8
CES_Twosec_MobLa_MobW	-0.04	-1.15	-0.05	-2.41	-0.27	-5.27	-0.01	-0.64	-0.03	0.16	-0.03	-0.68	0.00	0.86	-0.15	-2.48	-0.04	-0.65	-0.02	-0.53	-0.1	-1.3
CES_Twosec_SlugLa_MobW	-0.04	-1.14	-0.05	-2.27	-0.25	-4.94	-0.01	-0.59	-0.04	-0.04	-0.03	-0.72	-0.01	0.38	-0.15	-2.45	-0.04	-0.64	-0.02	-0.49	-0.1	-1.3
CES_Twosec_MobLa_SlugW	-0.04	-1.46	-0.02	-2.55	-0.34	-8.89	0.01	-0.44	-0.04	-0.30	-0.04	-0.96	-0.01	0.67	-0.14	-2.80	-0.05	-1.04	-0.04	-0.93	-0.1	-1.9
CES_Twosec_SlugLa_SlugW	-0.04	-1.41	-0.02	-2.34	-0.31	-8.55	0.01	-0.37	-0.05	-0.57	-0.04	-1.08	-0.02	0.02	-0.14	-2.93	-0.05	-1.03	-0.03	-0.89	-0.1	-1.9
Q-Leontief_Onesec_MobLa_SlugW	-0.76	-34.44	-1.18	-30.75	-1.71	-56.51	-0.22	-2.85	0.49	-23.73	0.18	2.34	0.55	-49.46	-0.50	-22.78	0.00	-24.45	-0.57	-34.87	-0.4	-27.8
Q-Leontief_Onesec_SlugLa_SlugW	-0.73	-33.14	-1.03	-29.77	-1.57	-56.40	-0.20	-2.39	0.37	-24.60	0.14	0.94	0.47	-49.48	-0.53	-23.23	-0.03	-24.77	-0.54	-35.39	-0.4	-27.8
Q-Leontief_Twosec_MobLa_MobW	-0.51	-37.85	-0.45	-39.70	-1.64	-47.90	-0.56	-19.56	0.36	-9.10	0.29	63.65	0.76	-43.19	-1.94	-69.59	-0.23	-17.08	-0.93	-24.88	-0.5	-24.5
Q-Leontief_Twosec_SlugLa_MobW	-0.51	-36.28	-0.41	-38.10	-1.47	-47.12	-0.51	-18.92	0.27	-10.38	0.24	60.07	0.67	-43.30	-1.88	-69.06	-0.25	-17.42	-0.84	-24.95	-0.5	-24.5
Q-Leontief_Twosec_MobLa_SlugW	-0.74	-32.37	-0.77	-16.45	-1.91	-55.52	-0.33	21.45	0.41	-31.75	0.27	-23.51	0.91	-52.64	-1.68	-39.44	-0.17	-16.50	-0.85	-37.85	-0.5	-28.5
Q-Leontief_Twosec_SlugLa_SlugW	-0.71	-31.28	-0.67	-16.24	-1.74	-55.59	-0.31	20.16	0.30	-32.03	0.22	-23.78	0.80	-52.65	-1.64	-39.51	-0.20	-16.64	-0.78	-38.10	-0.5	-28.6

B3. Price impacts.

Irr. agri	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	2.5	110.7	4.7	178.9	2.4	118.7	4.1	130.6	6.7	226.4	3.1	122.9	8.0	305.6	2.5	96.5	2.3	104.6	4.3	170.0	4.1	156.5
CES_Onesec_MobLa_SlugW	2.4	105.8	4.6	171.1	2.2	109.7	4.1	125.4	6.5	215.8	2.9	114.0	7.7	294.7	2.5	92.6	2.3	99.8	4.2	162.7	3.9	149.2
CES_Twosec_MobLa_MobW	1.6	37.5	3.1	62.9	1.9	57.3	3.2	58.7	6.2	153.0	2.4	55.3	7.2	221.1	2.4	58.0	2.1	55.0	3.6	78.8	3.4	83.8
CES_Twosec_SlugLa_MobW	1.7	39.1	3.2	65.5	2.1	61.1	3.2	60.3	6.4	157.7	2.5	58.8	7.4	228.0	2.4	59.5	2.2	56.8	3.6	81.0	3.5	86.8
CES_Twosec_MobLa_SlugW	2.4	105.6	4.6	170.8	2.2	109.4	4.1	125.1	6.4	215.1	2.9	113.8	7.7	294.1	2.5	92.4	2.3	99.6	4.2	162.4	3.9	148.8
CES_Twosec_SlugLa_SlugW	2.5	110.5	4.7	178.7	2.4	118.3	4.1	130.3	6.7	225.5	3.1	122.7	8.0	305.0	2.5	96.4	2.3	104.5	4.3	169.6	4.1	156.1
Q-Leontief_Onesec_MobLa_SlugW	51.4	9013.0	60.6	9813.9	52.3	8074.0	50.8	7650.3	63.9	4250.5	54.6	3919.9	68.7	4065.7	44.4	4689.9	49.7	6652.9	60.5	8888.0	55.7	6701.8
Q-Leontief_Onesec_SlugLa_SlugW	51.6	9009.0	60.7	9810.3	52.5	8071.3	50.9	7647.2	64.0	4248.7	54.8	3918.6	68.8	4064.2	44.5	4688.4	49.8	6649.9	60.7	8884.7	55.8	6699.2
Q-Leontief_Twosec_MobLa_MobW	38.2	3478.6	45.3	3320.6	41.6	5021.0	42.1	4962.4	54.6	2431.2	43.7	2636.1	63.4	2076.4	36.5	2988.2	39.7	3576.1	47.7	5112.1	45.3	3560.3
Q-Leontief_Twosec_SlugLa_MobW	38.3	3477.1	45.4	3319.4	41.7	5018.7	42.2	4958.3	54.6	2430.4	43.9	2635.5	63.4	2075.8	36.5	2987.0	39.7	3574.7	47.8	5110.6	45.4	3558.7
Q-Leontief_Twosec_MobLa_SlugW	51.3	8592.3	60.6	9050.6	52.2	7382.0	50.5	6202.8	63.6	4004.9	54.9	3780.3	69.9	3791.0	44.1	4723.3	49.5	6500.4	60.4	8483.4	55.7	6251.1
Q-Leontief_Twosec_SlugLa_SlugW	51.4	8590.1	60.7	9049.5	52.4	7382.2	50.6	6201.4	63.7	4004.1	55.1	3779.7	70.0	3790.3	44.2	4722.4	49.6	6498.8	60.5	8481.9	55.8	6250.0

Energy	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	0.0	-1.0	0.0	-1.3	0.0	-1.5	0.0	-1.6	-0.1	-4.6	-0.1	-2.7	-0.5	-14.4	-0.1	-2.7	-0.1	-2.4	-0.1	-2.0	-0.1	-3.4
CES_Onesec_MobLa_SlugW	0.0	-0.9	0.0	-1.2	0.0	-1.4	0.0	-1.5	-0.1	-4.4	-0.1	-2.5	-0.4	-13.9	-0.1	-2.6	-0.1	-2.3	-0.1	-1.9	-0.1	-3.3
CES_Twosec_MobLa_MobW	0.1	1.8	0.3	4.1	0.1	0.4	0.1	1.1	0.0	-1.2	0.2	2.1	-0.1	-6.1	0.1	0.5	0.1	1.0	0.1	1.3	0.1	0.5
CES_Twosec_SlugLa_MobW	0.1	1.8	0.3	4.1	0.0	0.4	0.1	1.1	0.0	-1.2	0.2	2.1	-0.1	-6.3	0.1	0.5	0.1	1.0	0.1	1.3	0.1	0.5
CES_Twosec_MobLa_SlugW	0.1	-0.1	0.2	0.7	0.0	-1.0	0.0	-0.7	-0.1	-3.7	0.1	-1.4	-0.3	-12.3	0.0	-1.7	0.0	-1.4	0.1	-1.0	0.0	-2.2
CES_Twosec_SlugLa_SlugW	0.1	-0.2	0.2	0.7	0.0	-1.0	0.0	-0.8	-0.1	-3.9	0.1	-1.5	-0.3	-12.7	0.0	-1.9	0.0	-1.5	0.1	-1.1	0.0	-2.4
Q-Leontief_Onesec_MobLa_SlugW	-0.4	-45.3	-0.4	-57.1	-0.6	-60.3	-0.6	-52.4	-1.4	-66.8	-1.1	-53.6	-3.4	-42.7	-0.9	-64.5	-0.9	-64.4	-0.7	-64.4	-1.0	-57.1
Q-Leontief_Onesec_SlugLa_SlugW	-0.4	-45.3	-0.4	-57.1	-0.6	-60.3	-0.6	-52.4	-1.4	-66.8	-1.1	-53.6	-3.4	-42.7	-0.9	-64.5	-0.9	-64.3	-0.7	-64.4	-1.0	-57.1
Q-Leontief_Twosec_MobLa_MobW	2.3	205.0	3.8	347.1	0.8	35.0	1.4	60.2	0.4	33.3	2.4	162.9	-0.6	45.7	1.2	52.6	1.5	57.5	1.6	55.9	1.5	105.5
Q-Leontief_Twosec_SlugLa_MobW	2.3	204.9	3.8	346.9	0.8	34.9	1.4	60.2	0.4	33.3	2.4	162.8	-0.6	45.7	1.2	52.6	1.5	57.5	1.6	55.8	1.5	105.5
Q-Leontief_Twosec_MobLa_SlugW	1.2	190.7	2.3	198.9	0.3	157.5	0.9	179.2	0.0	146.9	1.1	109.5	0.1	88.0	0.5	159.0	0.7	171.6	1.0	173.4	0.8	157.5
Q-Leontief_Twosec_SlugLa_SlugW	1.2	190.6	2.3	198.8	0.3	157.4	0.9	179.2	-0.1	146.8	1.1	109.4	0.1	87.9	0.5	158.9	0.7	171.6	1.0	173.3	0.8	157.4

Rainfed	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	0.0	0.4	0.0	0.6	0.3	6.3	0.0	-0.1	-0.1	-4.4	0.0	-0.2	-0.4	-13.6	0.0	0.0	0.0	-1.0	0.0	-0.3	0.0	-1.2
CES_Onesec_MobLa_SlugW	0.0	0.4	0.0	0.7	0.3	6.6	0.0	-0.1	-0.1	-4.7	0.0	-0.5	-0.4	-14.4	0.0	-0.2	0.0	-1.0	0.0	-0.4	0.0	-1.4
CES_Twosec_MobLa_MobW	0.0	0.5	0.0	0.8	0.2	3.6	0.0	0.1	-0.1	-4.0	0.0	-0.2	-0.4	-12.3	0.1	0.3	0.0	-0.3	0.0	-0.1	0.0	-1.2
CES_Twosec_SlugLa_MobW	0.0	0.5	0.0	0.7	0.2	3.3	0.0	0.1	-0.1	-3.7	0.0	0.0	-0.4	-11.6	0.1	0.3	0.0	-0.3	0.0	-0.1	0.0	-1.1
CES_Twosec_MobLa_SlugW	0.0	0.4	0.0	0.5	0.3	6.6	0.0	-0.1	-0.1	-4.8	0.0	-0.6	-0.4	-14.7	0.1	0.1	0.0	-0.7	0.0	-0.3	0.0	-1.4
CES_Twosec_SlugLa_SlugW	0.0	0.4	0.0	0.5	0.3	6.3	0.0	-0.1	-0.1	-4.5	0.0	-0.3	-0.4	-13.9	0.1	0.3	0.0	-0.7	0.0	-0.3	0.0	-1.2
Q-Leontief_Onesec_MobLa_SlugW	-0.1	-25.4	-0.3	-38.1	0.3	-12.4	-0.3	-39.4	-2.5	-58.5	-1.3	-71.4	-4.4	4.1	-0.8	-52.3	-1.3	-39.1	-0.4	-43.3	-1.1	-37.6
Q-Leontief_Onesec_SlugLa_SlugW	-0.2	-26.6	-0.4	-38.9	0.2	-13.0	-0.4	-40.0	-2.3	-58.5	-1.3	-71.4	-4.2	4.0	-0.8	-52.4	-1.2	-39.1	-0.5	-43.5	-1.1	-37.9
Q-Leontief_Twosec_MobLa_MobW	-0.1	-14.8	-0.5	-22.5	0.3	-14.6	-0.2	-30.8	-2.3	-56.0	-1.2	-73.4	-4.6	-34.1	0.1	9.7	-0.5	-24.0	-0.2	-36.7	-0.9	-29.7
Q-Leontief_Twosec_SlugLa_MobW	-0.1	-16.6	-0.5	-24.5	0.1	-16.2	-0.3	-31.8	-2.2	-56.0	-1.2	-73.4	-4.5	-34.1	0.0	8.0	-0.5	-24.1	-0.3	-37.3	-0.9	-30.6
Q-Leontief_Twosec_MobLa_SlugW	-0.1	-29.7	-0.5	-46.2	0.4	-18.6	-0.4	-56.0	-2.5	-56.8	-1.5	-66.5	-5.2	7.4	-0.2	-43.7	-0.9	-40.4	-0.4	-43.3	-1.1	-39.4
Q-Leontief_Twosec_SlugLa_SlugW	-0.2	-30.5	-0.6	-46.4	0.2	-18.6	-0.5	-56.0	-2.4	-56.8	-1.4	-66.5	-4.9	7.4	-0.3	-43.7	-0.9	-40.4	-0.5	-43.3	-1.1	-39.5

B4. Imports Impacts.

Irr. Agri	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	-0.95	-2.74	2.34	41.95	-3.24	-19.4	2.84	32.69	5.97	110.6	-2.27	-21	11.4	313.8	-1.56	-12.41	-3.01	-24.4	0.86	21.88	1.23	44.11
CES_Onesec_MobLa_SlugW	-0.94	-2.74	2.32	41.15	-3.52	-21.6	2.9	32.39	5.78	110	-2.43	-23.3	10.9	315.8	-1.48	-11.97	-2.98	-24.2	0.82	21.72	1.13	43.73
CES_Twosec_MobLa_MobW	-1.05	-9.96	1.09	15.94	-1.88	2.6	2.09	23.31	6.53	162	-1.5	-7.11	11.5	510.3	-0.56	5.48	-1.39	0.2	1.91	36.82	1.67	73.95
CES_Twosec_SlugLa_MobW	-1.05	-9.97	1.13	16.65	-1.68	4.58	2.04	23.39	6.69	163.1	-1.38	-5.29	12	519.9	-0.63	4.96	-1.42	-0.16	1.89	36.35	1.75	75.36
CES_Twosec_MobLa_SlugW	-0.94	-2.74	2.31	41.26	-3.51	-21.7	2.87	31.96	5.75	109.2	-2.42	-23.3	10.8	315	-1.44	-12.07	-2.95	-24.3	0.83	21.48	1.13	43.48
CES_Twosec_SlugLa_SlugW	-0.95	-2.75	2.33	42.07	-3.23	-19.5	2.81	32.26	5.94	109.8	-2.26	-20.9	11.3	313	-1.52	-12.51	-2.98	-24.5	0.87	21.63	1.23	43.86
Q-Leontief_Onesec_MobLa_SlugW	2.35	50.57	19.4	79.39	0.89	93.81	10.75	74.58	17.3	-72.4	3.66	-87	28.1	-79.87	-3.4	-49.91	-3.07	-61.9	12.43	-12.88	8.84	-6.56
Q-Leontief_Onesec_SlugLa_SlugW	2.35	50.55	19.43	79.39	0.98	93.82	10.75	74.56	17.23	-72.4	3.81	-87	27.9	-79.87	-3.4	-49.9	-3.05	-62	12.44	-12.88	8.85	-6.57
Q-Leontief_Twosec_MobLa_MobW	0.42	13.73	14.71	45.41	2.97	193.5	11.87	84.68	19.31	-55	5.48	-45.8	45.5	-82.59	-1.84	-19.35	-1.7	-36	13.21	130.2	11	22.88
Q-Leontief_Twosec_SlugLa_MobW	0.43	13.72	14.75	45.39	3.05	193.4	11.81	84.57	19.16	-55	5.66	-45.8	45.3	-82.58	-1.85	-19.36	-1.7	-35.9	13.19	130.26	10.98	22.87
Q-Leontief_Twosec_MobLa_SlugW	2.35	51.24	19.59	68.51	0.51	72.48	10.26	-11.05	16.46	-72.3	4.28	-85	30.9	-82.09	-3.84	-39.07	-3.63	-52.6	12.1	-7.83	8.9	-15.76
Q-Leontief_Twosec_SlugLa_SlugW	2.36	51.22	19.62	68.53	0.61	72.57	10.26	-11.05	16.39	-72.3	4.44	-85	30.8	-82.09	-3.85	-39.07	-3.62	-52.6	12.11	-7.84	8.91	-15.76

Energy	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	0.05	1.88	0.05	2.03	0.01	0.53	0.01	0.57	-0.27	-8.18	-0.03	-1.21	-0.73	-26.96	-0.04	-0.89	-0.09	-2.77	-0.03	-0.79	-0.11	-3.58
CES_Onesec_MobLa_SlugW	0.05	1.8	0.05	1.95	0.01	0.5	0.01	0.55	-0.26	-7.86	-0.03	-1.05	-0.71	-26.15	-0.04	-0.87	-0.09	-2.67	-0.03	-0.77	-0.1	-3.46
CES_Twosec_MobLa_MobW	0.04	1.31	0.45	7.29	-0.04	-0.4	-0.04	-0.46	-0.3	-6	0.25	4.36	-0.39	-15	-0.08	-1.15	-0.07	-1.06	-0.02	-0.18	-0.02	-1.13
CES_Twosec_SlugLa_MobW	0.04	1.35	0.45	7.38	-0.04	-0.4	-0.04	-0.47	-0.3	-6.13	0.25	4.36	-0.4	-15.47	-0.08	-1.16	-0.07	-1.1	-0.02	-0.18	-0.02	-1.18
CES_Twosec_MobLa_SlugW	0.04	1.76	0.34	4.61	-0.03	0.09	-0.02	0.23	-0.3	-8.04	0.1	0.18	-0.59	-24.44	-0.07	-1.11	-0.09	-2.7	-0.04	-0.85	-0.07	-3.03
CES_Twosec_SlugLa_SlugW	0.04	1.83	0.34	4.68	-0.03	0.12	-0.02	0.25	-0.3	-8.36	0.1	0.02	-0.61	-25.23	-0.07	-1.12	-0.09	-2.79	-0.04	-0.88	-0.07	-3.15
Q-Leontief_Onesec_MobLa_SlugW	0.55	83.96	0.66	42.12	0.12	-7.41	0.17	89.86	-2.11	-81.2	-0.77	-29.6	-4.87	-62.77	-0.22	-15.66	-0.95	-74.9	-0.16	-48.19	-0.76	-10.37
Q-Leontief_Onesec_SlugLa_SlugW	0.55	83.96	0.66	42.18	0.12	-7.39	0.17	89.98	-2.11	-81.2	-0.77	-29.6	-4.88	-62.77	-0.22	-15.65	-0.94	-74.9	-0.16	-48.18	-0.76	-10.35
Q-Leontief_Twosec_MobLa_MobW	1.41	116.5	5.52	262.1	-0.58	-5.54	-0.59	-8.24	-2.55	-60.3	3.72	81.78	-3.11	-64.49	-0.95	-14.7	-0.83	-49.4	-0.49	-15.72	0.16	24.2
Q-Leontief_Twosec_SlugLa_MobW	1.41	116.5	5.52	261.9	-0.58	-5.56	-0.6	-8.25	-2.54	-60.2	3.71	81.81	-3.11	-64.48	-0.95	-14.7	-0.83	-49.4	-0.49	-15.71	0.15	24.19
Q-Leontief_Twosec_MobLa_SlugW	0.74	31.46	3.52	33.36	-0.45	-16.4	-0.19	-25.69	-2.25	-75.8	1.79	-76.8	-1.05	-87.11	-0.71	-36.24	-1.06	-68.3	-0.07	-34.04	0.03	-35.55
Q-Leontief_Twosec_SlugLa_SlugW	0.74	31.43	3.52	33.37	-0.45	-16.4	-0.19	-25.68	-2.25	-75.8	1.8	-76.8	-1.05	-87.11	-0.71	-36.23	-1.06	-68.3	-0.08	-34.03	0.03	-35.55

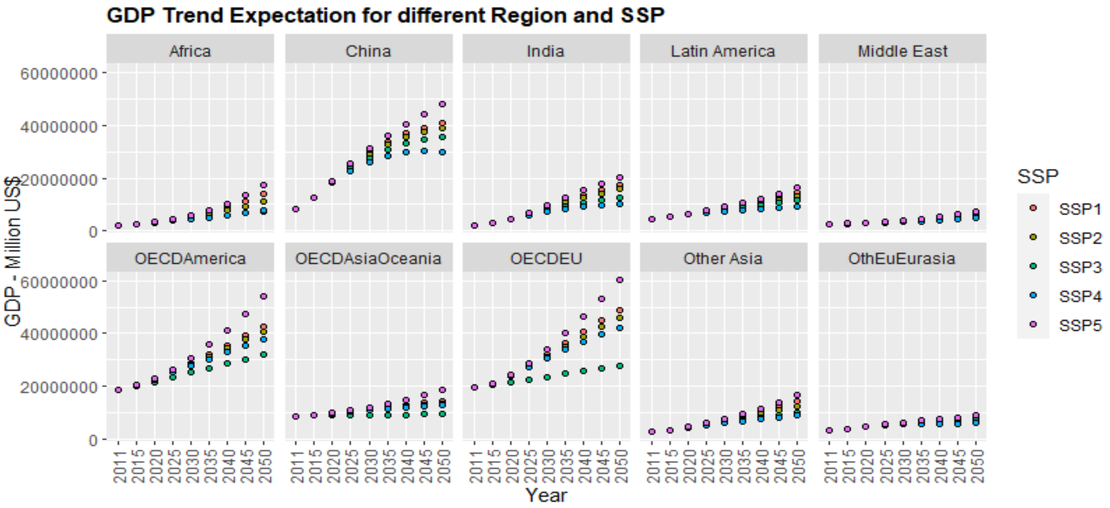
Rainfed	1 OECDEU		2 OECDAmerica		3 OECDAsiaOce		4 OthEUEuras		5 Other Asia		6 China		7 India		8 MiddleEast		9 Africa		10 LatinAmerica		Mean % change	
Model Description	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)	Min (-10%)	Max (-50%)
CES_Onesec_SlugLa_SlugW	0.02	1.19	0.04	1.74	0.22	5.65	-0.01	1.61	-0.24	-8.15	0.03	1.07	-0.97	-30.68	-0.03	-0.47	-0.1	-3.46	-0.04	-1.27	-0.11	-3.28
CES_Onesec_MobLa_SlugW	0.03	1.21	0.04	1.9	0.23	5.97	-0.01	1.7	-0.25	-8.24	0.02	0.57	-1.02	-31.79	-0.04	-0.55	-0.09	-3.37	-0.04	-1.34	-0.11	-3.39
CES_Twosec_MobLa_MobW	0.03	0.95	0.05	1.79	0.17	3.01	-0.04	0.58	-0.28	-6.71	0.02	0.87	-1.09	-27.65	-0.04	-0.59	-0.05	-1.75	-0.05	-1.06	-0.13	-3.06
CES_Twosec_SlugLa_MobW	0.03	0.94	0.05	1.7	0.15	2.73	-0.04	0.46	-0.27	-6.52	0.03	1.06	-1.04	-26.58	-0.04	-0.65	-0.05	-1.79	-0.06	-1.06	-0.12	-2.97
CES_Twosec_MobLa_SlugW	0.02	1.2	0.03	1.79	0.23	5.97	-0.04	1.4	-0.26	-8.23	0.02	0.55	-1.09	-32.32	-0.03	-0.48	-0.05	-2.97	-0.03	-1.25	-0.12	-3.43
CES_Twosec_SlugLa_SlugW	0.02	1.18	0.03	1.66	0.21	5.63	-0.04	1.31	-0.25	-8.17	0.03	1.05	-1.04	-31.18	-0.03	-0.44	-0.06	-3.07	-0.04	-1.23	-0.12	-3.33
Q-Leontief_Onesec_MobLa_SlugW	0.49	37.06	0.43	14.27	0.72	35.19	0.59	38.92	-3.31	-64.5	-1.33	-89.4	-7.86	290.1	-0.72	-49.6	-2.12	-35.8	-0.26	-35.1	-1.34	14.11
Q-Leontief_Onesec_SlugLa_SlugW	0.47	35.35	0.33	12.5	0.64	34.92	0.54	37.35	-3.05	-64.4	-1.12	-89.3	-7.53	291	-0.7	-49.44	-2	-35	-0.24	-34.87	-1.27	13.8
Q-Leontief_Twosec_MobLa_MobW	0.46	47.86	0.3	51.56	0.55	34.52	-0.16	14.63	-3.14	-51.7	-1.09	-89.3	-8.96	11.25	-0.44	25.72	-0.85	1.37	-0.09	-17.54	-1.34	2.83
Q-Leontief_Twosec_SlugLa_MobW	0.46	45.59	0.27	46.87	0.44	32.87	-0.26	12.66	-2.97	-51.7	-0.89	-89.2	-8.58	11.68	-0.49	24.75	-0.76	3.07	-0.17	-17.9	-1.29	1.87
Q-Leontief_Twosec_MobLa_SlugW	0.51	37.04	0.32	-7.93	0.72	23.71	0.13	-44.52	-3.27	-64.7	-1.34	-82.9	-9.65	278.2	-0.57	-28.25	-1.44	-16.7	-0.13	-29	-1.47	6.49
Q-Leontief_Twosec_SlugLa_SlugW	0.49	35.65	0.26	-8.22	0.6	23.88	0.08	-44.23	-3.06	-64.7	-1.12	-82.8	-9.17	278.6	-0.6	-28.21	-1.34	-16.5	-0.17	-28.9	-1.4	6.45

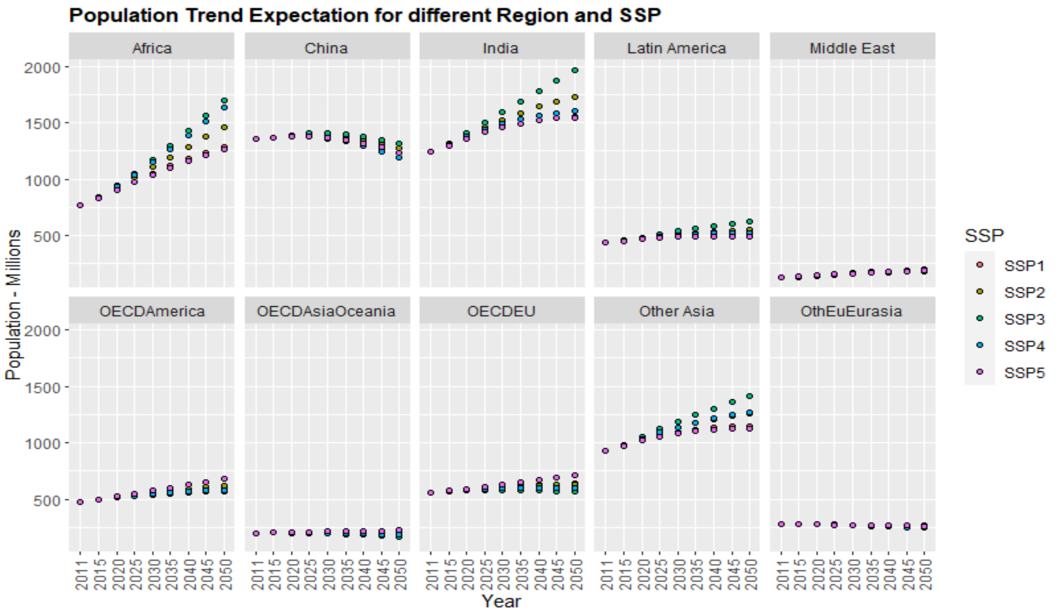
Section C. SSP Differences in cumulated GDP due to Water-Energy Link

C1. SSP Definition and Variable`s trends (GDP – POP)

The Shared Socioeconomic Pathways identifies five narratives which describes the future of societal development based on different demographic, economic, institutional, technological, and environmental variables. Moreover, they address uncertainty in terms of (socioeconomic) challenges to mitigation and adaptation of climate change. In general, the pathways can be identified as follows:

- SSP1 – Sustainability: low challenges for both mitigation and adaptation
- SSP2 – Middle of the Road: medium challenges for both mitigation and adaptation
- SSP3 – Regional Rivalry: high challenges for both mitigation and adaptation
- SSP4 – Inequality: low challenges for mitigation, high challenges for adaptation
- SSP5 – Fossil-fueled Development: high challenges for mitigation, low challenges for adaptation



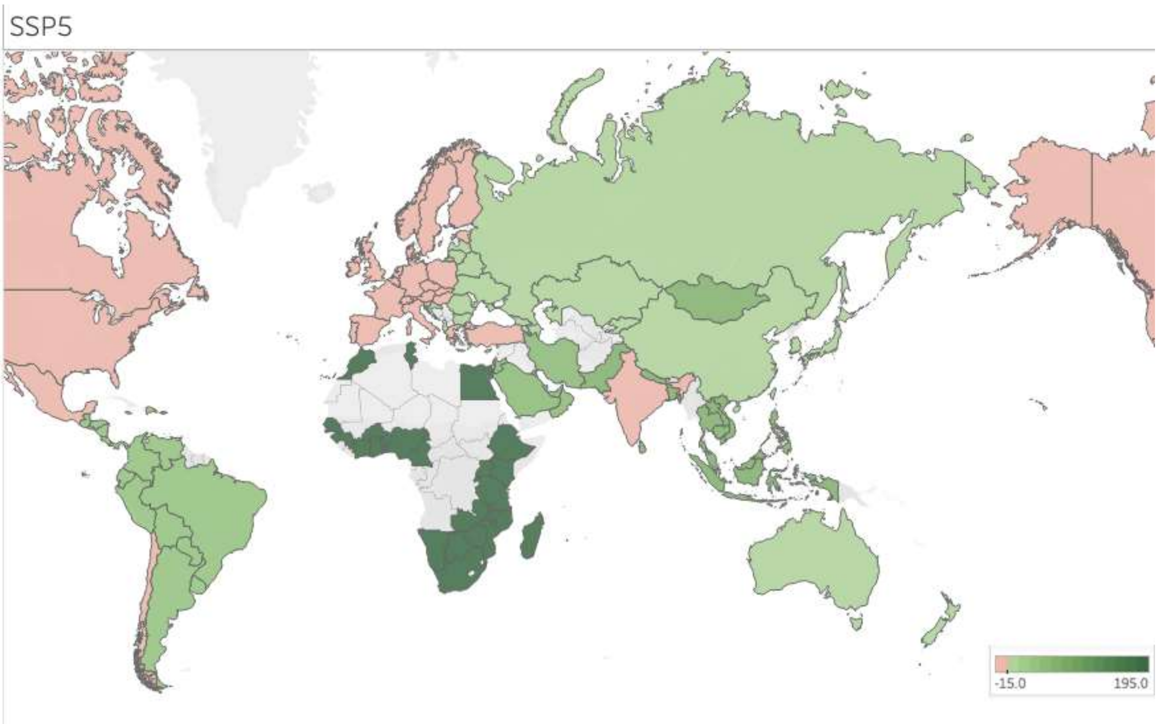


C2. Difference in GDP % output change of model with and without Water-Energy link, 2011–2050 – Dynamic simulations of socio-economic pathway (SSP1)

C3. Difference in GDP % output change of model with and without Water-Energy link, 2011–2050 – Dynamic simulations of socio-economic pathway (SSP3)

C4. Difference in GDP % output change of model with and without Water-Energy link, 2011–2050 – Dynamic simulations of socio-economic pathway (SSP4)

C5. Difference in GDP % output change of model with and without Water-Energy link, 2011–2050 – Dynamic simulations of socio-economic pathways (SSP5)



On the Macroeconomic implications of Water availability Pathways under a Changing Climate: a CGE assessment[24]

Abstract: The paper analyses the macroeconomic implications of the explicit representation of Water as a factor of production, and its role in the Water-Energy-Food Nexus under different socio-climatic pathways, with a specific focus on the role of water scarcity. To do so, it uses a Computable General Equilibrium (CGE) model that implements water as a primary production factor for (irrigated) agriculture and multiple energy sectors. Furthermore, it implements a strategy to create a detailed projection of Nexus water withdrawal pathways up to 2050. The first aim of this study is to assess the relative macroeconomic impacts of potential water constraints and the overall water-climate relationship in two Representative Concentration Pathways (RCP): 6.0 and 2.6. The second objective is to evaluate the implementation of a water allocation framework driven by economic efficiency as a possible adaptation policy. The results show that 1) water scarcity and the overall-water climate relationship will have significant repercussions in terms of GDP impacts 2) implementing a resource distribution/coordination mechanism is generally associated with an improvement of the macroeconomic conditions, even if its implementation does not allow to reduce the damages associated to an RCP 6.0 to the levels associated with RCP 2.6, and 3) macroeconomic gains in context of water mobility are particularly strong when it leads to a specific specialization path (i.e. accelerates a low carbon/low water energy transition).

Keywords: Computable General Equilibrium, Water-Energy-Food Nexus, Resource Economics

1. Introduction

The finiteness of natural resources and their significant interconnection with economic growth and human well-being have been extensively investigated by the economic literature e.g. [1], [2]. Water plays a central role within this debate, due to its tight relationship with food and energy production, which are basic

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[24] This chapter has been partially developed during the visiting period at the Institute for Sustainable Resources at the University College London, with the contribution of Professor Alvaro Calzadilla, as well as the contributions of Dr. Gabriele Standardi and Professor Francesco Bosello, of Ca' Foscari University | CMCC.

Contributions: Conceptualization E.B.; Methodology E.B., G.S., A.C.; Formal Analysis E.B., F.B., Validation E.B., G.S., A.C. Writing- Original draft preparation E.B.; Supervision F.B., Writing – Reviewing and Editing E.B., F.B., G.S., A.C.

human needs [2], [3]. Furthermore, water, along with food, and energy, is part of the Water-Energy-Food (WEF) Nexus [4], [5], a concept that addresses explicitly the undetected feedback between them and the importance of their recognition in order to improve the level of detail and reliability of the modelling frameworks in addressing the aforementioned issues. In this perspective, the economic modelling literature has been recently devolving increasing attention to frameworks able to describe how resources and sectors influence each other, especially from a WEF point of view [6]–[8]. Computable General Equilibrium models (CGEs), with their capability of assessing intersectoral influences and feedback, present significant advantages in addressing this type of analysis. As such, there are several examples of CGEs applied to assess the consequences of economic e.g. [9] or physical e.g. [10], [11] shocks on Nexus-related topics [12]. Furthermore, a consistent stream of literature connects the use of CGE models to the analysis of potential consequences of climate impacts [12]–[20] and policies [21]–[28] at both at global [29]–[33] and at regional level [34]–[37]. Significant literature has also been produced on specific climate-WEF relevant issues, such as impacts of climate on agriculture [29], [35], [38]–[43], on the water resource [10], [11], [44]–[48] and directly on the WEF-climate connection [49], [50]. However, a significant gap can be found in these literatures about the explicit representation of water as a production input. In particular, one of the most important issues regards the representation of water as an input for energy production [51], which prevents the proper consideration of the water-energy link and the relative water competition between energy and agriculture. This paper addresses this gap, extending [52]–[54] and introducing water as an endowment not only for irrigated agriculture but also for a detailed energy sector. Then, it applies this improved framework to the assessment of the macroeconomic consequences of climate change impacts on water withdrawals[25] in two combinations of social-economic and climate change scenarios, under different assumptions of sectoral competition/water mobility.

In particular, extensions with respect to [52]–[54] regard the more realistic climate scenarios examined, with water availability and climate projections derived from the ISIMIP database, and the improved description of the energy sector[26].

In what follows, Section 2 presents the materials and methods, Section 3 presents the results and Section 4 provides a general discussion of the findings and the conclusions.

2. Materials and Methods

2.1 Data

The model chosen for the analysis is the ICES, a global, recursive-dynamic computable general equilibrium model describing demand and supply of domestic and foreign market interactions between representative firms, consumers, and the public sector, calibrated on the Global Trade Analysis Project (GTAP) Database, version 9 [55], with base year 2011. As standard in CGE models, firms are rational agents that, endowed with a given production technology, combine primary and intermediate factors of production to produce goods and services with the aim to minimize production costs. The framework proposed in [52], [53] extended the supply side of ICES introducing water as a

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[25] To be noted, this implies that the assessments concern only shocks relative to water withdrawals (i.e. the production factor in the model). Complementary climatic impacts on rainfed agriculture, which does not use withdrawals by definition, or any other additional impacts on the WEF are not considered in this context. A more complete assessment of the impacts of climate change on all the Nexus is therefore left to future research.

[26] These issues were highlighted as potential improvements in the previous Chapters of this thesis, respectively, in Chapter One, i.e. [51] and Chapter One and Two, i.e. [51], [52].

primary production factor used by irrigated agriculture and energy production, as well as the associated competition for this endowment. The current paper further improves the framework by implementing a wider description of water uses by the energy sector. Indeed, differently from [52], [53] where energy was an undifferentiated macro-sector, here energy is disentangled into seven major energy generation technologies (Coal, Gas, Oil, Fossil Electricity, Renewables, Hydro and Nuclear) and a Transmission and distribution sector[27]. For each energy generation sector, specific water withdrawals have been identified based on multiple data sources, i.e.: [56]–[62]. In general, the renewables sector, i.e. wind and solar have the lower water withdrawal requirement (i.e. around a mean of 10^2 litres per Megawatt-hour (MWh), even though the specific technology and cooling system implemented can significantly increase its water requirement. Indeed, there are specific exceptions such as for concentrating solar power technologies, which being based on parabolic trough, solar tower and Fresnel technologies have withdrawals comparable with fossil fuel-based and nuclear power plants using the same cooling system, which have the highest water withdrawal levels. Primary coal oil and gas have generally higher levels of withdrawals with respect to renewables and use water in different stages of production. For example primary oil and gas use water for activities such as drilling, well completion, oil sands mining, and upgrading and refining oil and gas into final products. Primary coal uses water for activities such as cutting and dust suppression in mining, and hauling and for washing to improve coal quality. The intensity of the withdrawal level of primary coal oil and gas is relatively differentiated based on the specific production method (e.g. conventional gas has lower requirements than refined oil but gas-to-liquids has

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[27] A detailed description of the regional and sectoral aggregation and the representation of the production function are reported in Table S1 and S2 and Figure S1 in the supplementary information.

higher withdrawals) for a mean of 10^4 litres per MWh. The highest withdrawals are associated with fossils electricity and nuclear power production, which use water for activities such as boiler feed, i.e. the water used to produce steam or hot water and for cooling, and are similarly distinguished by method of production (cooling towers have lower levels of withdrawals than cooling ponds, with both having lower levels of withdrawals respect to once-though technologies) spanning from 10^4 MWh up to 10^6 litres per MWh. [56], [63]. For the moment, no data of withdrawals are associated with the transmission and distribution as all the sectors are considered as self-abstracting as in [10] i.e. they directly retrieve the water resource for production uses.

Be noted, in this framework hydropower is a peculiar sector, as it is not directly associated with water withdrawals. Indeed, according to the literature [64]–[71] and reflected in several databases[28] hydropower does not withdraw water [72], [73]. Nevertheless, this type of energy is associated with high levels of water consumption, which can strongly affect the functioning of the hydrological system. The basic difference between withdrawal and consumption is that withdrawals identify the amount of water extracted from the environment to allow sectoral production (i.e. is a mean of production), while water consumption, which accounts for the water that evaporates due to production, considers the fraction of water that is permanently dispersed from its source due to production activities. This alters the standard phases of the hydrological cycle and *de facto* sets water consumption as an environmental damage related to production. Acknowledging its importance, we also introduced in the model a water consumption indicator proportional to the sectorial production (i.e. assuming constant water efficiency), though the analysis of this environmental

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[28] OECD (2021), Water withdrawals (indicator). doi: 10.1787/17729979-en – Hydro excluded. World Bank https://databank.worldbank.org/metadataglossary/world-development-indicators/series/ER.H2O.FWIN.ZS; Aquastat [91], [92]

externality is outside the scope of this specific work. The base year calibration of the indicator derives from [74] for hydropower; from [56], for other energy sources; and from [75] for irrigated agriculture.

Concerning the social-economic development assumptions, they were addressed by coupling GDP and population trends from the Shared Socioeconomic Pathway 2 [76]–[78] with emissions and energy mix consistent with the Representative Concentration Pathways (RCPs), 6.0 (high climate change) and 2.6 (low climate change). In particular, the emissions relative to the energy sectors have been calibrated by imposing a carbon tax that replicates the emission levels for specific RCP in [79]–[81].

The data to assess future water availability, defined as having a runoff level in the region higher than the withdrawal expectations, are derived from the ISIMIP project [82]. As such, runoff data are extracted and used in the evaluation of the environmental compatibility for the overall level of projected withdrawals (i.e. are set as the upper constraint that limits the potential increase of demand-driven water supply). Runoff data are taken with integrated societal change[29], as this variable is used as an external control factor and not explicitly implemented in the model. Additionally, the ISIMIP data highlight that while energy-sector water withdrawals are affected only by water availability, agriculture water withdrawals are influenced by both water availability and by an additional response related to the soil and crop characteristics (e.g. due to land evaporation patterns). This effect is retrieved from the ISIMIP database "at fixed social change" to isolate the pure climate change effect since the influence of social-economic factors is accounted for via the model calibration processes. Finally, to account for the uncertainty related to climate and water availability projections, the data were retrieved from three different hydrological models (i.e. Matsiro,

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[29] The scenario includes human influences such as land use and land management, calibrated on SSP2.

Lpjml and H08) and 4 General Circulation models (GCM) (i.e. GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5), which are used both to compute the ensemble median and to offer confidence intervals. The ISIMIP data were then aggregated to match the ICES model's regional and temporal resolution and smoothed to reduce the inter-annual variability [30].

2.2. Experiments' design

The overall experiment is based on three sets of scenarios:

1. An "unconstrained water" set producing two baselines, where water demand and supply are left free to vary endogenously in response to the growth of GDP and population associated with the SSP2 socio-economic development, coupled with the energy mix and emissions profiles that stem from the RCP 6.0 and 2.6. These scenarios are set as references.
2. A climate set, producing four "climate-constrained water" scenarios, which in turn introduce specific assumptions on water withdrawals, availability, and additional water requirement by agriculture projected in the RCP 2.6 and 6.0. In particular, the first two concern an availability assessment comparing withdrawals vs. runoff and analyzing the feasibility of the required demand levels. These scenarios are labelled as "Availability". The other two assess the availability also including the additional impact on agriculture and are labelled as "Overall Climate". These latter two types of scenarios are

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[30] The smoothing procedure was developed after controlling for possible seasonality and trend patterns. In particular, the yearly time series were checked via the STL test [93] with the standard stats packages in the software R, under which they showed no evidence of seasonality. Trend detection was developed through the Mann-Kendall test [94] in the R package Kendall. The rejection level was set to a two-sided p-value of 0.05. Eventually, the time series were smoothed using Exponential Smoothing in case of no rejection of the null of trend existence and Holt smoothing [95]–[97] in case of rejection of the null hypothesis. The p-values of the single time series test are reported in Tables S3 to S6 of the Supplementary Information.

separated to properly highlight the role and significance of water constraints vis-a-vis overall climate-water effects.

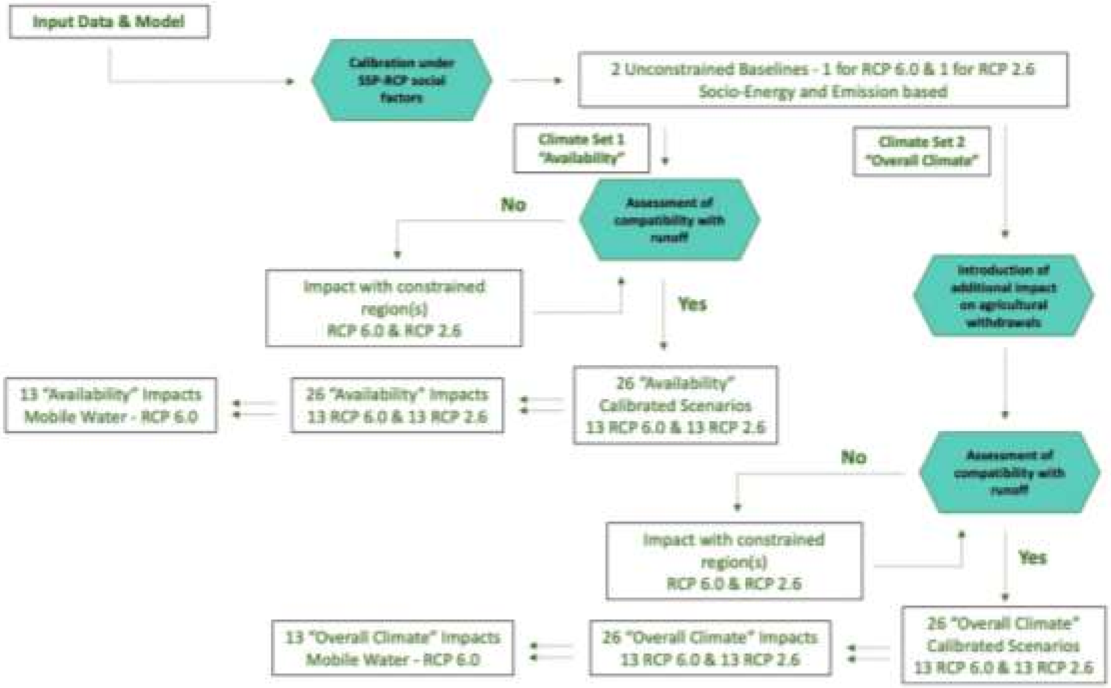
Be noted, in both sets 1) and 2) water is not mobile across sectors.

3. A policy assessment set, producing two scenarios, simulated just for the RCP 6.0 - one for "Availability" and one for "Overall Climate", where water is perfectly mobile across sectors. This aims to emphasize the role of market-driven adaptation and discuss to what extent an efficient water distribution framework could mitigate climate change damages.

As such, the experimental framework overall consists of two baselines (SSP2-RCP 6.0 and SSP2-RCP 2.6), 52 water calibration simulations (26 for RCP 6.0 and 26 for RCP 2.6, i.e. one for all the combinations of CGM and Hydrological models plus the multi-model median) and three sets of impact scenarios (RCP 6.0 no mobility, RCP 2.6 no mobility, RCP 6.0 with adaptation mechanism (i.e. water mobility)), for a total of 78 impact scenarios - 39 Availability and 39 Overall climate impact.

Concerning the water calibration procedure, the water withdrawal trends are estimated by endogenising the water supply, whose behaviour is described by a function combining socioeconomic and physical drivers (see Equation 1 in Supplementary Information). For the baseline calibration, water supply is allowed to follow unconstrainedly the water-dependent productions driven by the socioeconomic variables. In the "climate-constrained" scenarios, instead, a multi-step process has been implemented. More in detail, the first step requires to identify the water-constrained regions. This is done by comparing the baseline "unconstrained" water withdrawal against region-specific water availability. If a region is water-constrained, a runoff (water-supply) trend is imposed on the water-scarce region. Then, the model is re-run with this (these) constraint(s) so that other unconstrained regions can adjust their production and consequent water requirements. Should other water-constrained regions emerge, the procedure is repeated. In practice, the process always ended after two steps. A schematic representation of the overall experimental design is shown in Fig. 1.

Figure 1. Experimental Design’s structure



Note: The single arrow sign marks the steps through which the scenarios were created, and the double line marks the steps in which the scenarios used for the analysis were produced.

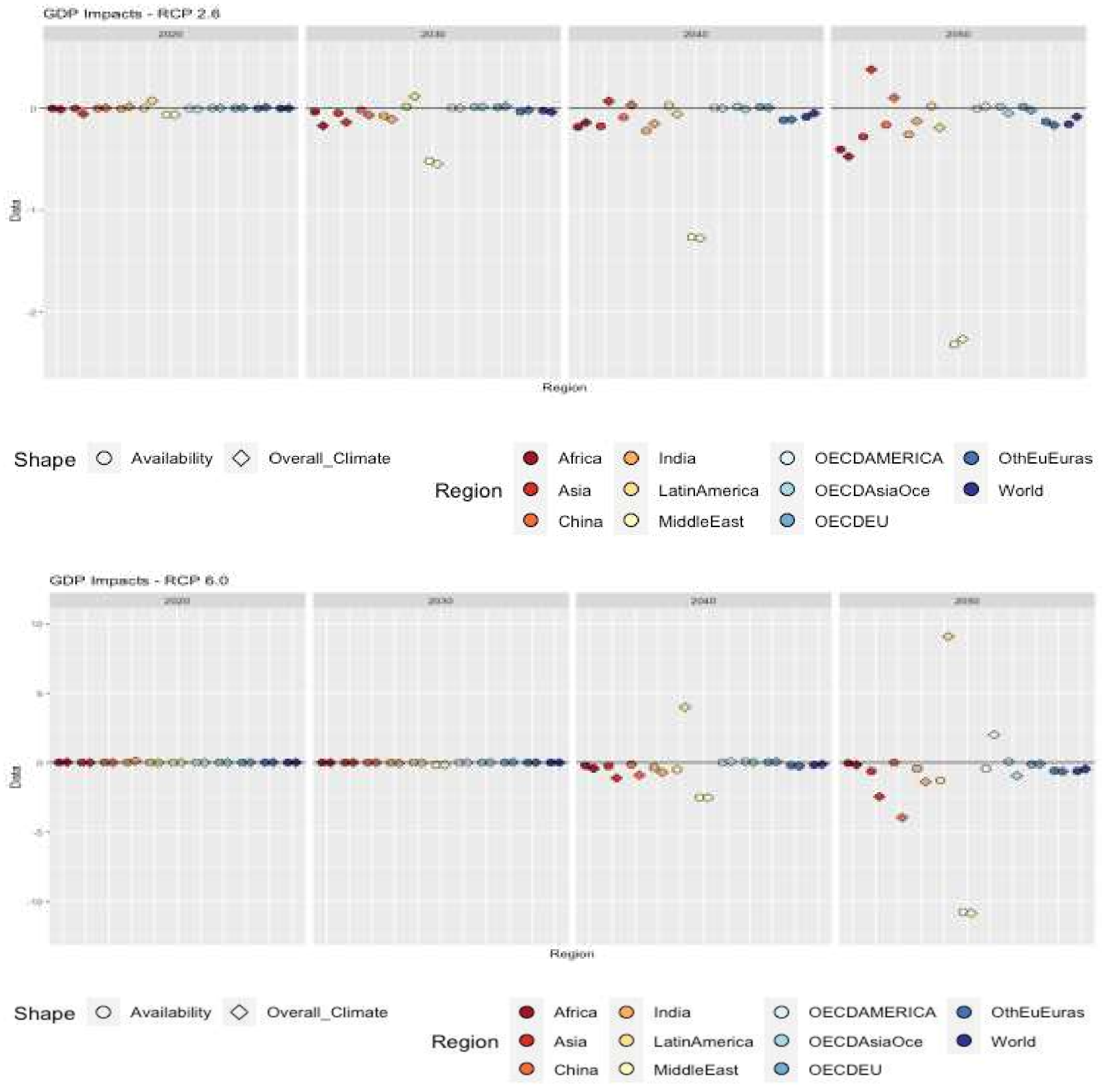
3. Results

3.1 GDP impacts

For the sake of compactness, this section conveys only the findings originated using the muti-model median of the physical inputs. Extended results and uncertainty ranges are reported in Figure S2 in the Supplementary Information.

In our simulations, the Middle East is the only region that will experience water availability constraints by the mid-century. This result, though, is significantly influenced by the coarseness of our regional aggregation. Indeed, water scarcity problems are likely to be widespread and affect several world regions, but these local effects are averaged out in large geopolitical blocs. Future research will aim to increase the regional resolution of the analysis to better capture the sub-regional effects and identify currently undetected high-risk areas. The Middle East is the region showing the most significant losses in all scenarios, including in RCP 2.6. These results are produced following a specific chain of effects. Under water scarcity, the regional production in irrigated agriculture, the main water user, significantly contracts. Rainfed agriculture attracts part of the freed (other) factors of production and its output increases (Figure S3 in Supplementary Information). On the other hand, a significant share of these endowments is redirected to Gas and Oil production, which slightly increase. This is due to the fact that, especially in the "Overall Climate" scenarios, the demand for imports of these products from the neighbours (mainly European regions and OECD America) increases, leading to Middle east to raise its production and the exports of primary fossils in the global market. This process, combined with the dependency of Oil and Gas on the water endowment and the quasi-Leontief specification, i.e. almost zero [83] between water and the other factors of production, leads to strong demand for the substitution of water with capital and labour, whose reallocation is altered at the point that they are retrieved also from all the other sectors, including industries and services. This leads to an overall contraction in the production of all the sectors with the exception of rainfed agriculture, oil, and gas, which causes the significant GDP contractions shown in the region. As such, the relatively efficient decision of producing and exporting primary oil and gas is not enough to offset the damages relative to the required contraction in the rest of the regional economy, which therefore is highly damaged. Concerning the other regions, climate change impacts on water resources can have both positive and negative influences on GDP, varying according to the intensity and direction of the climatic signal on agriculture (Figure 2). These are moderate in the RCP 2.6 ranging, in the 2040-2050 decade, between -0.5% and +0.4% compared to the baseline (excluding Middle East). They are instead more pronounced in the RCP6.0, especially when the full effect of climate change is considered, ranging, without Middle East, between -4% and +10%. At the global level, net GDP impacts are -0.6% in RCP 6.0 and -0.1% in RCP 2.6 for both types of climate scenarios. Therefore, climate impacts smooth out at the world level.

Figure 2. % GDP Impact of Scenarios with respect to Baseline



The results also emphasize that the difference across RCPs not only concerns the intensity of the impacts, but they are also significantly differentiated at the regional level. For example, in RCP 2.6 China and Asian countries are moderately advantaged by climate change. This, however, does not hold in RCP 6.0 where these regions incur in the second-highest losses. Analogously, Latin America is a region showing macroeconomic losses in RCP 2.6, but it is expected to gain in RCP 6.0. Therefore, these results clearly show that climate-driven changes in the actual withdrawals for agriculture, particularly in a context of strong climate change, are important drivers of macroeconomic impacts. Furthermore, these findings generally align with [10], [11], [44], [84], [85] and [86]–[89] stating that agricultural-driven water stress is going to be stronger near the equator, with particular significance in North Africa, Middle East, and Tropical Asia.

In examining the macroeconomic (GDP) changes, which are driven by many economic factors, it can be important to identify and disentangle the single driving forces. To this purpose, we disaggregated the Equivalent Variation (EV)[31] responses of the different scenarios into their constituent parts (Figure 3). Between them, three specific factors emerge as the most important drivers: Two are related to the productivity and quantity of the production factors, which is coherent with the type of shocks imposed affecting the water input. The third is the terms of trade, a factor that captures changes in competitiveness associated with the new conditions. Since the changes in productivity and water availability are unevenly distributed, some regions will suffer more from climate change than others. This will change the regional comparative advantages generating winners and losers and changing the international trade patterns. In particular, these results signal that, immediately after the physical effects of climate change on the water input, the welfare is affected by climate-induced changes in competitiveness triggered by the regionally differentiated price and quantity changes.

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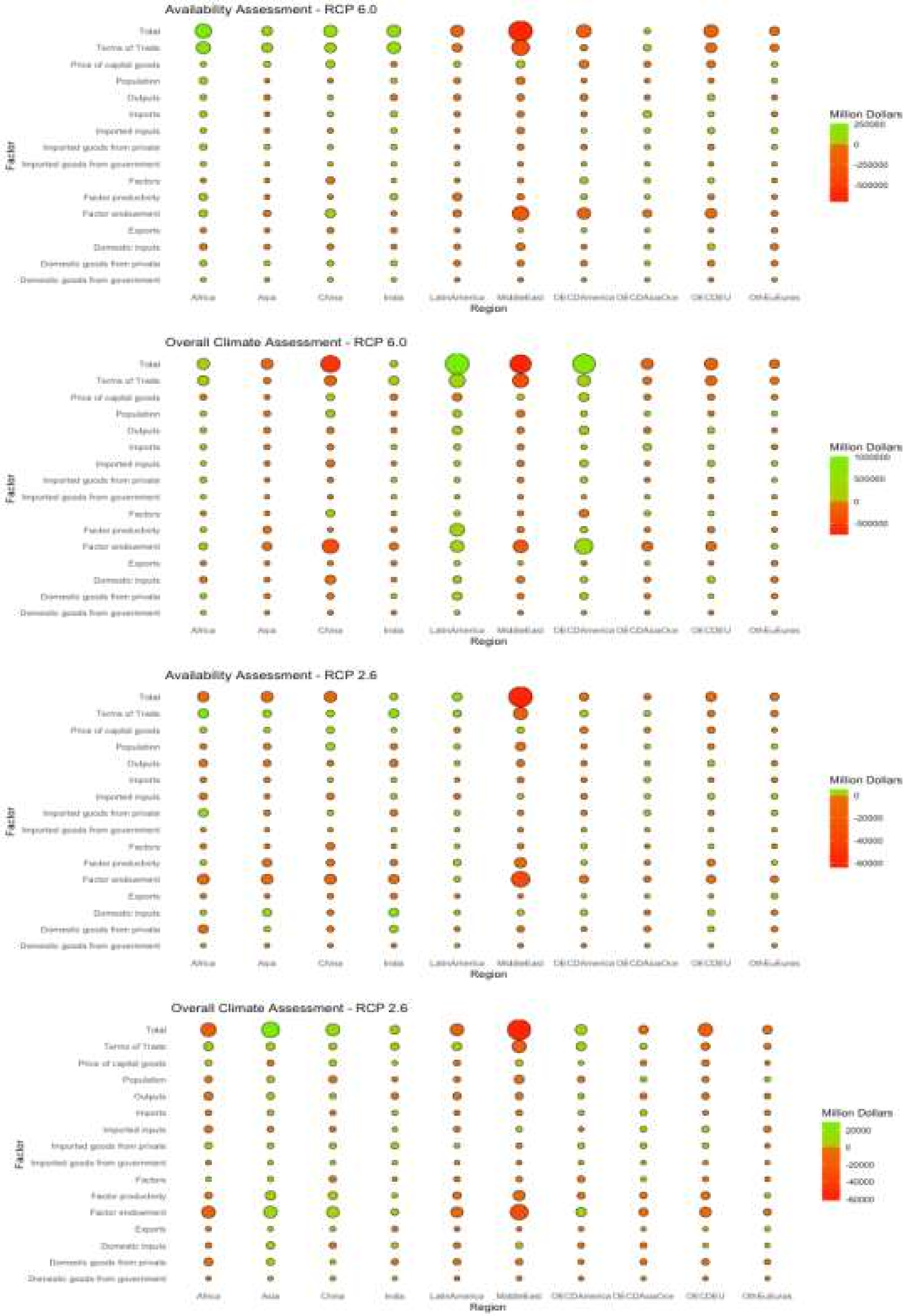
[31] The Equivalent Variation is a metric of welfare developed in terms of utility rather than in monetary terms [98]–[100]. More specifically, the EV concerns the change in the regional income at current prices that would have the same effect on welfare as the change in prices at unchanged income. In detail, our procedure closely follows the one proposed by [100].

Figure 3. Contribution to regional welfare variation (million USD$)



Availability Assessment - RCP 6.0

Overall Climate Assessment - RCP 6.0

Availability Assessment - RCP 2.6

Overall Climate Assessment - RCP 2.6

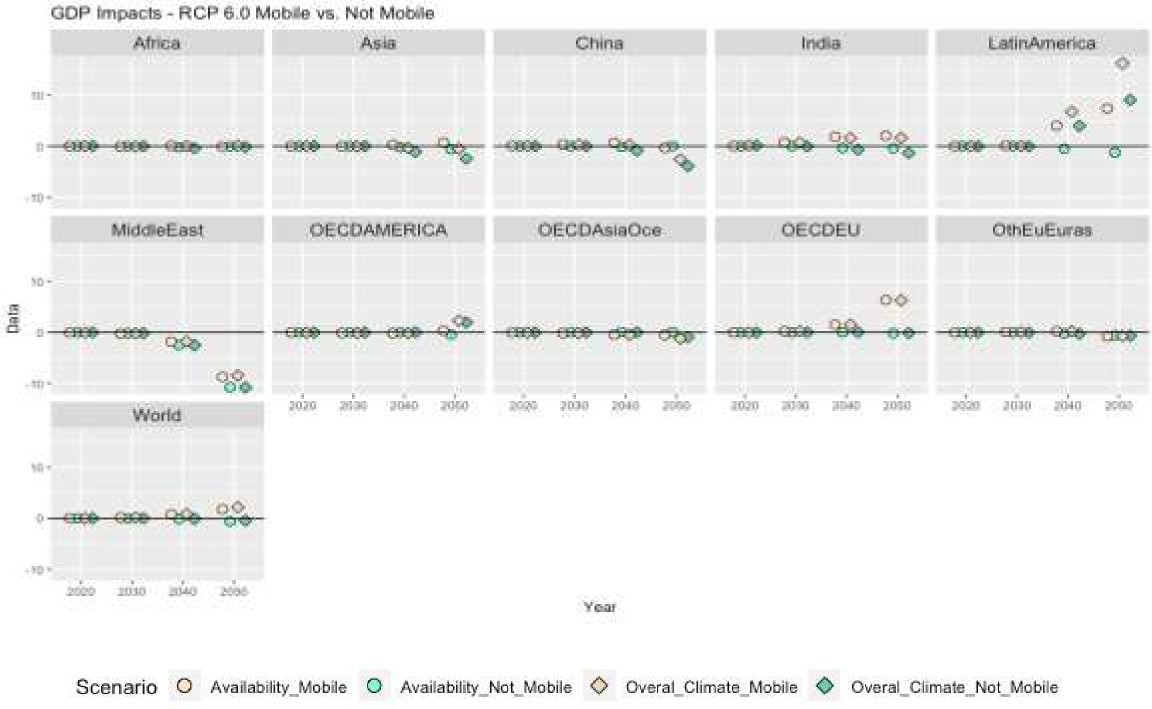
The analysis of sectoral production, imports, and exports can shed further light on these mechanisms. In general, the adjustments induced by the water dynamics in the agricultural sectors are quite clear (for an extended graphical representation of all the water-dependent sectorial impacts, see Figure S4-S9 in Supplementary Information). For instance, Middle East and Asian countries (China, India, and the rest of Asia) in the RCP 6.0, which are affected by significant GDP losses, decrease domestic production, reduce exports, and increase imports of agricultural commodities. This, associated with the observed increase in the world price of irrigated agricultural goods (Figure S10 in Supplementary Information), induces a worsening in the regional trade position, which is coherent with the macroeconomic damages.

This type of behaviour is less recognizable in the case of energy commodities. For instance, in the case of China in RCP 6.0 – the region with the highest losses after the water-constrained Middle East – energy production is lower than in the baseline, but the imports of fossil energy decrease and the exports for electricity (both fossils and not fossils) increase. Therefore, in this region, the contraction in domestic demand allows for the possibility of relocating (energy) resources to foreign markets, which is a "typical" positive second-order effect in trade patterns. This is, nevertheless, not enough to offset the macroeconomic losses induced by the water-climate influence in the agricultural sectors. In RCP 2.6 the trends in energy production are particularly close to the baseline and the effect on the terms of trade triggered by water impacts is marginal. As such, the energy sectors emerge to be generally more resilient to water-climate dynamics than those of agriculture.

3.3 **The role of water mobility**

This section analyses the possible macroeconomic implications of an "optimal allocation" of the water resource assuming perfect water mobility across irrigated agriculture and the energy sectors. This is done through a CET function which allows the water input to respond to price signals and be used where it receives the higher reward. We acknowledge that perfect water mobility is quite an unrealistic hypothesis, especially in the case of water. In fact, there are several technical and regulatory constraints to water distribution, especially in the presence of water scarcity. Nonetheless, this can still be an interesting case study highlighting the potential implications of an efficient resource management, particularly under high climate change and climate-induced macroeconomic losses. The results comparing GDP Impacts with and without water mobility are reported in Figure 4. In presence of water mobility, the negative global GDP performance turns into a positive one in the last two decades. Regionally, the highest benefits can be found in OECD America, Latin America, and, particularly, in OECD Europe and India, with the latter two also reversing the sign of their impacts from negative to positive. The Middle East also shows macroeconomic improvements but is still affected by substantial losses due to water scarcity. All in all, these results confirm the relevance of a water allocation mechanism shown by e.g. [11],[13], [49].

Figure 4. % GDP impacts with-without water mobility in RCP 6.0 vs Baseline



Furthermore, the detailed representation of the energy sector in our framework leads to the emergence of additional details with respect to the literature. Indeed, the water reallocations seem to follow two main trends: on one hand, water generally goes towards irrigated agriculture and away from energy production[32] (Table 1). On the other hand, the disaggregation of the energy sector highlights that this shift tends to affect more significantly the more water-intensive energies i.e. fossil energy production and nuclear, rather than the renewables, more water-efficient, whose water provision increases. Accordingly, an efficient water distribution seems partly to accelerate the effectiveness of a carbon tax and the overall decarbonization process. Furthermore, it questions the viability of the nuclear option in a climate-change future, due to its high-water input requirements. In particular, comparing Figure 4 and Figure 5 emerges that the increase in renewables production shows a significant correlation with the positive macroeconomic impacts with particular strength in the regions that additionally assume the role of exporters (i.e. Latin America and OECD Europe).

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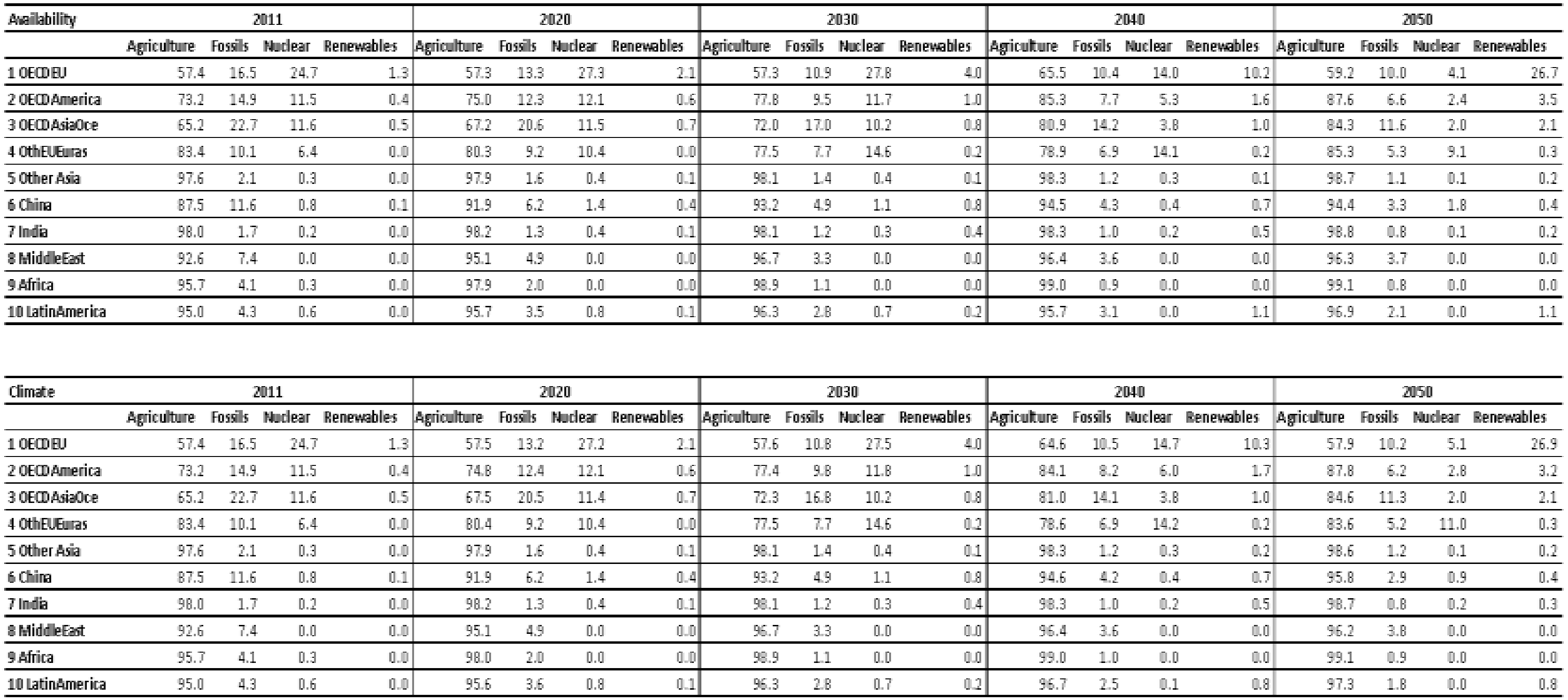
[32] This was also one of the general findings of Chapter Two in studying the competition dynamics between agriculture and aggregated energy [Section 3.2]

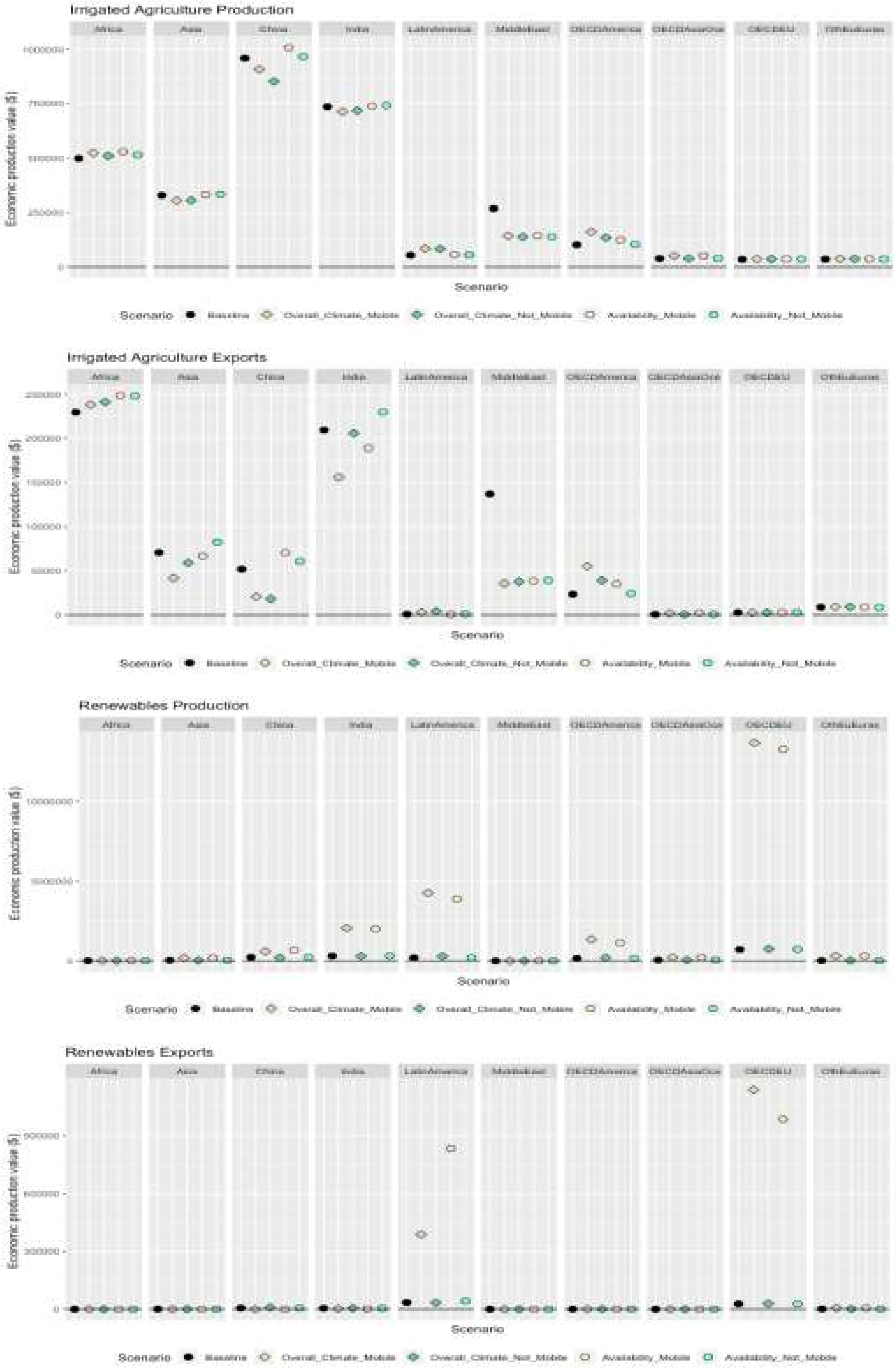
Table 1. RCP 6.0 % of sectorial water shares of total water uses by regions and time, under water mobility



Availability	2011				2020				2030				2040				2050			
	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables
1 OECD EU	57.4	16.5	24.7	1.3	57.3	13.3	27.3	2.1	57.3	10.9	27.8	4.0	65.5	10.4	14.0	10.2	59.2	10.0	4.1	26.7
2 OECD America	73.2	14.9	11.5	0.4	75.0	12.3	12.1	0.6	77.8	9.5	11.7	1.0	85.3	7.7	5.3	1.6	87.6	6.6	2.4	3.5
3 OECD AsiaOce	65.2	22.7	11.6	0.5	67.2	20.6	11.5	0.7	72.0	17.0	10.2	0.8	80.9	14.2	3.8	1.0	84.3	11.6	2.0	2.1
4 OthEUEuras	83.4	10.1	6.4	0.0	80.3	9.2	10.4	0.0	77.5	7.7	14.6	0.2	78.9	6.9	14.1	0.2	85.3	5.3	9.1	0.3
5 Other Asia	97.6	2.1	0.3	0.0	97.9	1.6	0.4	0.1	98.1	1.4	0.4	0.1	98.3	1.2	0.3	0.1	98.7	1.1	0.1	0.2
6 China	87.5	11.6	0.8	0.1	91.9	6.2	1.4	0.4	93.2	4.9	1.1	0.8	94.5	4.3	0.4	0.7	94.4	3.3	1.8	0.4
7 India	98.0	1.7	0.2	0.0	98.2	1.3	0.4	0.1	98.1	1.2	0.3	0.4	98.3	1.0	0.2	0.5	98.8	0.8	0.1	0.2
8 MiddleEast	92.6	7.4	0.0	0.0	95.1	4.9	0.0	0.0	96.7	3.3	0.0	0.0	96.4	3.6	0.0	0.0	96.3	3.7	0.0	0.0
9 Africa	95.7	4.1	0.3	0.0	97.9	2.0	0.0	0.0	98.9	1.1	0.0	0.0	99.0	0.9	0.0	0.0	99.1	0.8	0.0	0.0
10 LatinAmerica	95.0	4.3	0.6	0.0	95.7	3.5	0.8	0.1	96.3	2.8	0.7	0.2	95.7	3.1	0.0	1.1	96.9	2.1	0.0	1.1

Climate	2011				2020				2030				2040				2050			
	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables	Agriculture	Fossils	Nuclear	Renewables
1 OECD EU	57.4	16.5	24.7	1.3	57.5	13.2	27.2	2.1	57.6	10.8	27.5	4.0	64.6	10.5	14.7	10.3	57.9	10.2	5.1	26.9
2 OECD America	73.2	14.9	11.5	0.4	74.8	12.4	12.1	0.6	77.4	9.8	11.8	1.0	84.1	8.2	6.0	1.7	87.8	6.2	2.8	3.2
3 OECD AsiaOce	65.2	22.7	11.6	0.5	67.5	20.5	11.4	0.7	72.3	16.8	10.2	0.8	81.0	14.1	3.8	1.0	84.6	11.3	2.0	2.1
4 OthEUEuras	83.4	10.1	6.4	0.0	80.4	9.2	10.4	0.0	77.5	7.7	14.6	0.2	78.6	6.9	14.2	0.2	83.6	5.2	11.0	0.3
5 Other Asia	97.6	2.1	0.3	0.0	97.9	1.6	0.4	0.1	98.1	1.4	0.4	0.1	98.3	1.2	0.3	0.2	98.6	1.2	0.1	0.2
6 China	87.5	11.6	0.8	0.1	91.9	6.2	1.4	0.4	93.2	4.9	1.1	0.8	94.6	4.2	0.4	0.7	95.8	2.9	0.9	0.4
7 India	98.0	1.7	0.2	0.0	98.2	1.3	0.4	0.1	98.1	1.2	0.3	0.4	98.3	1.0	0.2	0.5	98.7	0.8	0.2	0.3
8 MiddleEast	92.6	7.4	0.0	0.0	95.1	4.9	0.0	0.0	96.7	3.3	0.0	0.0	96.4	3.6	0.0	0.0	96.2	3.8	0.0	0.0
9 Africa	95.7	4.1	0.3	0.0	98.0	2.0	0.0	0.0	98.9	1.1	0.0	0.0	99.0	1.0	0.0	0.0	99.1	0.9	0.0	0.0
10 LatinAmerica	95.0	4.3	0.6	0.0	95.6	3.6	0.8	0.1	96.3	2.8	0.7	0.2	96.7	2.5	0.1	0.8	97.3	1.8	0.0	0.8

Figure 5. Production and Exports of Irrigated Agriculture and Renewables, 2050, Million US$



4. Discussion and conclusions

The first aim of this paper is to assess the macroeconomic consequences and possible impacts on economic growth induced by water availability under climate change. To do so, water is introduced as a production factor used by the agricultural and multiple energy sectors in a recursive-dynamic CGE model. This methodologically advances the current CGE practice, which offers just a few examples of water modelling from a WEF Nexus perspective. Indeed, the explicit introduction of water as a factor of production in this literature is generally limited to agricultural uses, missing water competition dynamics across economic sectors [51]. The second aim of the paper is to examine the role that an efficient sectoral allocation of water resources could potentially play in smoothing the adverse effects of water scarcity.

As to the first point, it is shown that, according to climate change and socio-economic growth projections, only the Middle East will be water constrained i.e. will experience a water demand larger than water supply, both in RCP2.6 and 6.0, which highlights this region as one of the areas with the highest risk of water scarcity in the considered time horizon, coherently with the bio-physical based literature on the issue e.g. [86]–[89]. The other regions analysed will instead experience local phenomena of water scarcity, but these are averaged out and do not emerge due to the geographical scale used in this exercise. As a consequence, high economic losses are projected for the Middle East. Interestingly, also some non-water-constrained regions, like China, India, and other Asian countries in RCP 6.0, can have negative impacts due to the climate change impacts on water requirement by the agricultural sector and the relative implications in terms of production and international trade. At the sectoral level, these losses are mostly affecting irrigated agriculture, while the energy sector seems less affected by water scarcity shocks. All in all, the results show water constraints as the main driver of economic losses, followed by climatic impacts on agricultural withdrawals variations and the consequent changes in the production and trade patterns. Furthermore, RCP 6.0 has more intense impacts with respect to RCP 2.6, with global higher losses.

As to the second point, evidence is found that a flexible water distribution mechanism across sectors is critical in mitigating macroeconomic losses, even though the impacts associated with this framework in RCP 6.0 are still higher than the losses associated with RCP 2.6. An interesting insight is that the pursuit of intersectoral efficiency in the use of water may accelerate the transition towards a low-carbon energy mix given the lower water intensity of renewables compared to fossil energy sources. Indeed, water tends to be subtracted from fossil and directed toward renewable energy production. Thus, a potential synergy between water-efficient management policies and mitigation policies is highlighted. To be noted, a substantial shift of water is also evident in the nuclear sector, highlighting the necessity of carefully evaluating the feasibility of using this type of (water-intensive) energy source in the development of future strategies of mitigation pathways.

All in all, this paper finds that, from a macroeconomic perspective, water could be a "limit to growth", leading to substantial macroeconomic losses in contexts of water scarcity. Nevertheless, it also finds evidence that a flexible water distribution mechanism can successfully mitigate these macroeconomic losses, and, even more, can function as a growth accelerator under a certain combination of endowment availability and international trade incentives.

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Supplementary Information Chapter 3

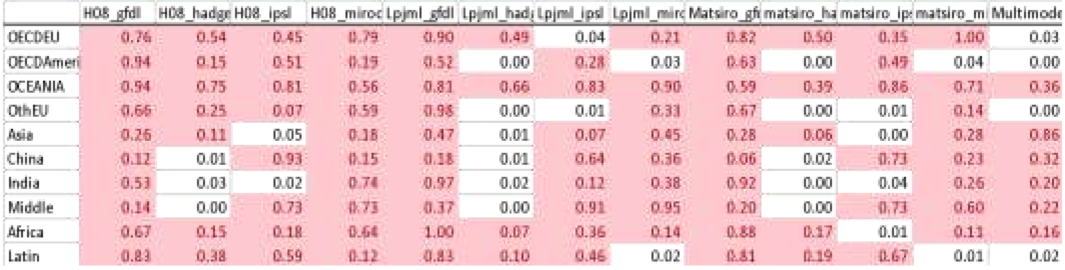
Table S1. Regional Aggregation

Region Name	GTAP Countries
OECD Europe	Austria; Belgium; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Luxembourg; Netherlands; Poland; Portugal; Slovakia; Slovenia; Spain; Sweden; United Kingdom; Switzerland; Norway; Rest of European Free Trade Association; Israel; Turkey
OECD America	Canada; United States of America; Mexico, Rest of North America; Chile
OECD Asia-Oceania	Australia; New Zealand; Rest of Oceania; Japan; Korea, Republic of
Other Europe and Eurasia	Cyprus; Latvia, Lithuania, Malta; Albania; Bulgaria; Belarus; Croatia; Romania; Russian Federation; Ukraine; Rest of Eastern Europe; Rest of Europe; Kazakhstan; Kyrgyzstan, Rest of Former Soviet Union; Armenia, Azerbaijan; Georgia
Asia	Mongolia; Rest of East Asia, Brunei Darussalam; Cambodia; Indonesia; Lao PDR; Malaysia; Philippines; Singapore; Thailand; Viet Nam; Rest of Southeast Asia; Bangladesh; Nepal; Pakistan; Sri Lanka; Rest of South Asia
China	China, Hong Kong, Special Administrative Region of China; Taiwan
India	India
Middle East	Bahrain; Iran, Islamic Republic of; Jordan; Kuwait; Oman; Qatar; Saudi Arabia; United Arab Emirates; Rest of Western Asia
Africa	Egypt; Morocco, Tunisia; Rest of North Africa; Benin; Burkina Faso; Cameroon; Cote d'Ivoire; Ghana; Guinea; Nigeria; Senegal; Togo; Rest of Western Africa; Rest of Central Africa; South Central Africa; Ethiopia; Kenya; Madagascar; Malawi; Mauritius; Mozambique; Rwanda; Tanzania, United Republic of; Uganda; Zambia; Zimbabwe; Rest of Eastern Africa; Botswana; Namibia; South Africa; Rest of South African Customs Union
Latin America	Argentina; Bolivia; Brazil; Colombia; Ecuador; Paraguay; Peru; Uruguay; Venezuela (Bolivarian Republic of); Rest of South America; Costa Rica; Guatemala; Honduras; Nicaragua; Panama; El Salvador; Rest of Central America; Dominican Republic; Jamaica; Puerto Rico; Trinidad and Tobago; Rest of Caribbean

Table S2. Sectoral Aggregation

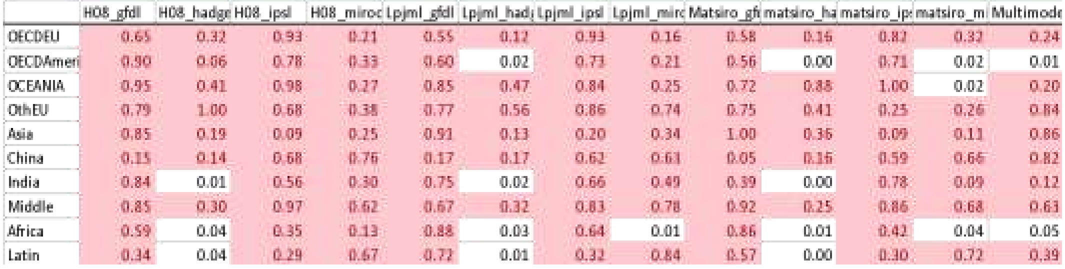
Sector Name	Sectors
Irrigated Agriculture	Irrigated: Paddy rice, Wheat, Cereals; Veg and Fruit; Oil seeds; Cane and Beet; Fibers crops; Other Crops
Rainfed Agriculture	Rainfed: Paddy rice, Wheat, Cereals; Veg and Fruit; Oil seeds; Cane and Beet; Fibers crops; Other Crops
Industries	Cattle; Other Animal Products; Raw milk; Wool; Forestry; Fishing; Other Mining Extraction; Cattle Meat; Other Meat; Vegetable Oils; Milk: dairy products; Processed Rice; Sugar and Molasses; Other Food; Beverages and Tobacco Products; Manufacture of textiles; Manufacture of wearing apparel; Manufacture of leather and related products; Lumber; Paper Products and Publishing; Chemical, rubber, plastic products; Mineral products nec; Ferrous metals; Metals nec; Metal products; Motor vehicles and parts; Transport equipment nec; Electronic equipment; Machinery and equipment nec; Manufactures nec;
Coal	Coal: mining and agglomeration of hard coal, lignite and peat
Oil	Oil: extraction of crude petroleum, service activities incidental to oil and gas extraction excluding surveying (part); Petroleum and Coke
Gas	Gas: extraction of natural gas, service activities incidental to oil and gas extraction excluding surveying (part), distributed gas
TnD	Transmission and Distribution of Electricity
Nuclear	Nuclear Base Load
Fossil Electricity	Coal Base load; Gas Base load; Oil Base load; Gas Peak load; Oil Peak load,
Renewables	Wind Base load; Other Base load; Solar peak load;
Hydropower	Hydropower Base load, Hydro peak load
Services	Water: collection, purification, and distribution; Construction: building houses factories offices and roads; Trade; Other transport; Water transport; Air transport; Communications; Other financial intermediation; Insurance; other business services, Dwellings, imputed rents of houses occupied by owners

Table S3. P-values RCP60 -Runoff



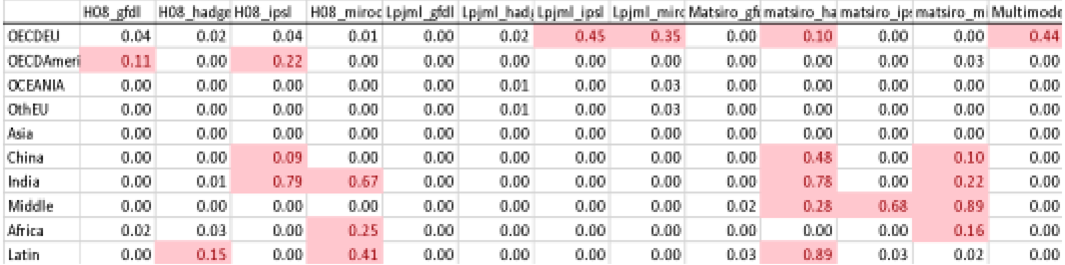
	H08_gfdl	H08_hadg	H08_ipsl	H08_miroc	Lpjml_gfdl	Lpjml_had	Lpjml_ipsl	Lpjml_mirc	Matsiro_gf	matsiro_ha	matsiro_ip	matsiro_m	Multimode
OECDEU	0.76	0.54	0.45	0.79	0.90	0.49	0.04	0.21	0.82	0.50	0.35	1.00	0.03
OECDAmeri	0.94	0.15	0.51	0.19	0.52	0.00	0.28	0.03	0.63	0.00	0.49	0.04	0.00
OCEANIA	0.94	0.75	0.81	0.56	0.81	0.66	0.83	0.90	0.59	0.39	0.86	0.71	0.36
OthEU	0.66	0.25	0.07	0.59	0.98	0.00	0.01	0.33	0.67	0.00	0.01	0.14	0.00
Asia	0.26	0.11	0.05	0.18	0.47	0.01	0.07	0.45	0.28	0.06	0.00	0.28	0.86
China	0.12	0.01	0.93	0.15	0.18	0.01	0.64	0.36	0.06	0.02	0.73	0.23	0.32
India	0.53	0.03	0.02	0.74	0.97	0.02	0.12	0.38	0.92	0.00	0.04	0.26	0.20
Middle	0.14	0.00	0.73	0.73	0.37	0.00	0.91	0.95	0.20	0.00	0.73	0.60	0.22
Africa	0.67	0.15	0.18	0.64	1.00	0.07	0.36	0.14	0.88	0.17	0.01	0.11	0.16
Latin	0.83	0.38	0.59	0.12	0.83	0.10	0.46	0.02	0.81	0.19	0.67	0.01	0.02

Table S4. P-values RCP26 -Runoff



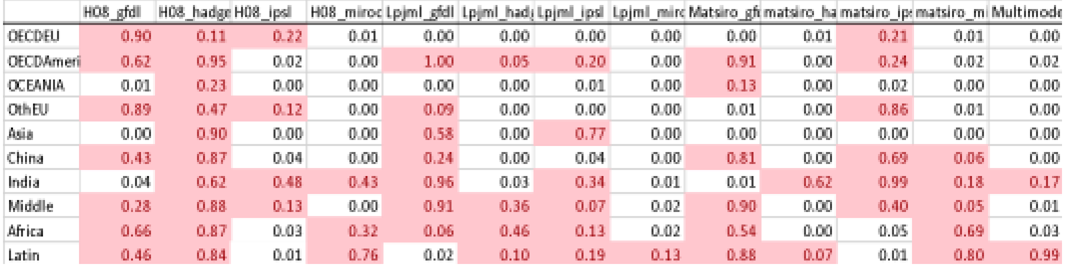
	H08_gfdl	H08_hadg	H08_ipsl	H08_miroc	Lpjml_gfdl	Lpjml_had	Lpjml_ipsl	Lpjml_mirc	Matsiro_gf	matsiro_ha	matsiro_ip	matsiro_m	Multimode
OECDEU	0.65	0.32	0.93	0.21	0.55	0.12	0.93	0.16	0.58	0.16	0.82	0.32	0.24
OECDAmeri	0.90	0.06	0.78	0.33	0.60	0.02	0.73	0.21	0.56	0.00	0.71	0.02	0.01
OCEANIA	0.95	0.41	0.98	0.27	0.85	0.47	0.84	0.25	0.72	0.88	1.00	0.02	0.20
OthEU	0.79	1.00	0.68	0.38	0.77	0.56	0.86	0.74	0.75	0.41	0.25	0.26	0.84
Asia	0.85	0.19	0.09	0.25	0.91	0.13	0.20	0.34	1.00	0.36	0.09	0.11	0.86
China	0.15	0.14	0.68	0.76	0.17	0.17	0.62	0.63	0.05	0.16	0.59	0.66	0.82
India	0.84	0.01	0.56	0.30	0.75	0.02	0.66	0.49	0.39	0.00	0.78	0.09	0.12
Middle	0.85	0.30	0.97	0.62	0.67	0.32	0.83	0.78	0.92	0.25	0.86	0.68	0.63
Africa	0.59	0.04	0.35	0.13	0.88	0.03	0.64	0.01	0.86	0.01	0.42	0.04	0.05
Latin	0.34	0.04	0.29	0.67	0.72	0.01	0.32	0.84	0.57	0.00	0.30	0.72	0.39

Table S5. P-values RCP60 -Actual Water Withdrawal for Irrigated Agriculture



	H08_gfdl	H08_hadg	H08_ipsl	H08_miroc	Lpjml_gfdl	Lpjml_had	Lpjml_ipsl	Lpjml_mirc	Matsiro_gf	matsiro_ha	matsiro_ip	matsiro_m	Multimode
OECDEU	0.04	0.02	0.04	0.01	0.00	0.02	0.45	0.35	0.00	0.10	0.00	0.00	0.44
OECDAmeri	0.11	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
OCEANIA	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00
OthEU	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00
Asia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
China	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.10	0.00
India	0.00	0.01	0.79	0.67	0.00	0.00	0.00	0.00	0.00	0.78	0.00	0.22	0.00
Middle	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.28	0.68	0.89	0.00
Africa	0.02	0.03	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00
Latin	0.00	0.15	0.00	0.41	0.00	0.00	0.00	0.00	0.03	0.89	0.03	0.02	0.00

Table S6. P-values RCP26 -Actual Water Withdrawal for Irrigated Agriculture



	H08_gfdl	H08_hadg	H08_ipsl	H08_miroc	Lpjml_gfdl	Lpjml_had	Lpjml_ipsl	Lpjml_mirc	Matsiro_gf	matsiro_ha	matsiro_ip	matsiro_m	Multimode
OECDEU	0.90	0.11	0.22	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.21	0.01	0.00
OECDAmeri	0.62	0.95	0.02	0.00	1.00	0.05	0.20	0.00	0.91	0.00	0.24	0.02	0.02
OCEANIA	0.01	0.23	0.00	0.00	0.00	0.00	0.01	0.00	0.13	0.00	0.02	0.00	0.00
OthEU	0.89	0.47	0.12	0.00	0.09	0.00	0.00	0.00	0.01	0.00	0.86	0.01	0.00
Asia	0.00	0.90	0.00	0.00	0.58	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00
China	0.43	0.87	0.04	0.00	0.24	0.00	0.04	0.00	0.81	0.00	0.69	0.06	0.00
India	0.04	0.62	0.48	0.43	0.96	0.03	0.34	0.01	0.01	0.62	0.99	0.18	0.17
Middle	0.28	0.88	0.13	0.00	0.91	0.36	0.07	0.02	0.90	0.00	0.40	0.05	0.01
Africa	0.66	0.87	0.03	0.32	0.06	0.46	0.13	0.02	0.54	0.00	0.05	0.69	0.03
Latin	0.46	0.84	0.01	0.76	0.02	0.10	0.19	0.13	0.88	0.07	0.01	0.80	0.99

Equation 1. Formula describing the endogenous water calibration process.

Water withdrawals in the calibration are endogenous and described by the following linearized equation. All variables are expressed in small letters and percentage change:

$$qoes(i,j,r) = \big(qo(j,r) - afe(i,j,r)\big) + qoessec(i,j,r) + ETRAE(i) * [pm(i,r) - pmes(i,j,r)]$$

where qoes is the supply of the water endowment, qo is the sectorial production, afe is a measure of water efficiency, qoessec is the sectoral impact in terms of sector-specific climatic impact (non-zero only for irrigated agriculture), ETRAE is the elasticity of transformation parameter for water mobility across sectors, pm is the shadow price of water and *pmes* is the price of water in each sector. *For the indices, i is the water index, j is the sector and r is the region.*

Fig. S1. Production function of the Energy disaggregated model

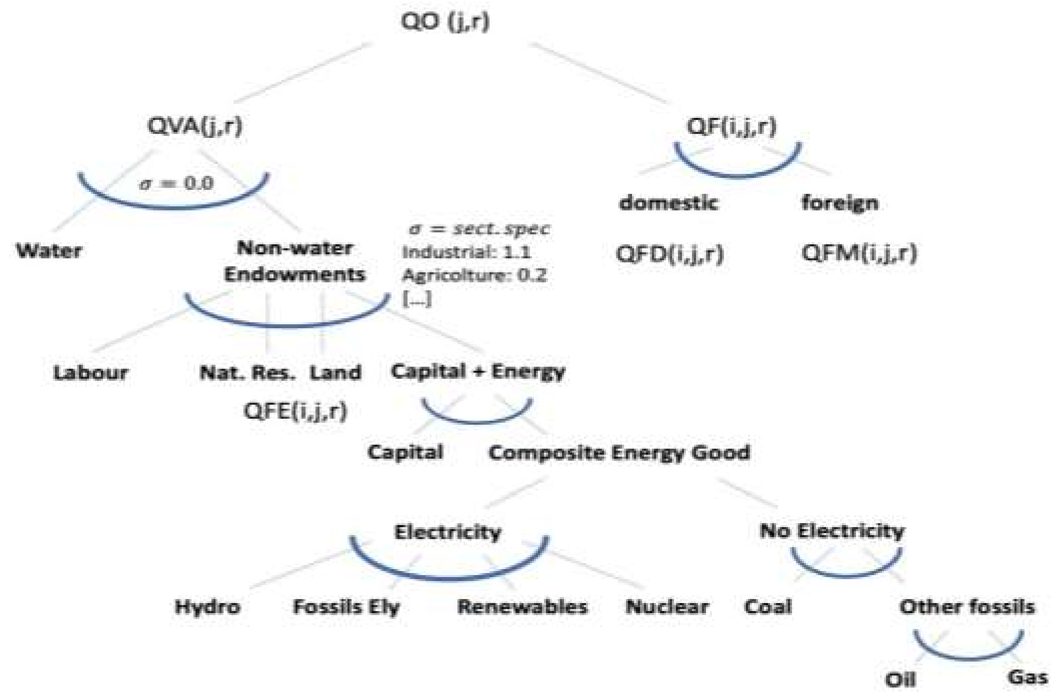
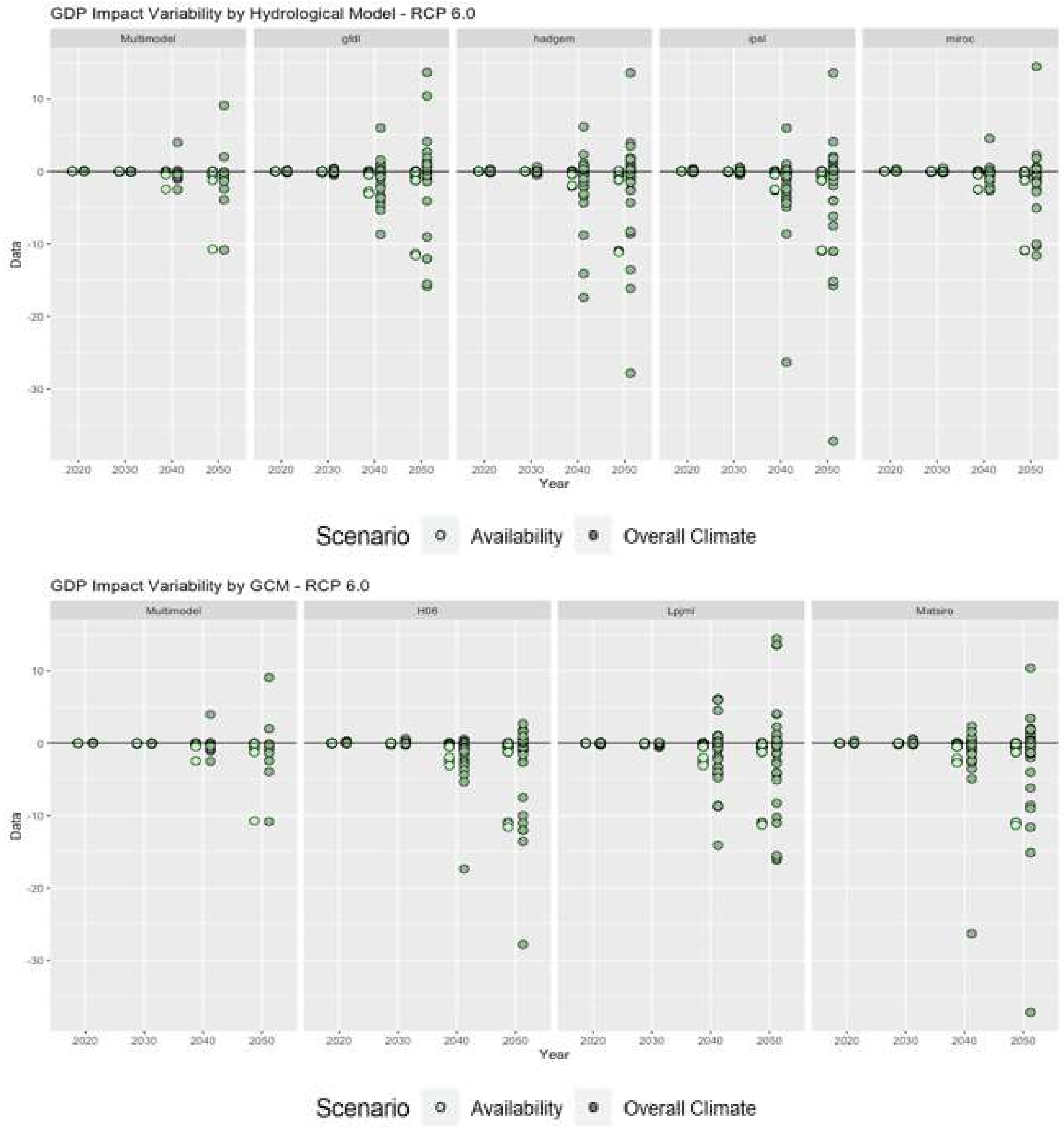
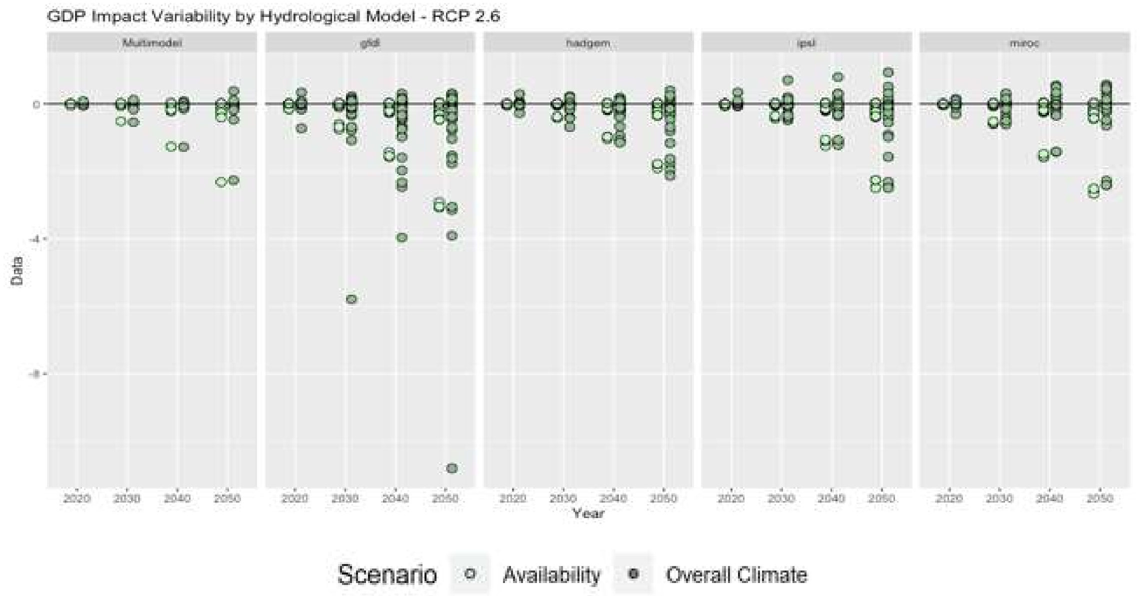
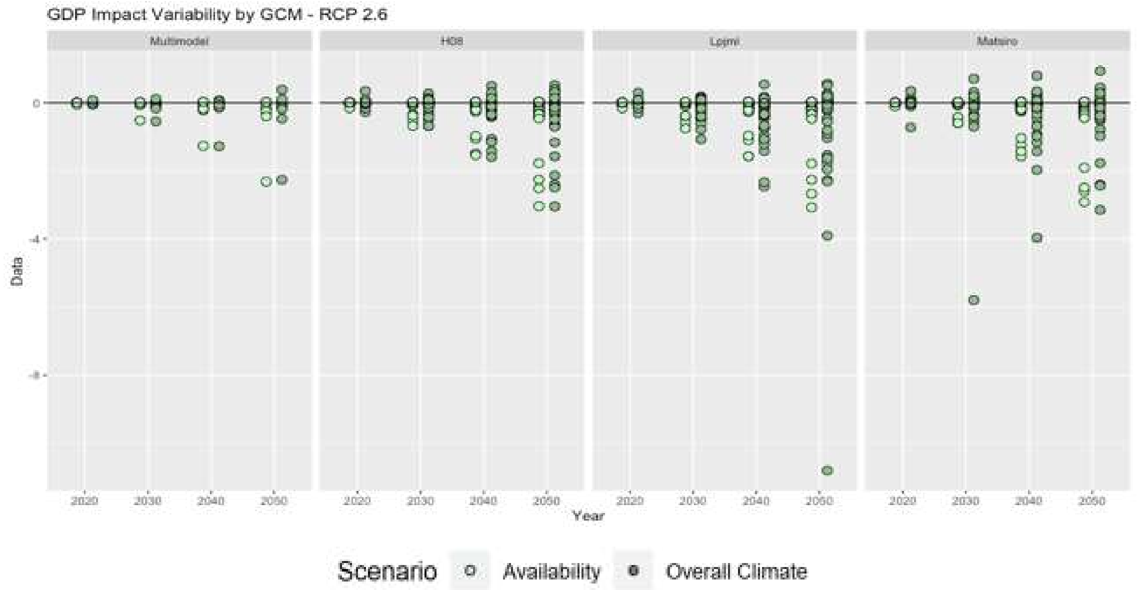


Figure S2. Disaggregation of % impact with respect to baseline by input model

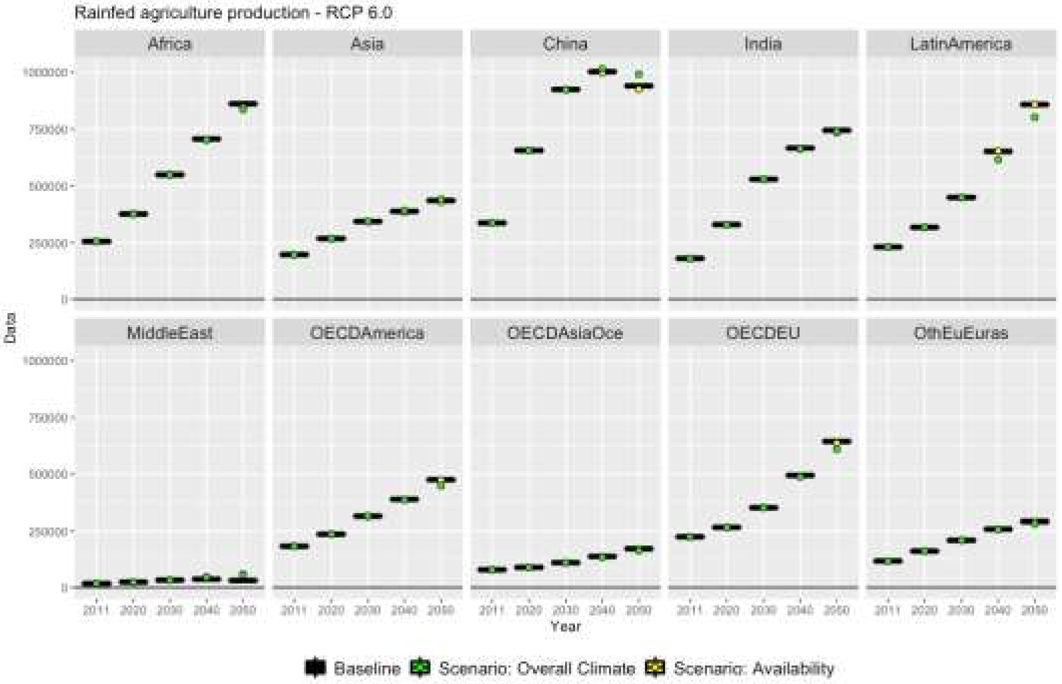


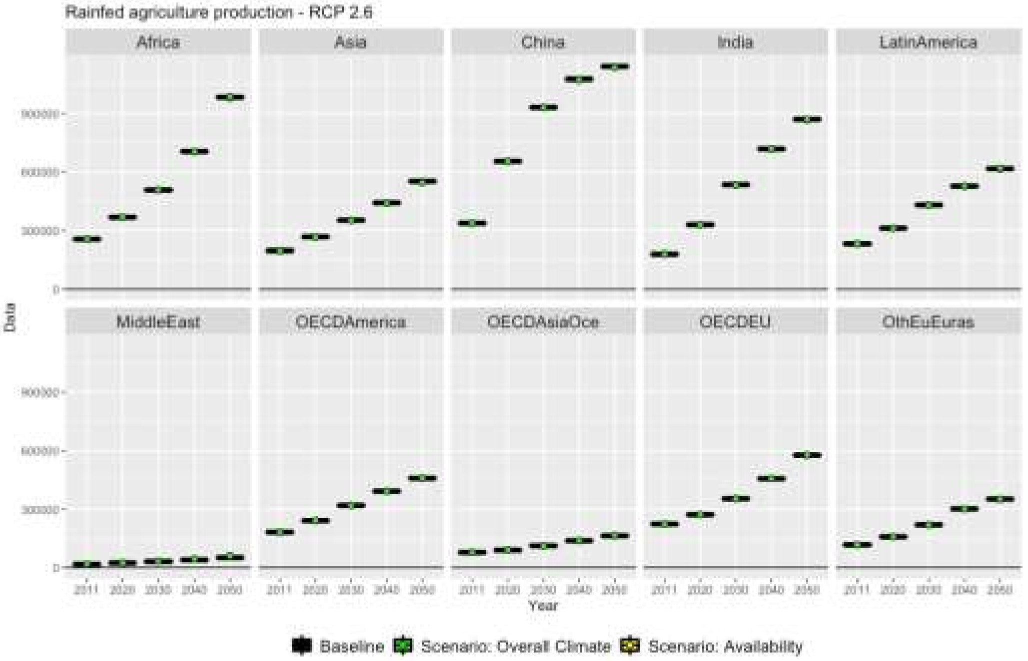




As shown in this figure, there is a significant difference between the two climate scenarios, with the highest climate having both higher intensity and variability in the entity of the macroeconomic impacts. Furthermore, disaggregating the data for the type of model shows a signal of uncertainty relative to the input model used. For RCP 6.0 the results disaggregated for GCM identify Matsiro as the most negative outlier and Lpjml as relatively more positive, while differentiating by hydrological models there are no clear outliers on the positive sign, while Ipsl is generally associated with the highest negative outliers. Concerning RCP 2.6, GFDL and Lpjml are associated with the highest negative outlier. All in all, the sensitivity analysis shows that there are significant differences as a consequence of the use of different physical models as inputs, which significantly affect the variability and intensity of the relative economic assessment. Therefore, while recognising the importance of the uncertainty relative to the specific Hydro|GCMs, the paper discusses only the result relative to the use of the multi-model median of the physical model as inputs.

Figure S3. Rainfed production in RCP 6.0 and 2.6, Baseline and Scenarios, Million US$[33]





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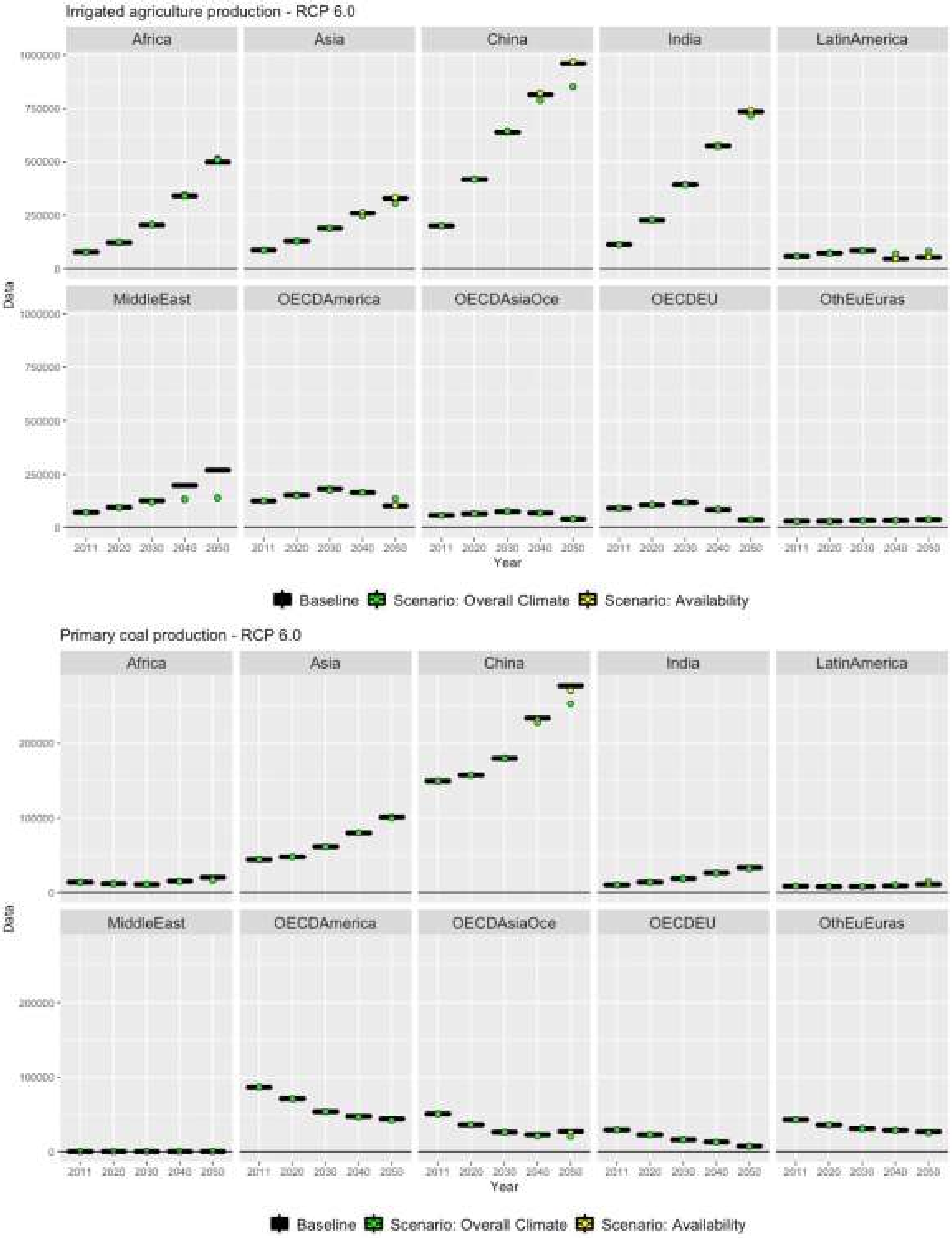
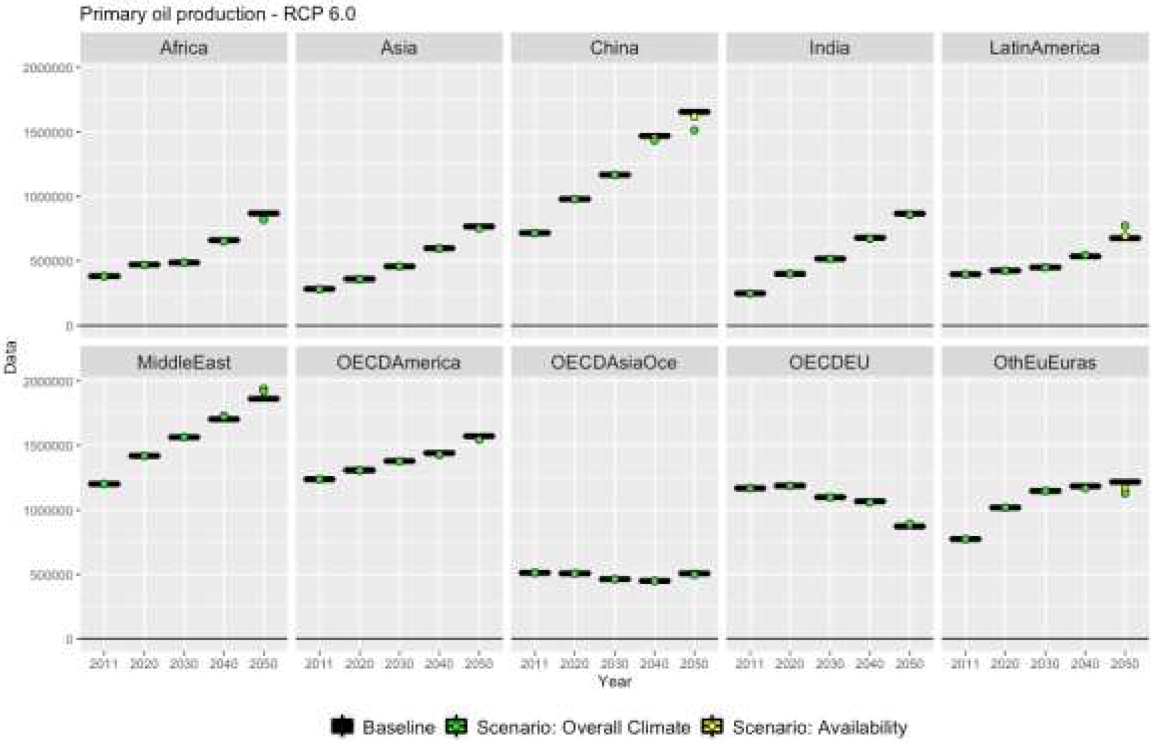
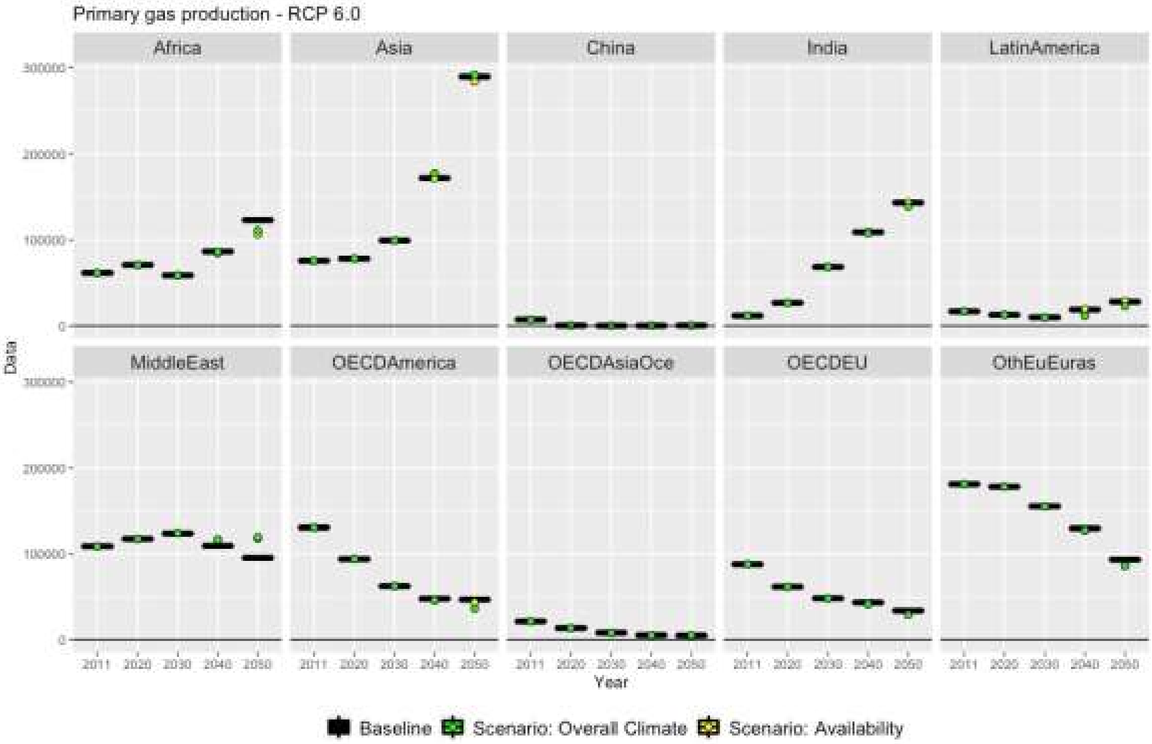
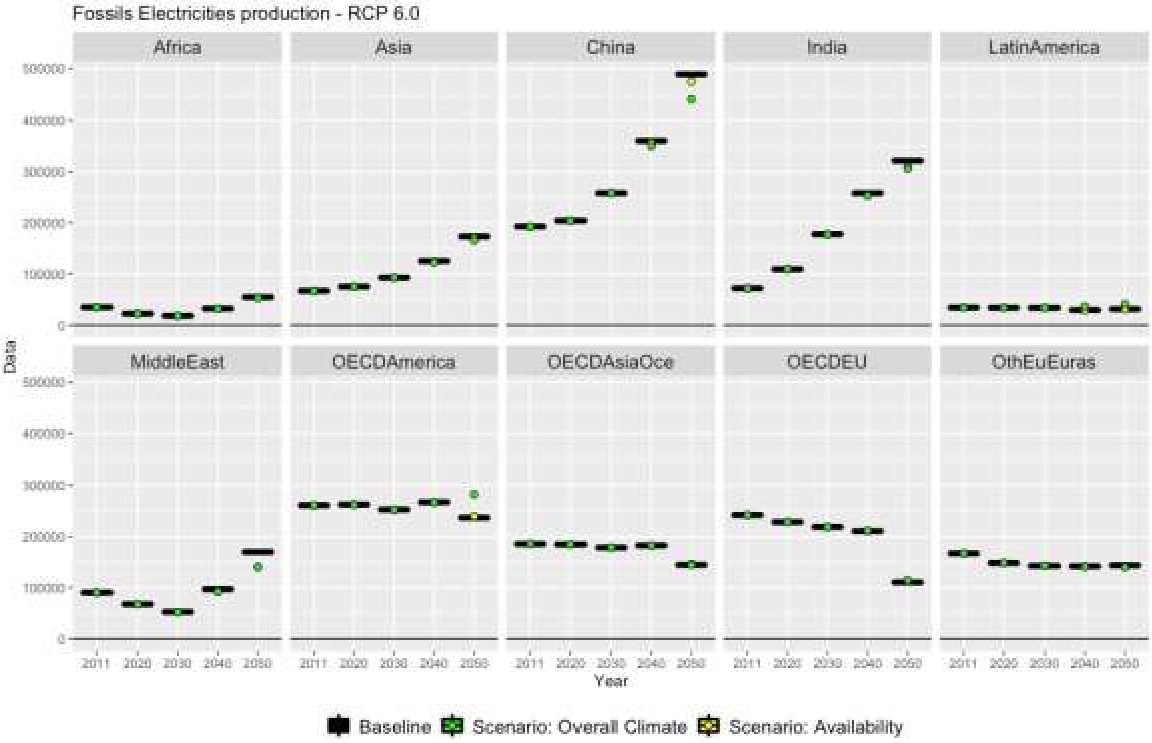
[33] In this Figure, as well as in Figure S4 to S10, if the two scenarios coincide, only the green scenario appears, since the two symbols superimpose.

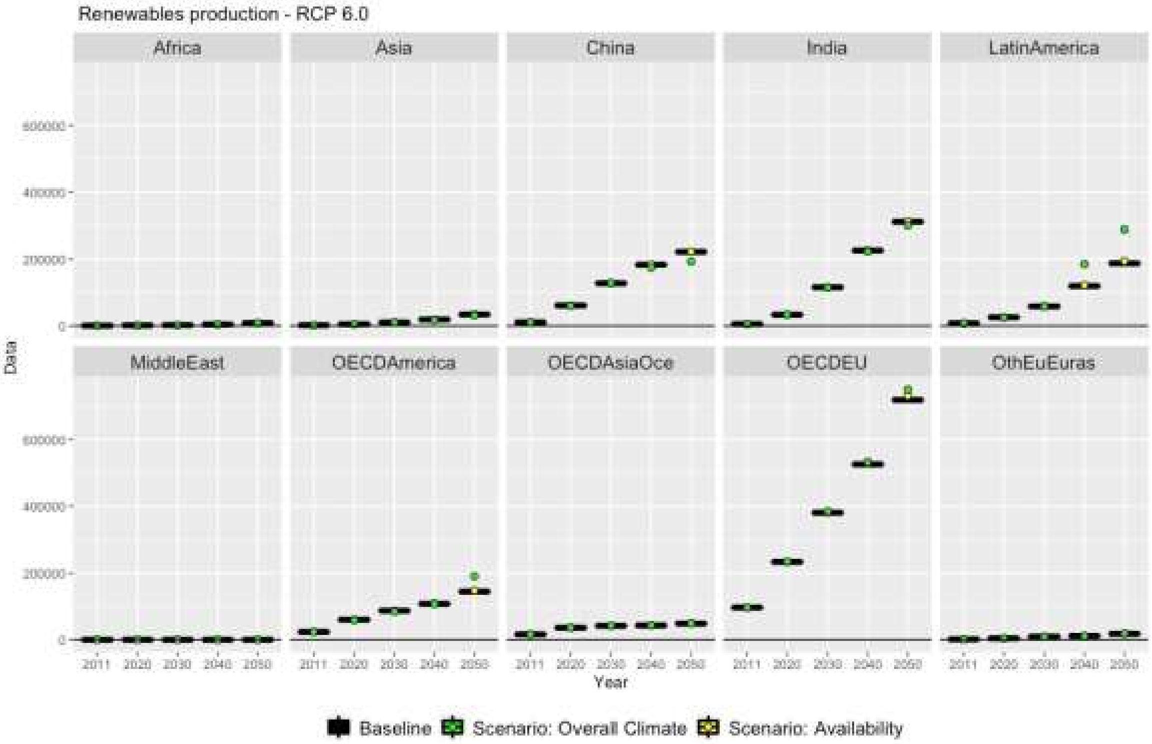
Figure S4. Irrigated Agriculture and Energy Production in RCP 6.0 Baseline and Scenarios, Million US$

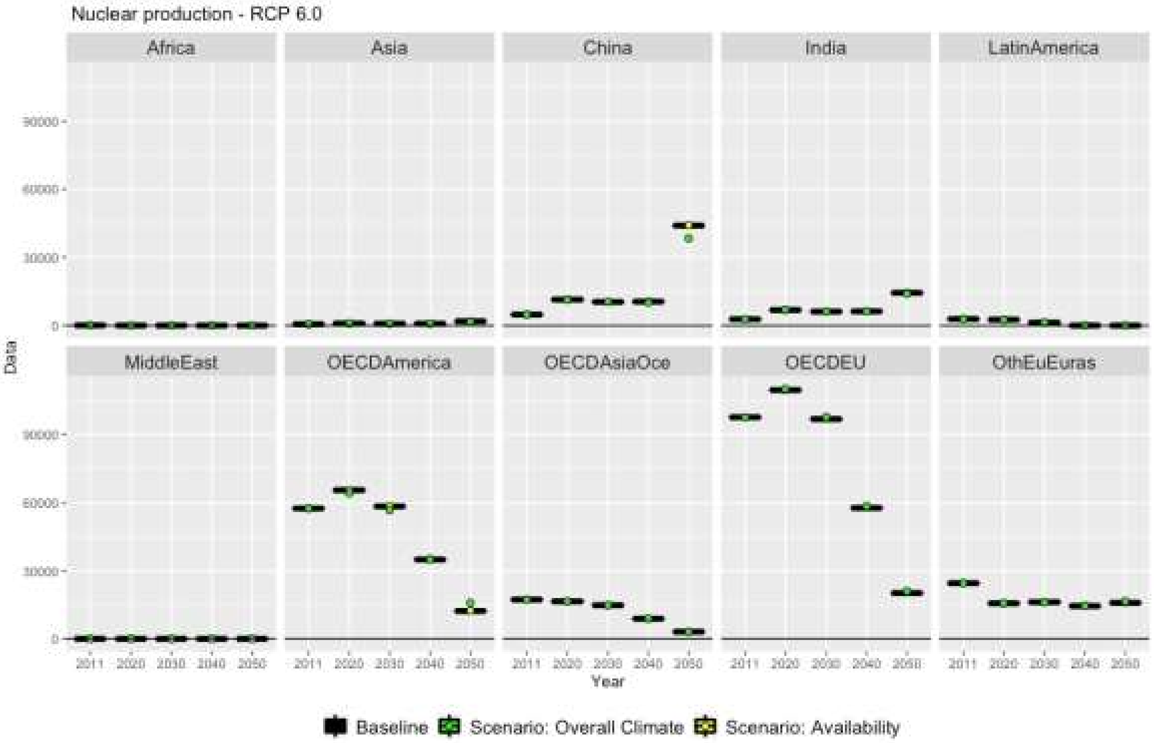



Primary oil production - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
2000000
1500000
1000000
500000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Primary gas production - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
300000
200000
100000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Fossils Electricities production - RCP 6.0


Renewables production - RCP 6.0


Nuclear production - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
30000
60000
90000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

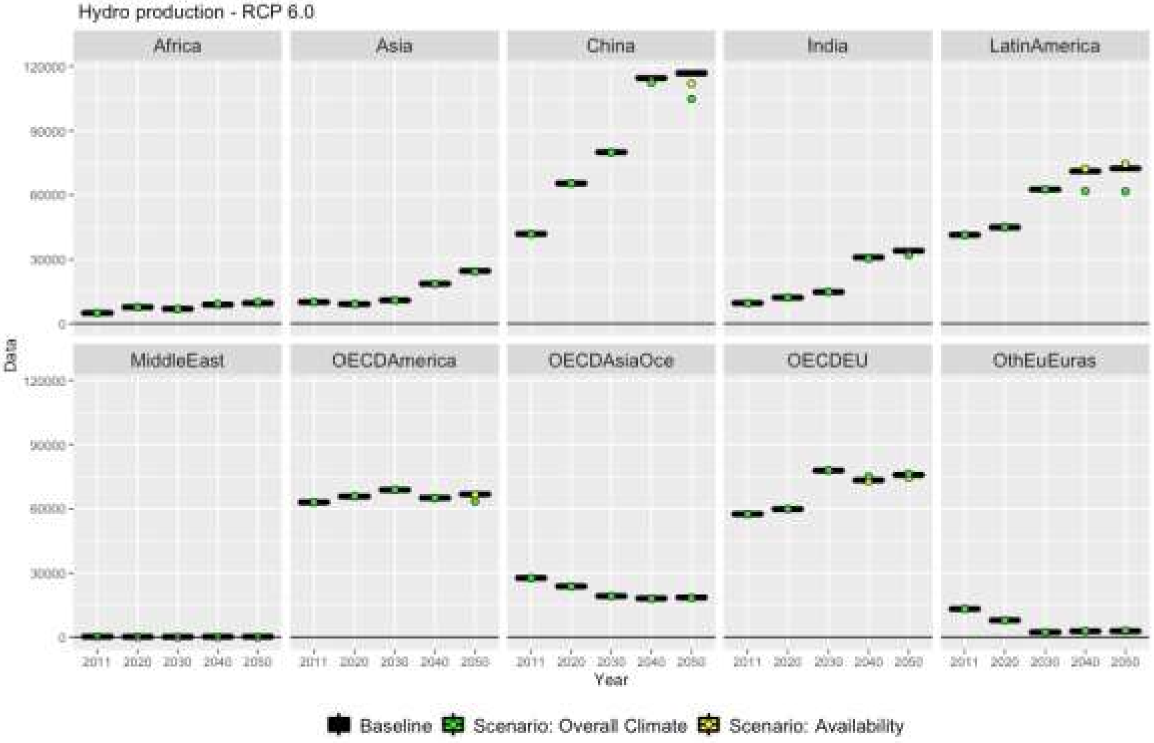
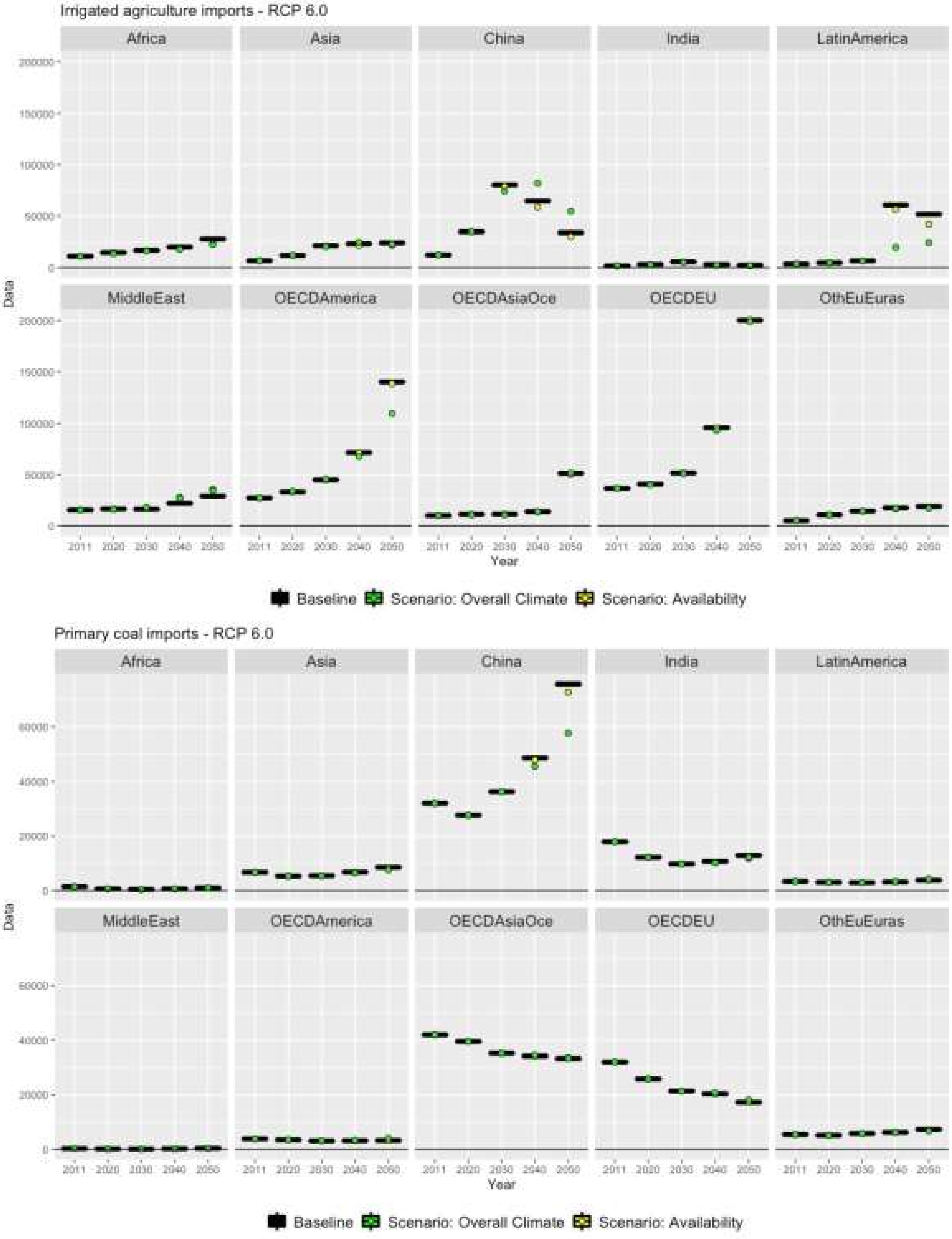
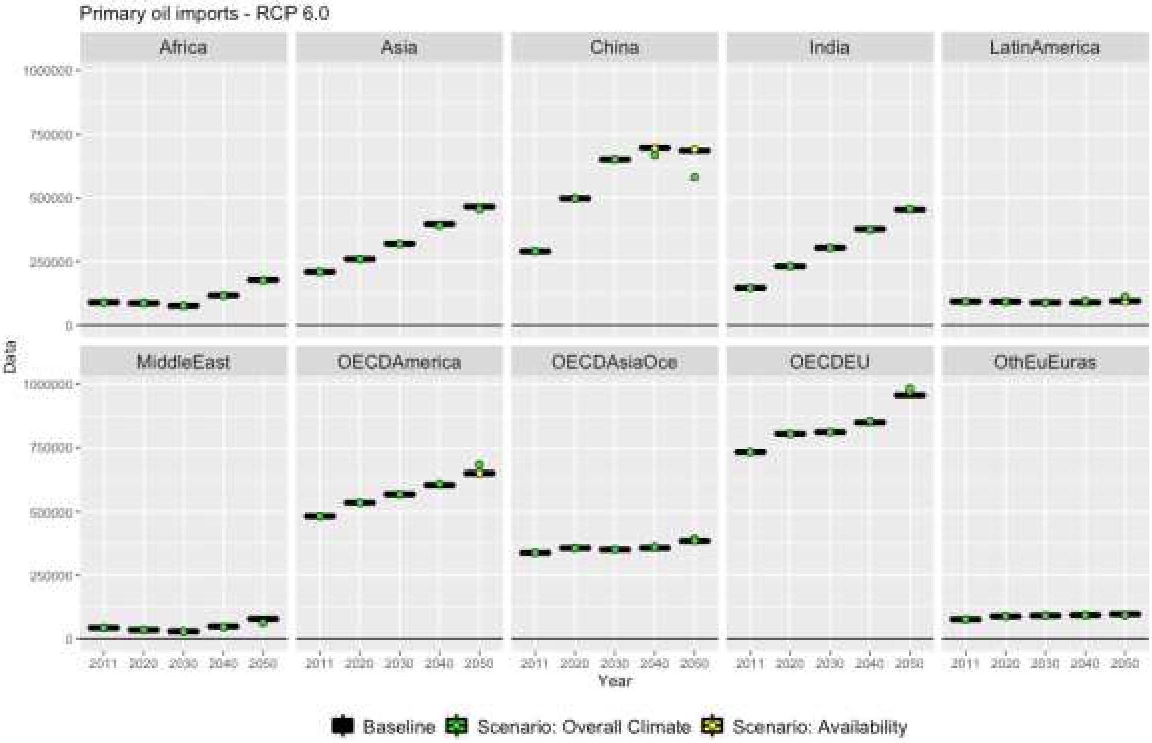
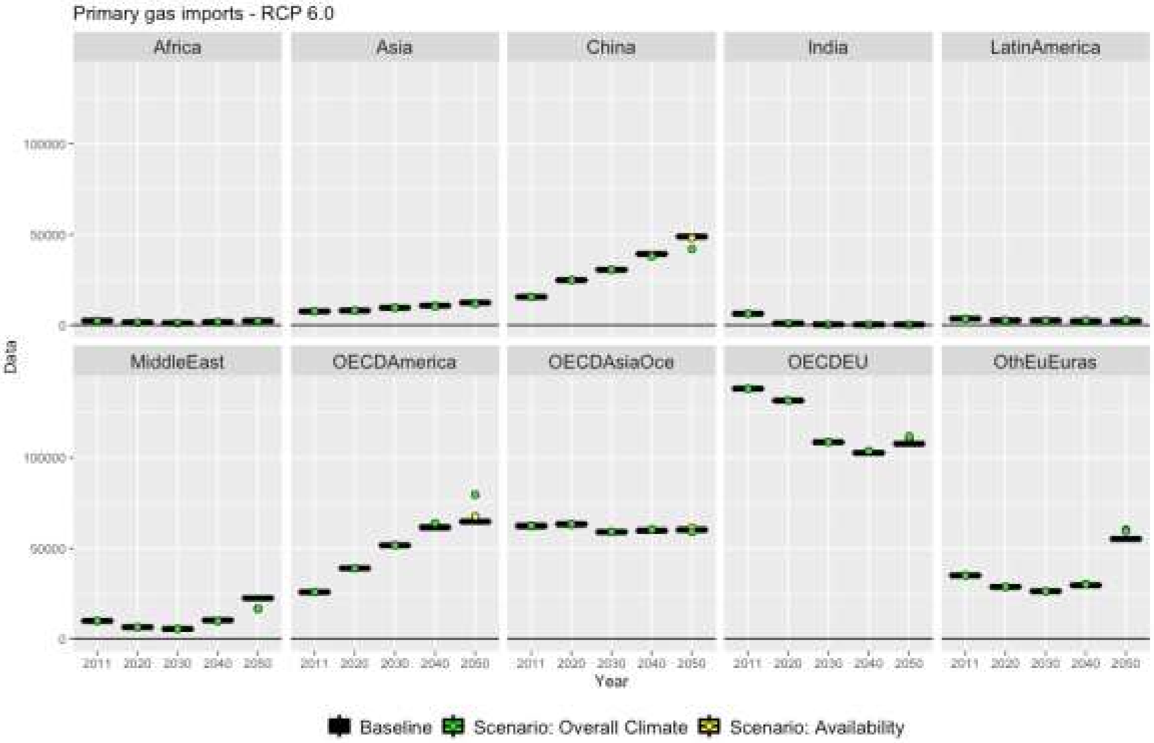
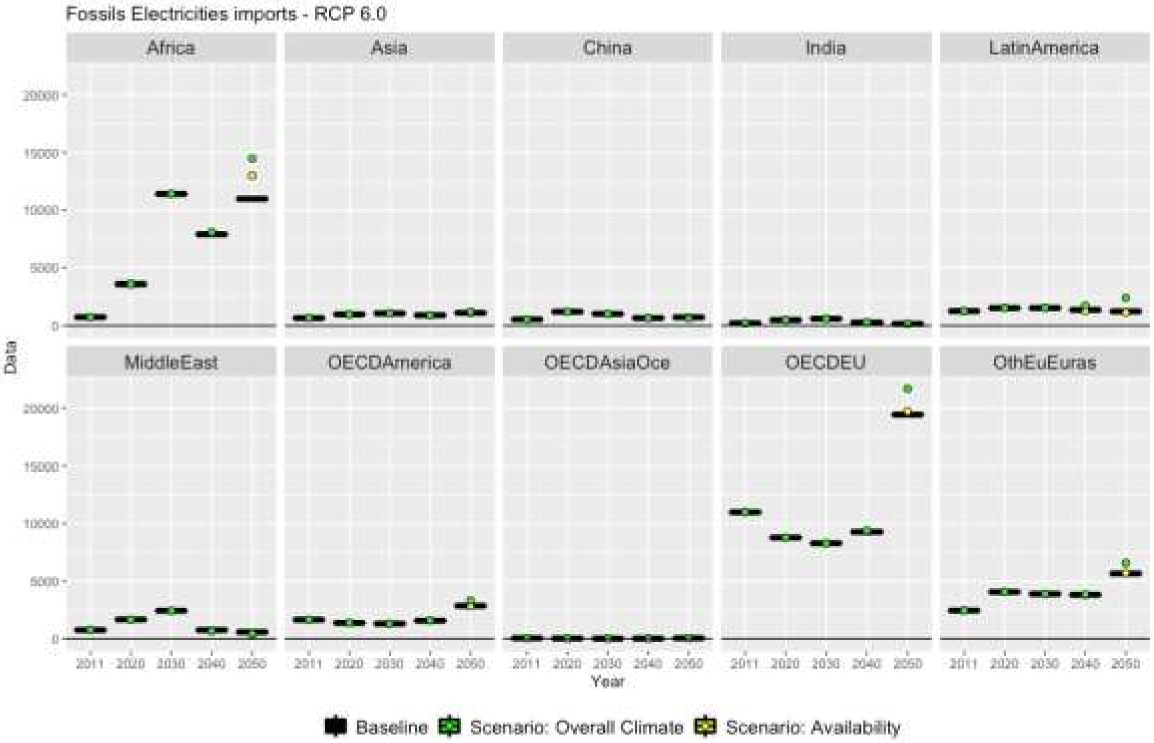

Hydro production - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
30000
60000
90000
120000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

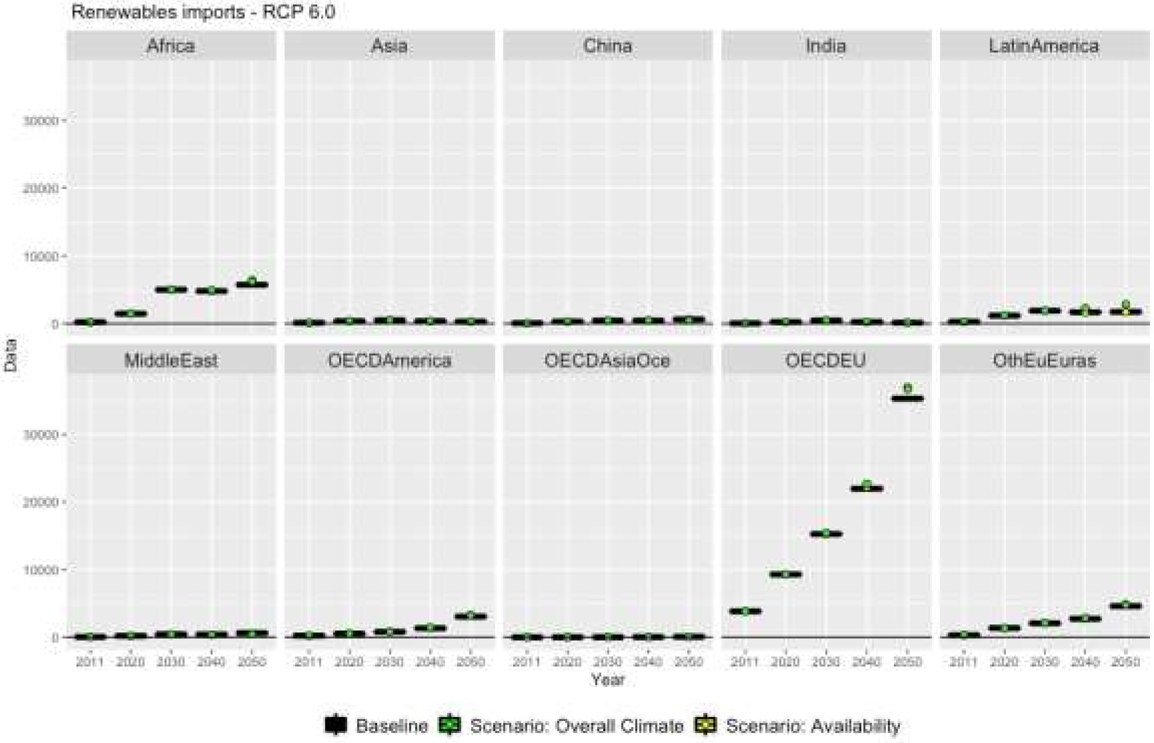
Figure S5. Irrigated Agriculture and Energy Imports in RCP 6.0 Baseline and Scenarios, Million US$

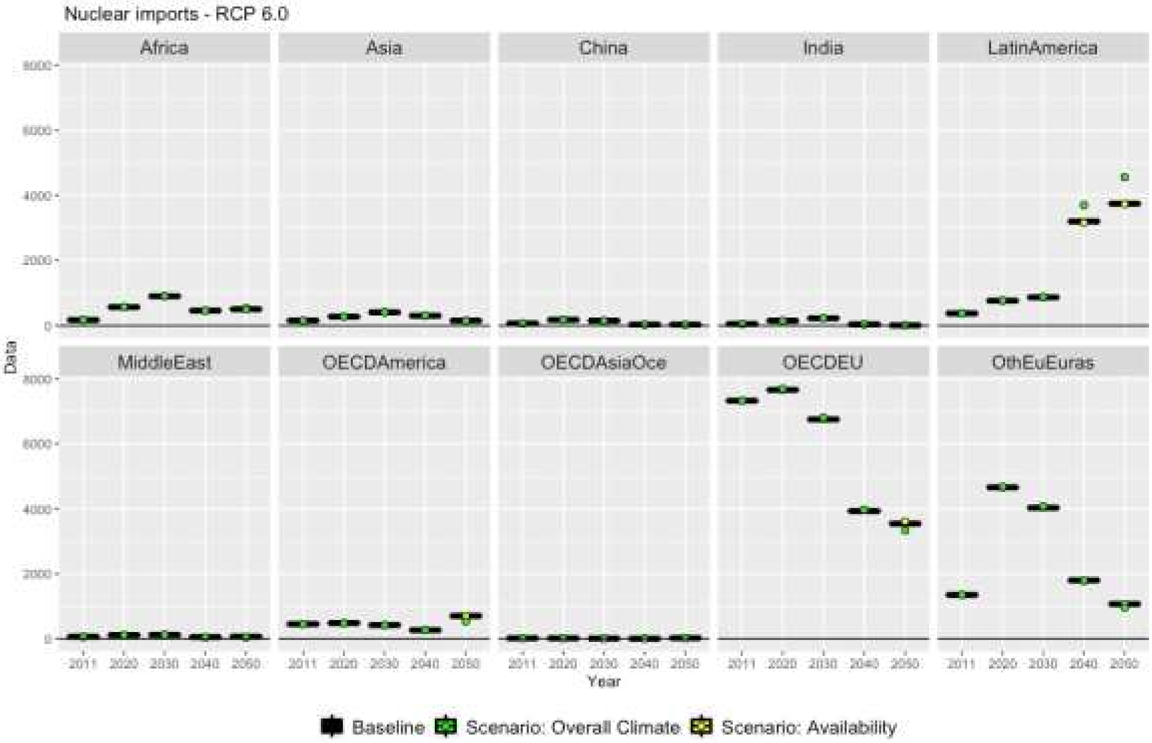



Primary oil imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
1000000
750000
500000
250000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Primary gas imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
100000
50000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Fossils Electricities imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
5000
10000
15000
20000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Renewables imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
10000
20000
30000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Nuclear imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
2000
4000
6000
8000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

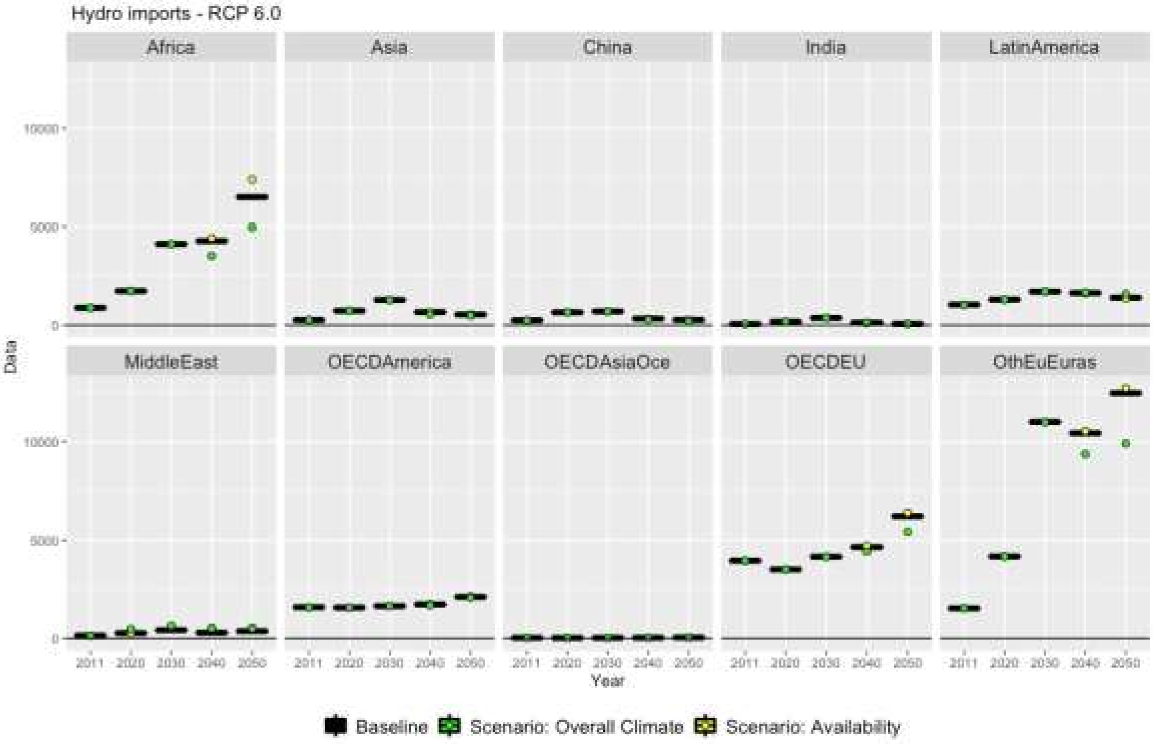
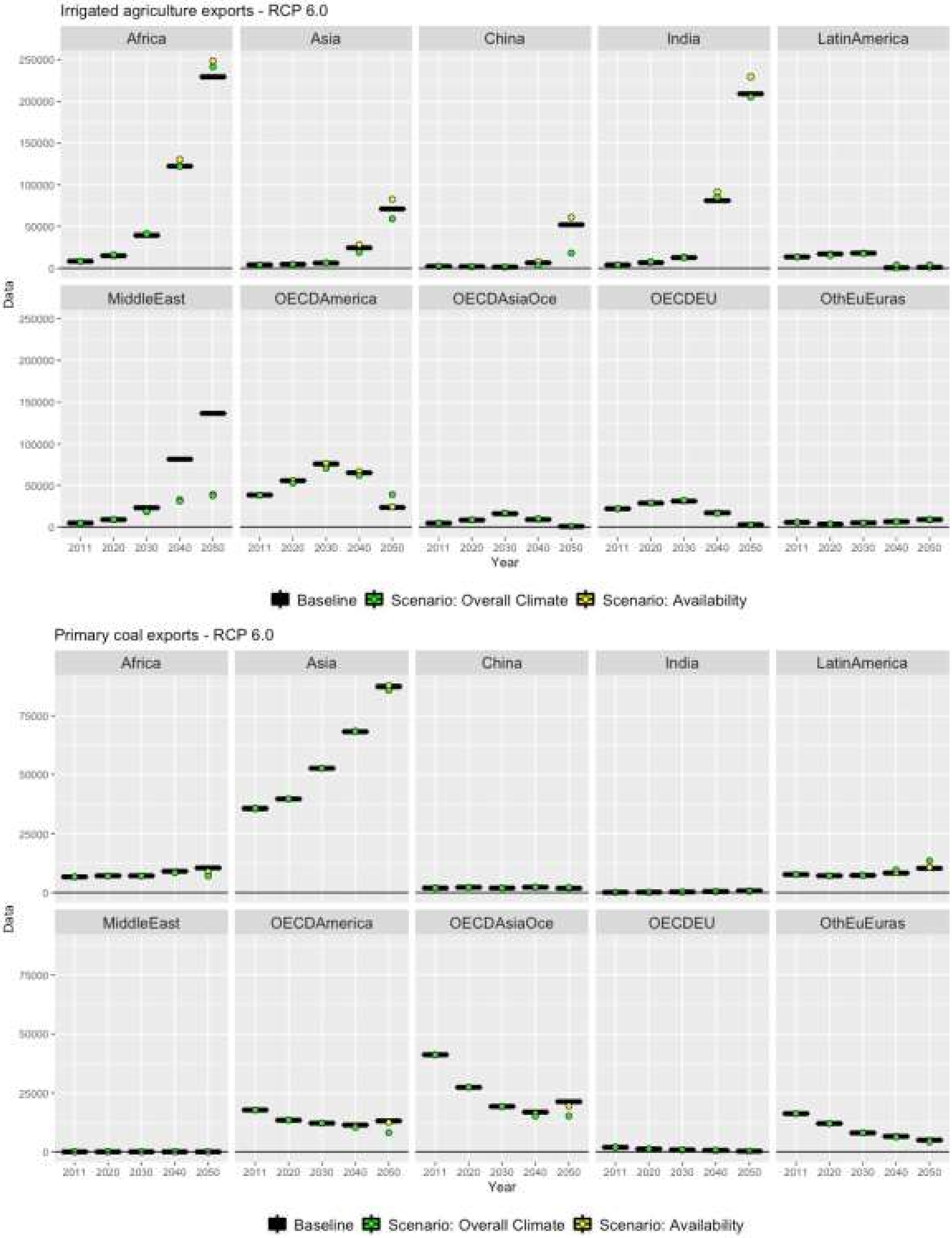
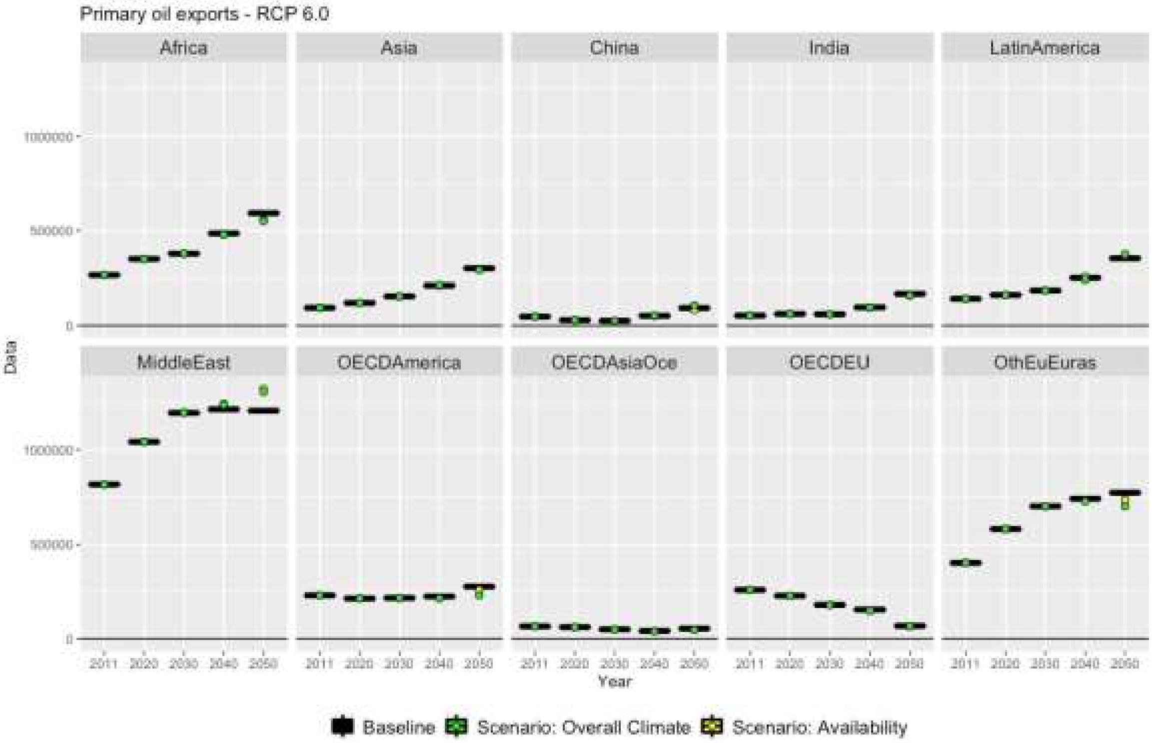
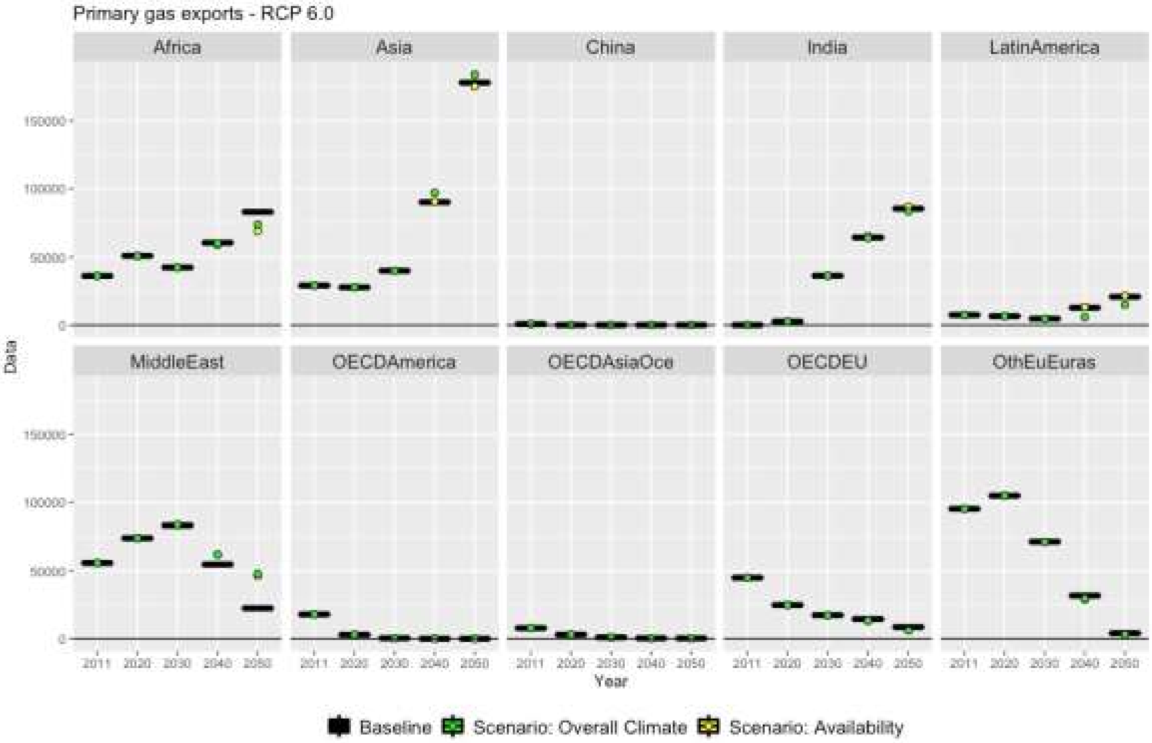
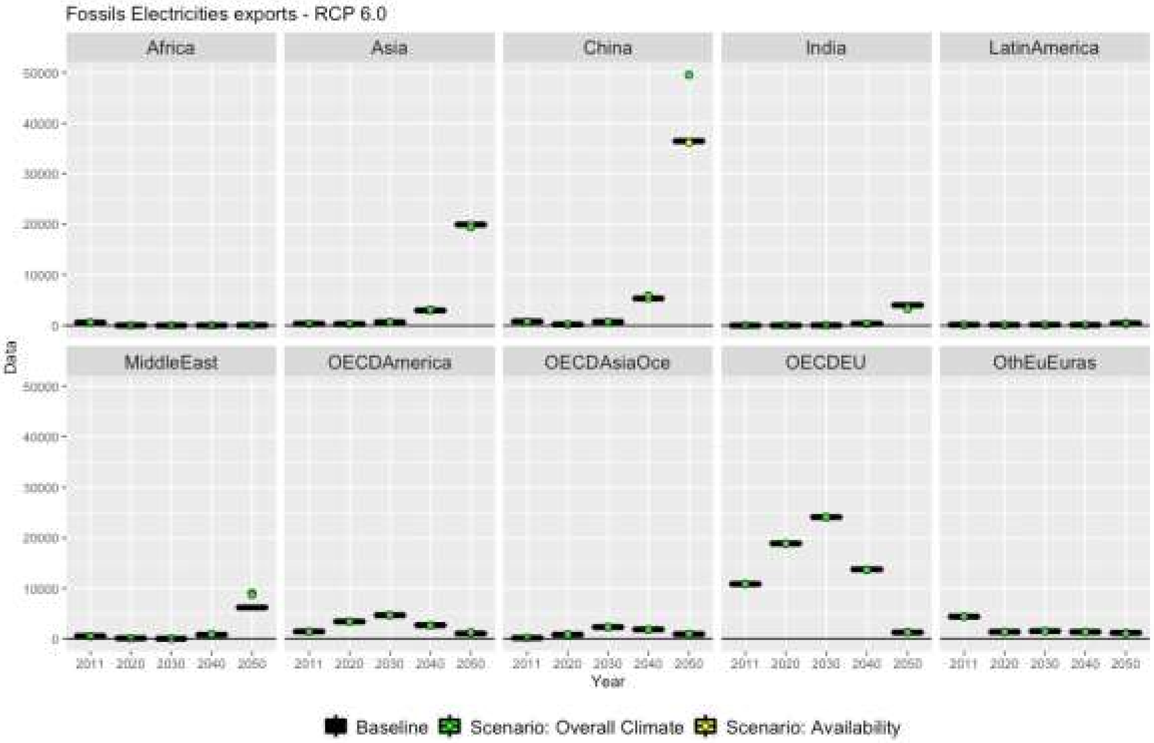

Hydro imports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
5000
10000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

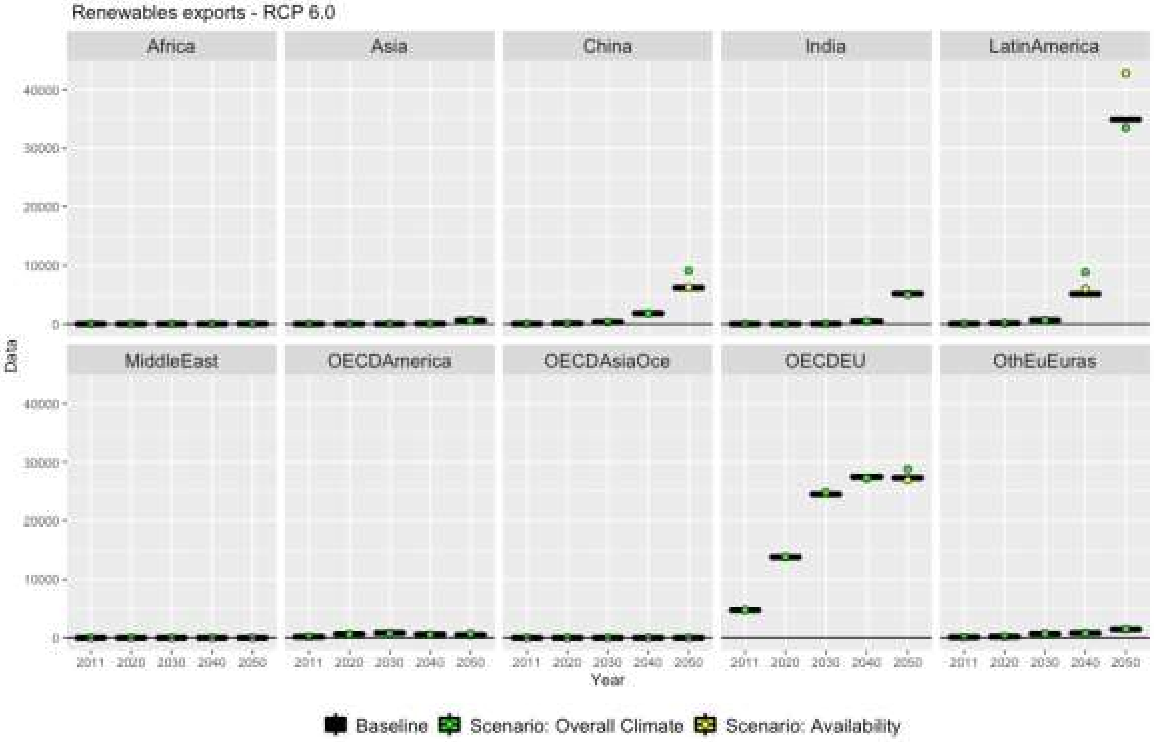
Figure S6. Irrigated Agriculture and Energy Exports in RCP 6.0 Baseline and Scenarios, Million US$

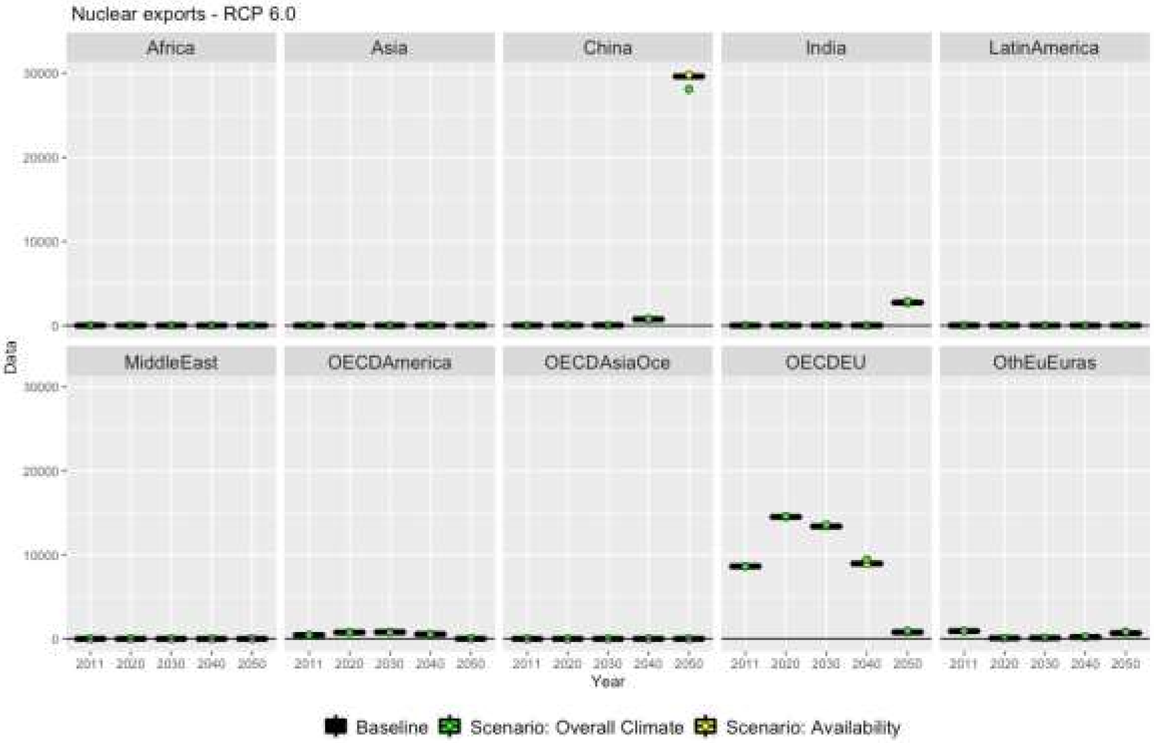



Primary oil exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
1000000
500000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Primary gas exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
150000
100000
50000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Fossils Electricities exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
10000
20000
30000
40000
50000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Renewables exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
0
10000
20000
30000
40000
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Nuclear exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
30000
20000
10000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

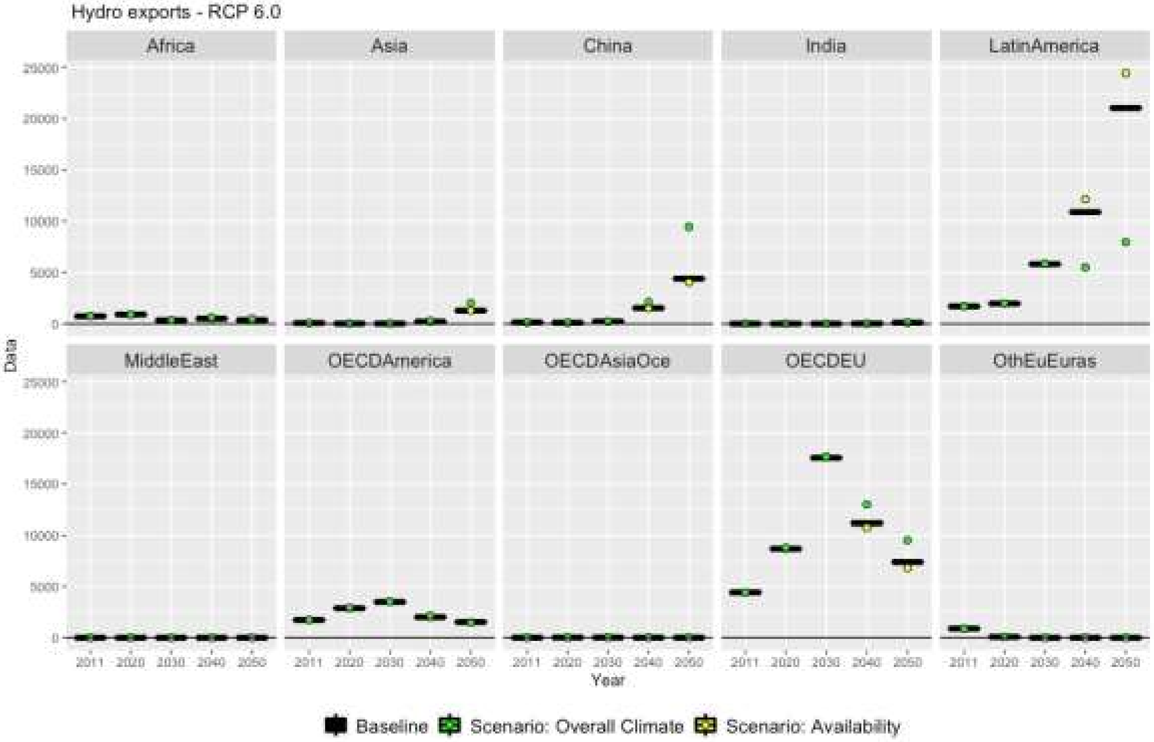
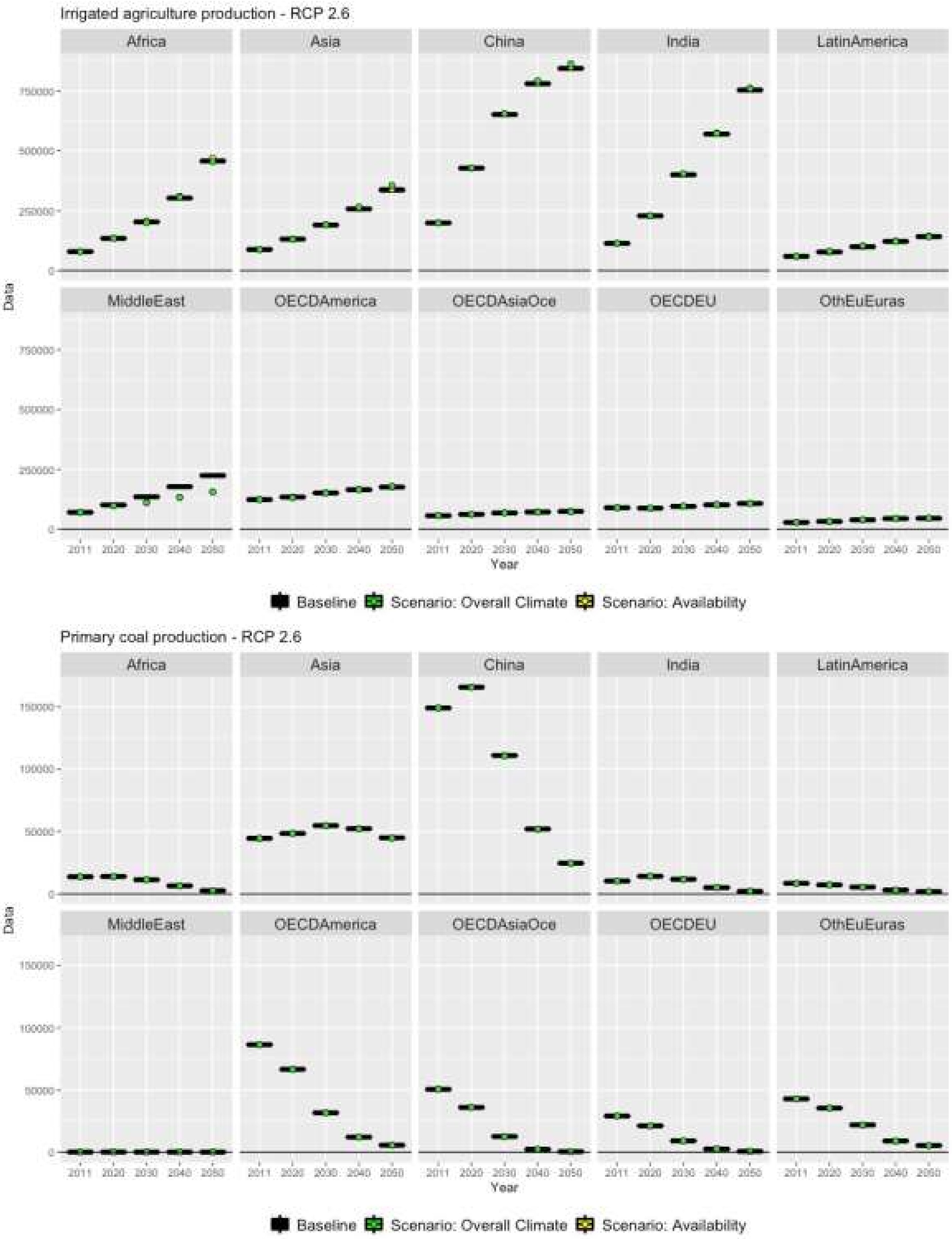
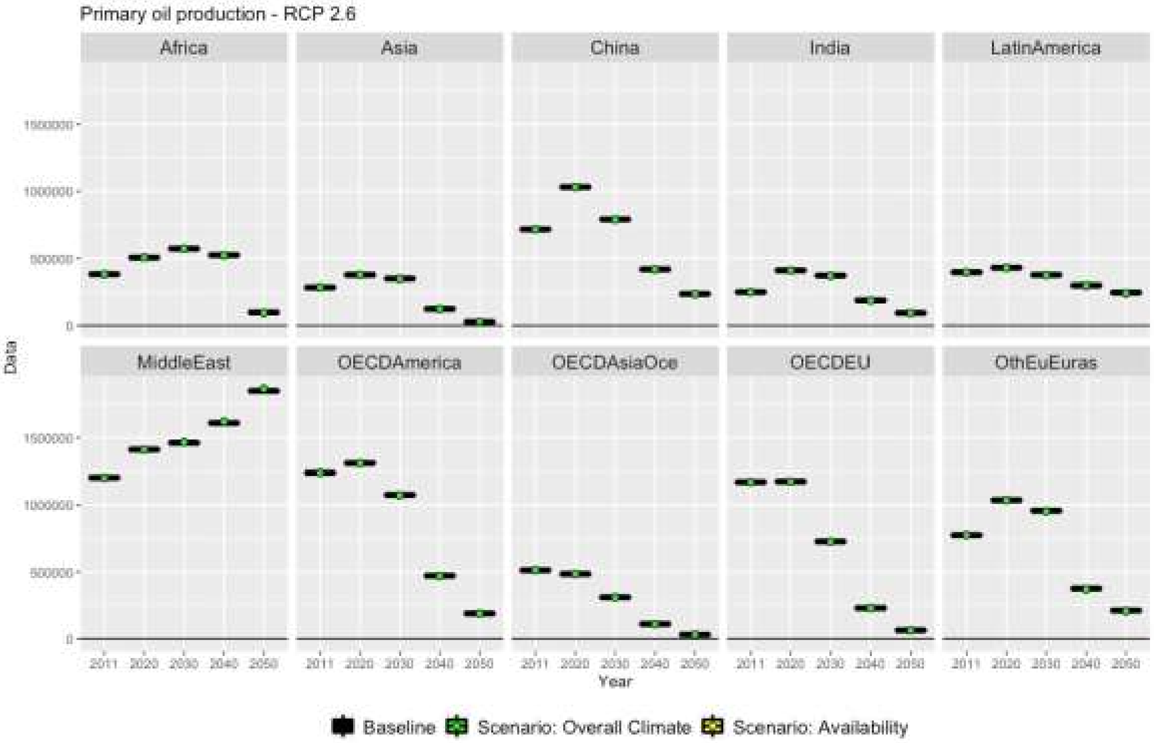
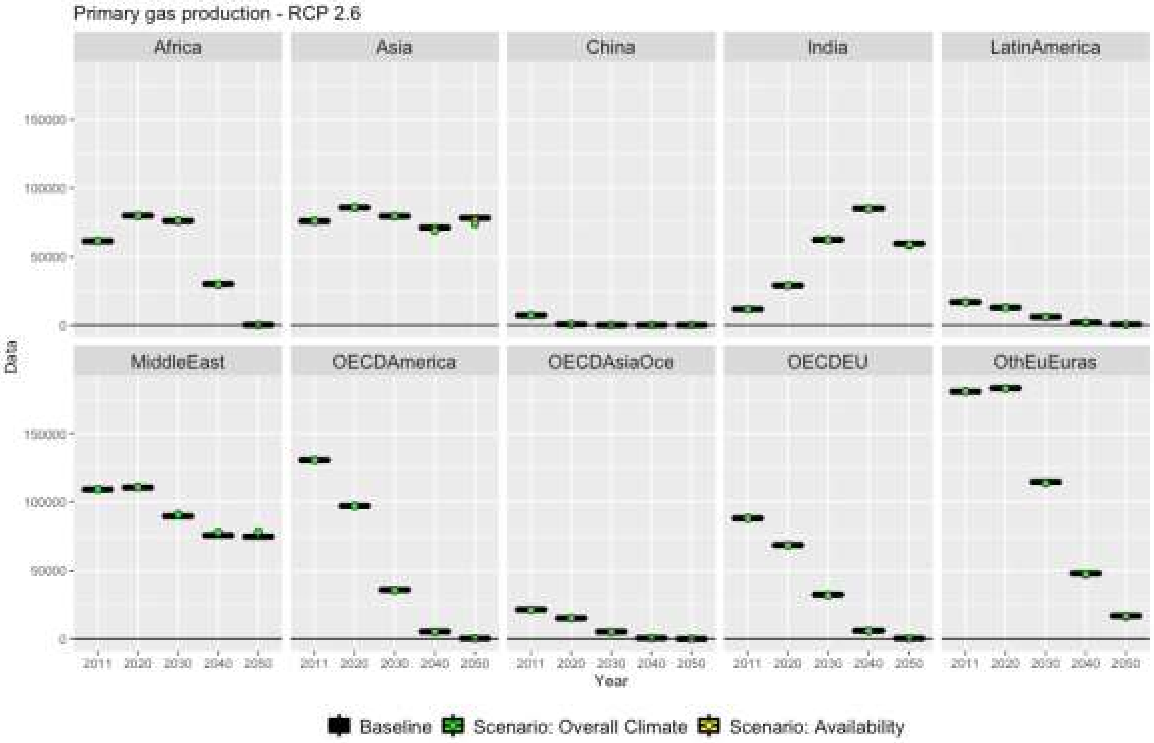
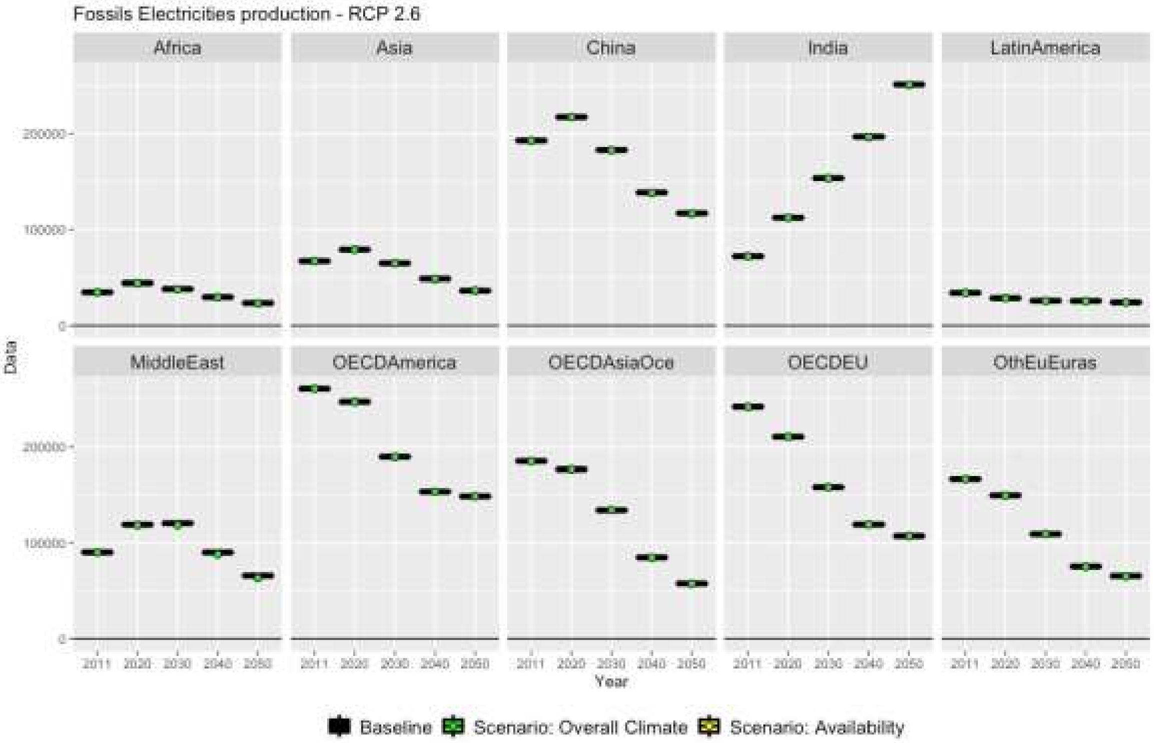

Hydro exports - RCP 6.0
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
25000
20000
15000
10000
5000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

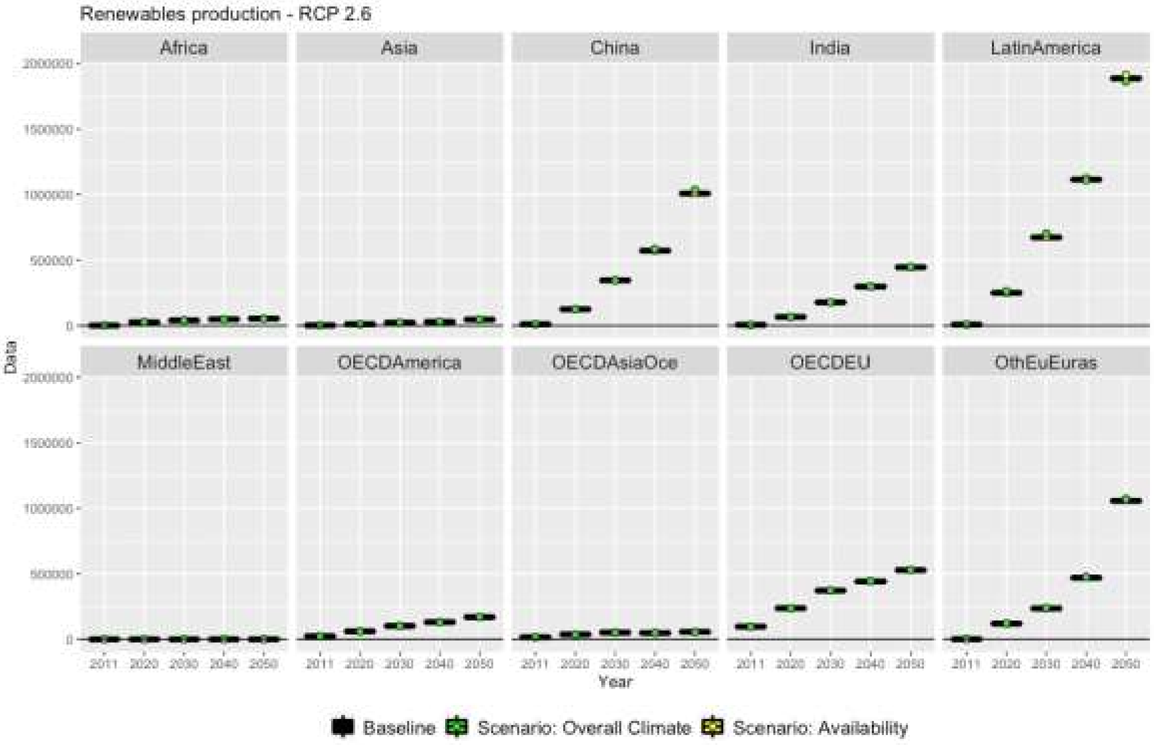
Figure S7. Irrigated Agriculture and Energy Production in RCP 2.6 Baseline and Scenarios, , Million US

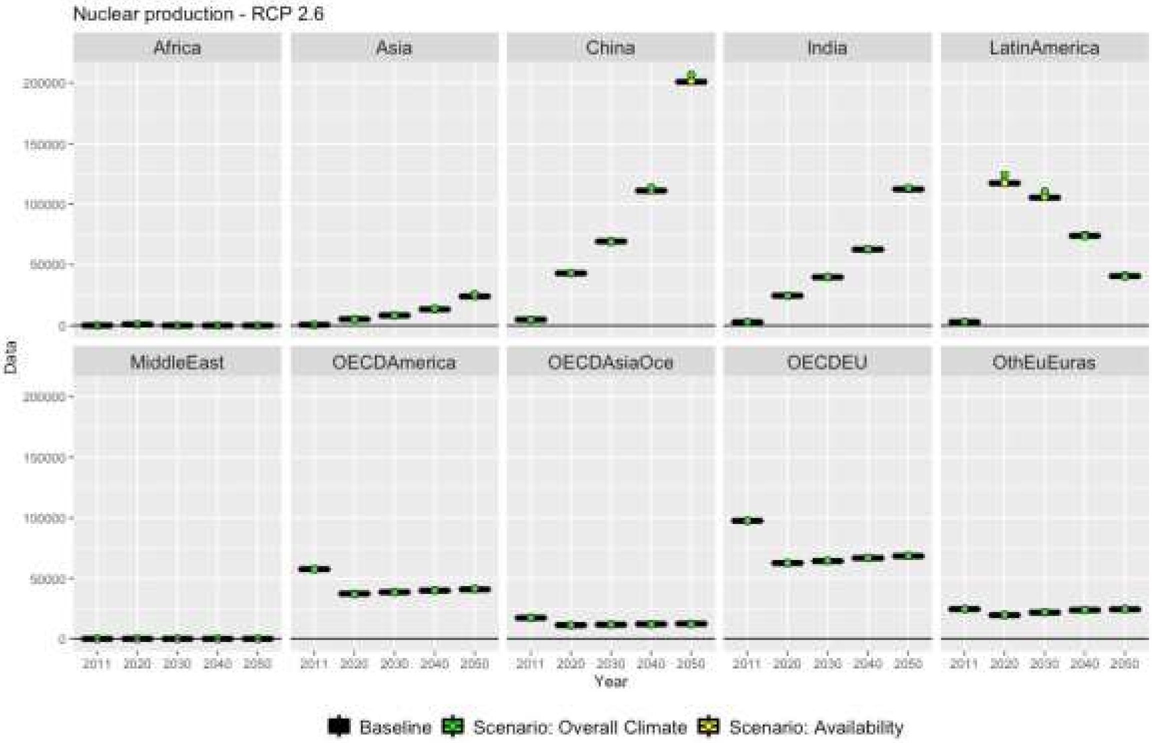



Primary oil production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
1500000
1000000
500000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Primary gas production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
150000
100000
50000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Fossils Electricities production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
200000
100000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Renewables production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
2000000
1500000
1000000
500000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Nuclear production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
200000
150000
100000
50000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

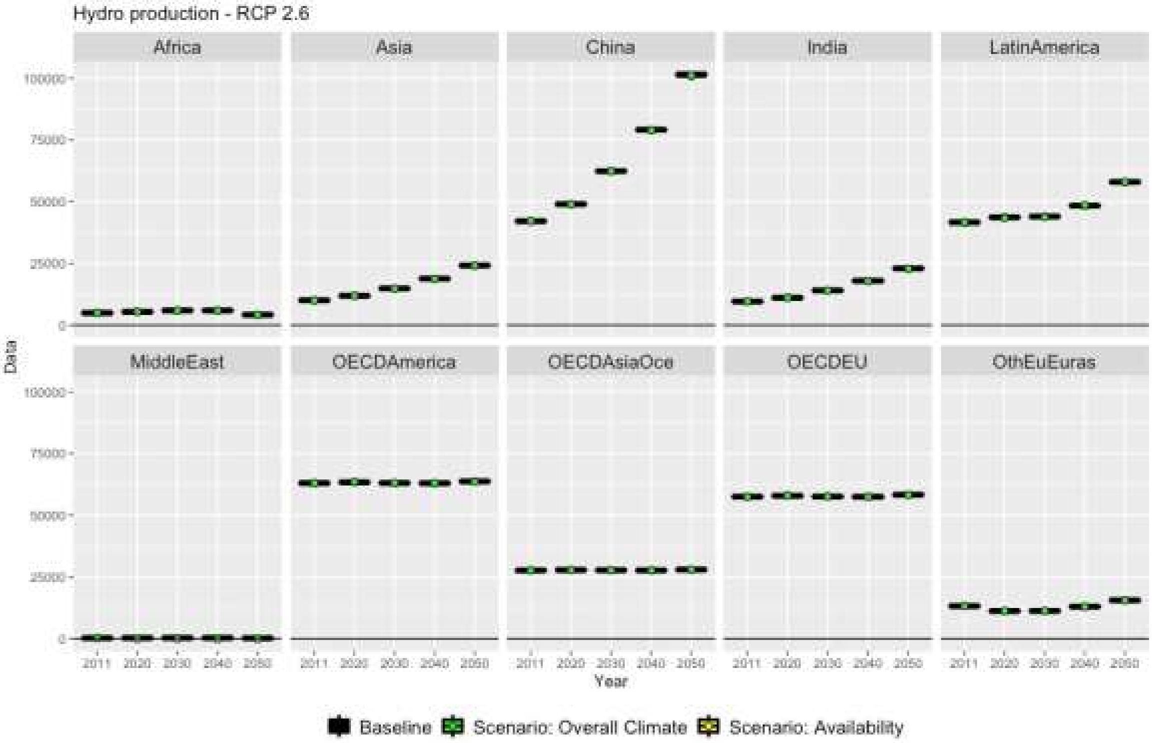
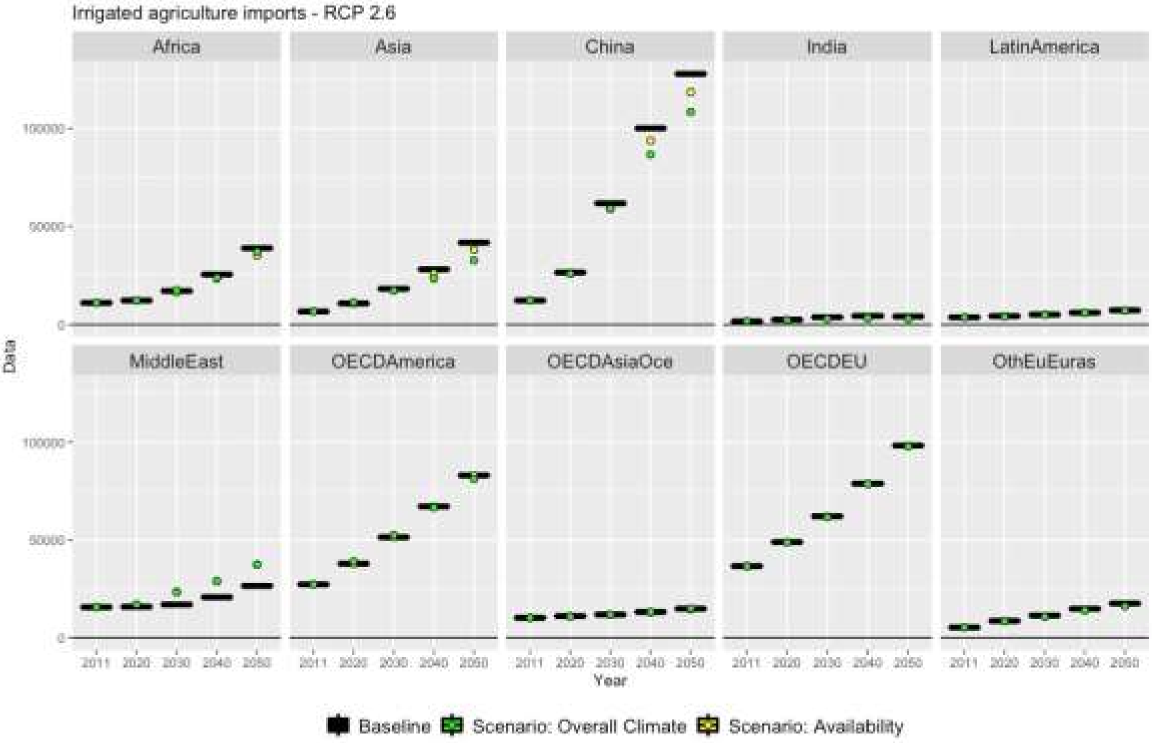
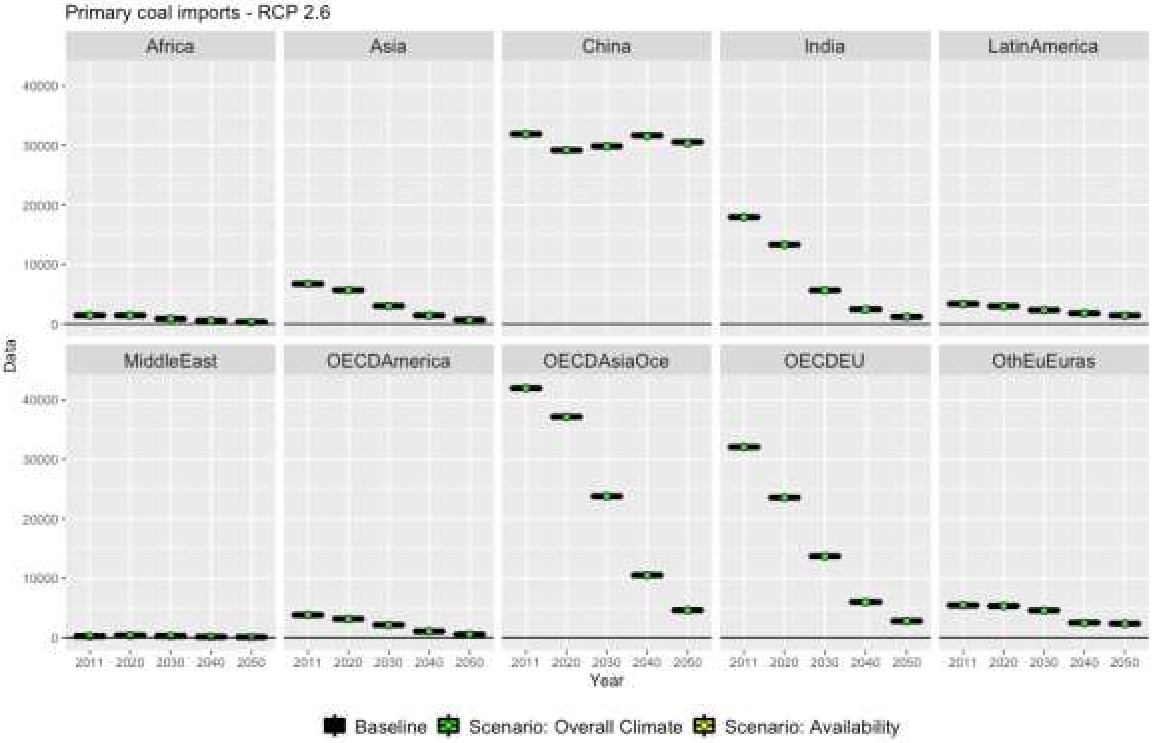
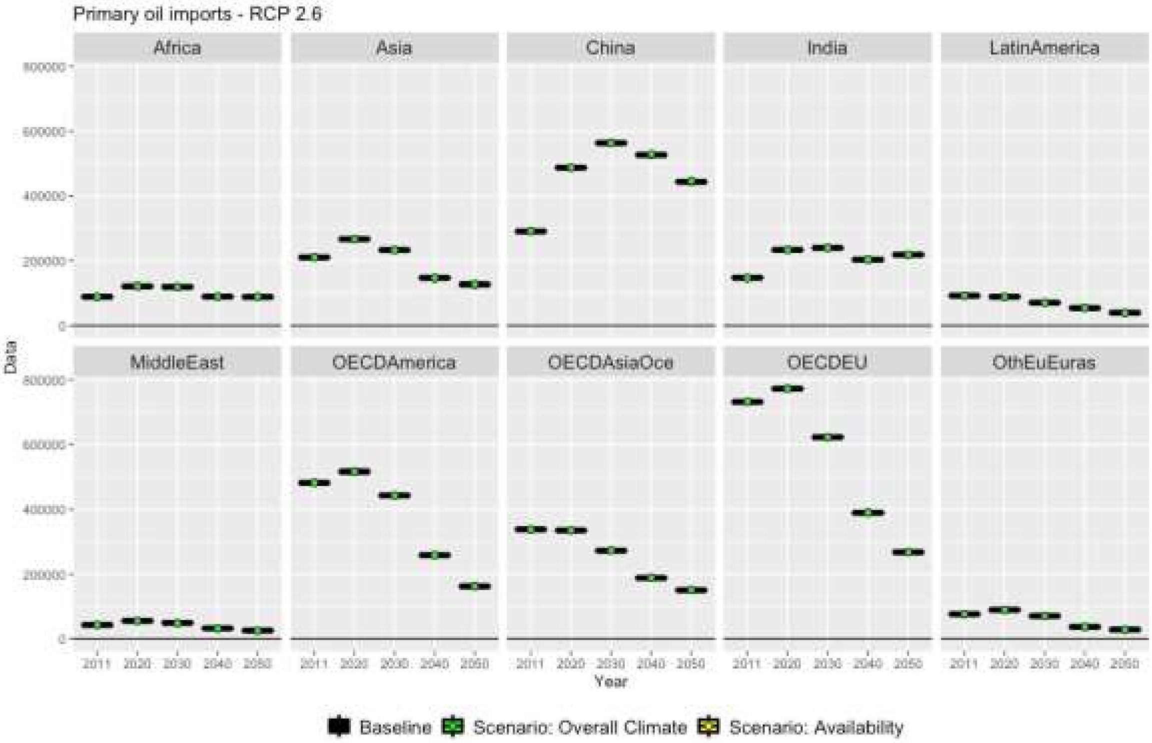
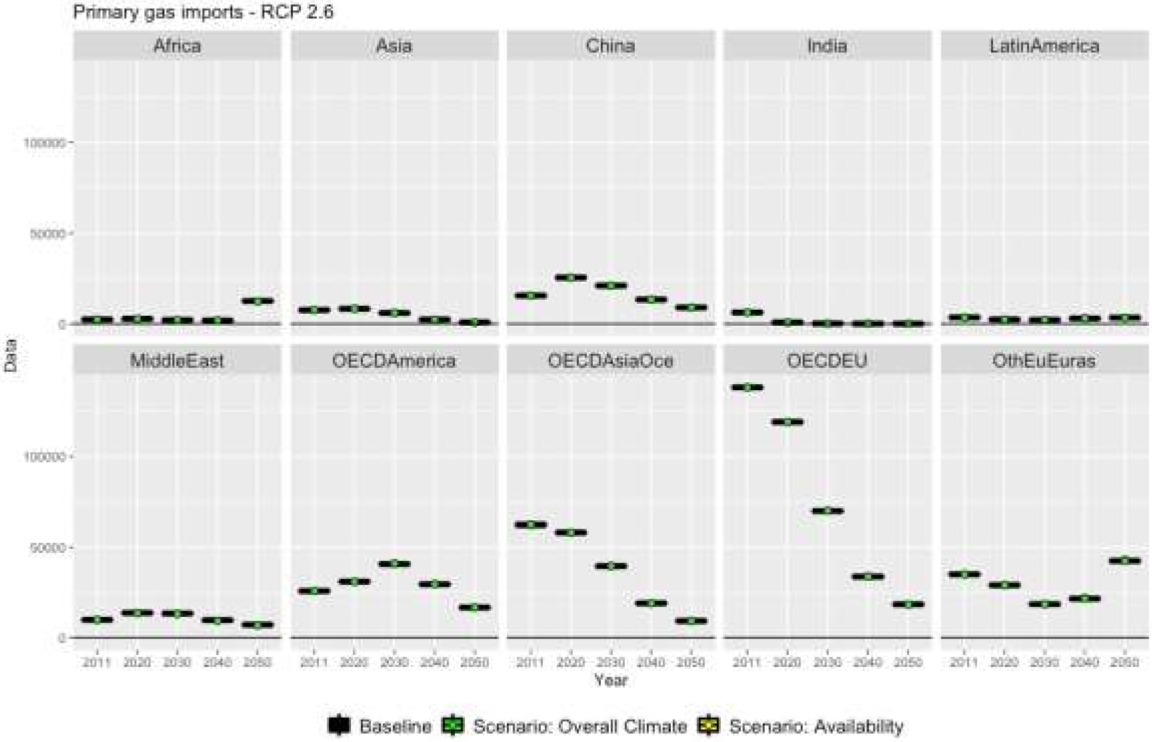

Hydro production - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
100000
75000
50000
25000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability

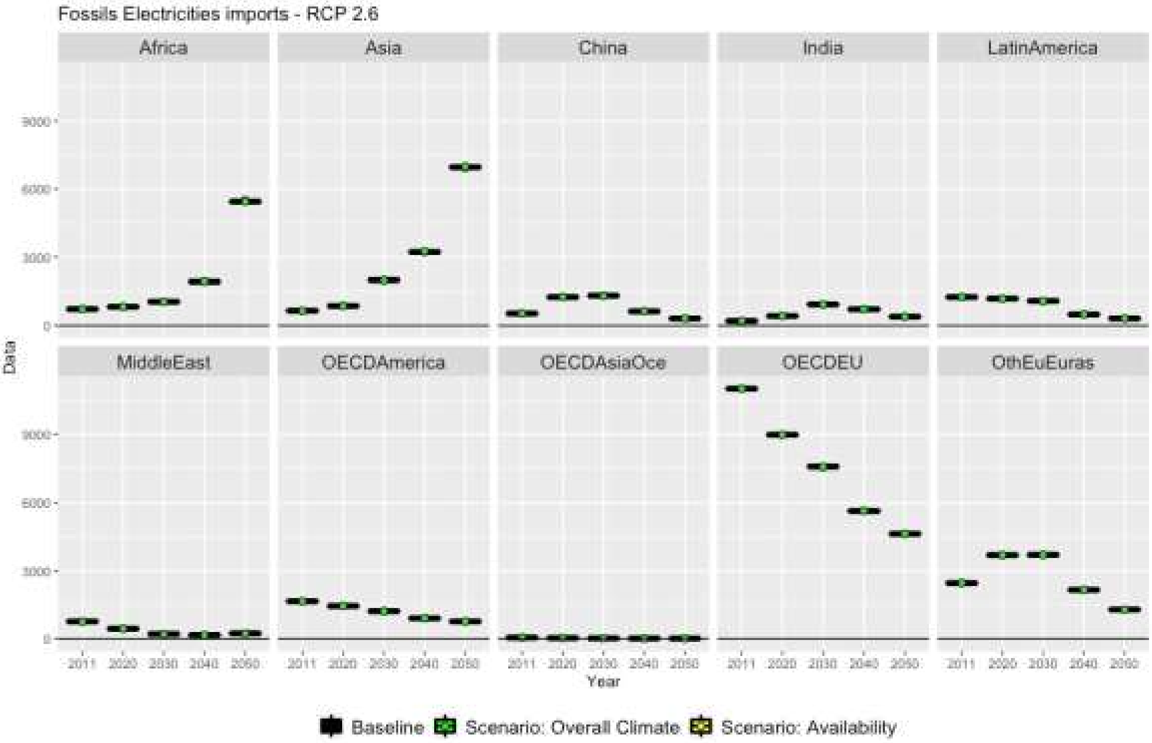
Figure S8. Irrigated Agriculture and Energy Imports in RCP 2.6 Baseline and Scenarios, Million US$



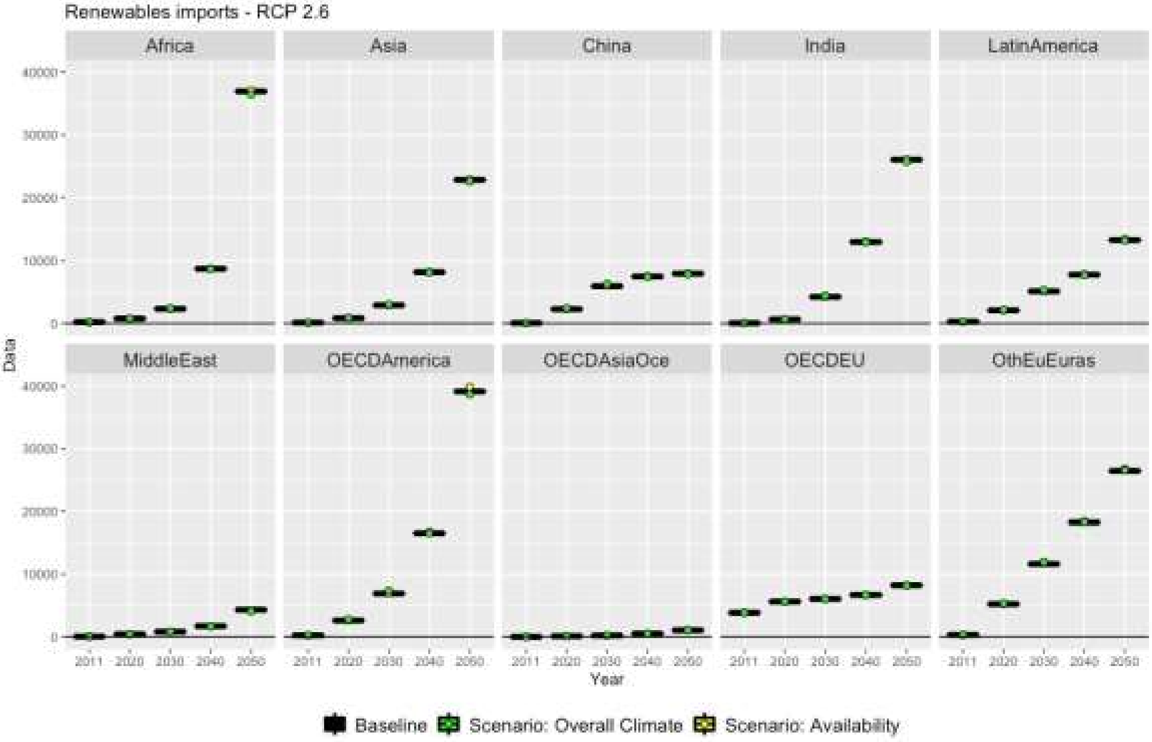



Primary oil imports - RCP 2.6

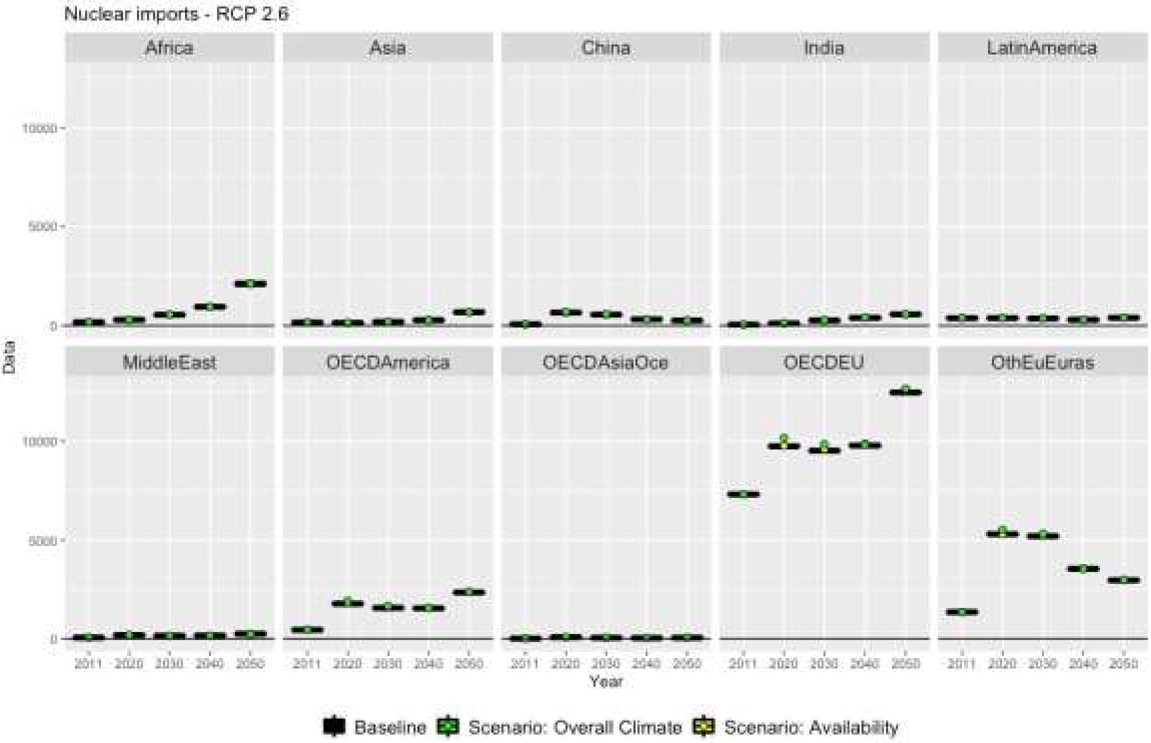

Primary gas imports - RCP 2.6



Fossils Electricities imports - RCP 2.6



Renewables imports - RCP 2.6


Nuclear imports - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
10000
5000
0
Year
2011
2020
2030
2040
2050
Baseline
Scenario: Overall Climate
Scenario: Availability

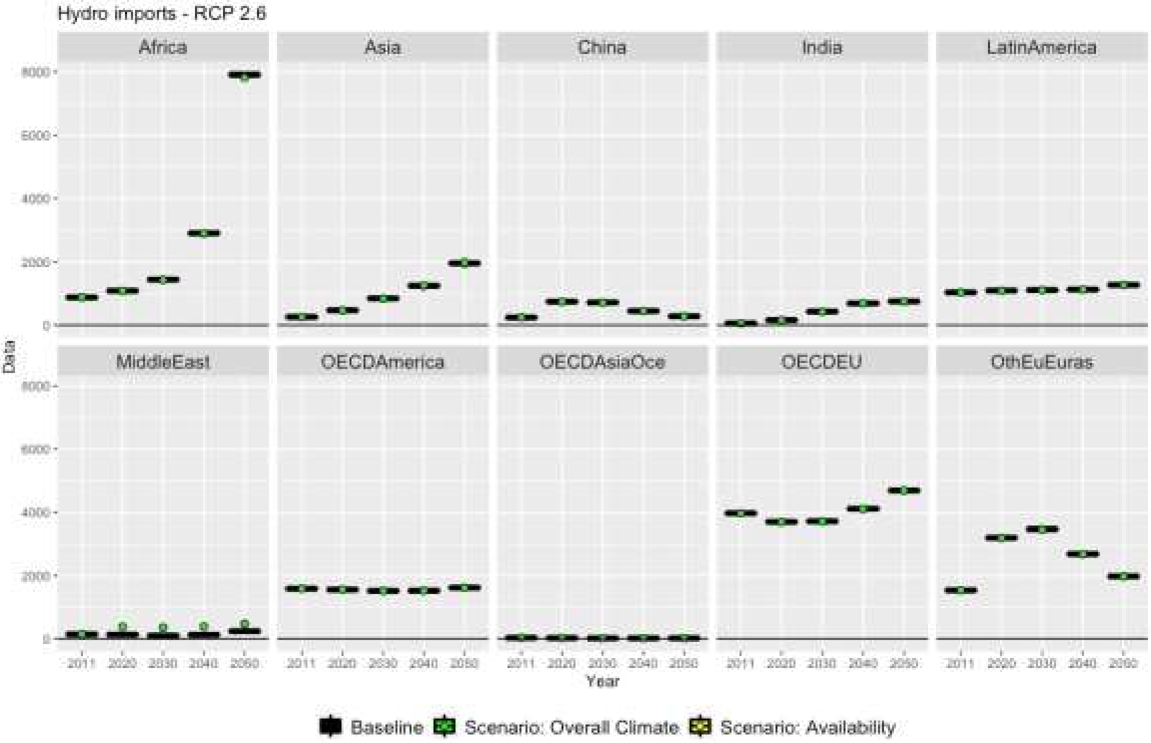
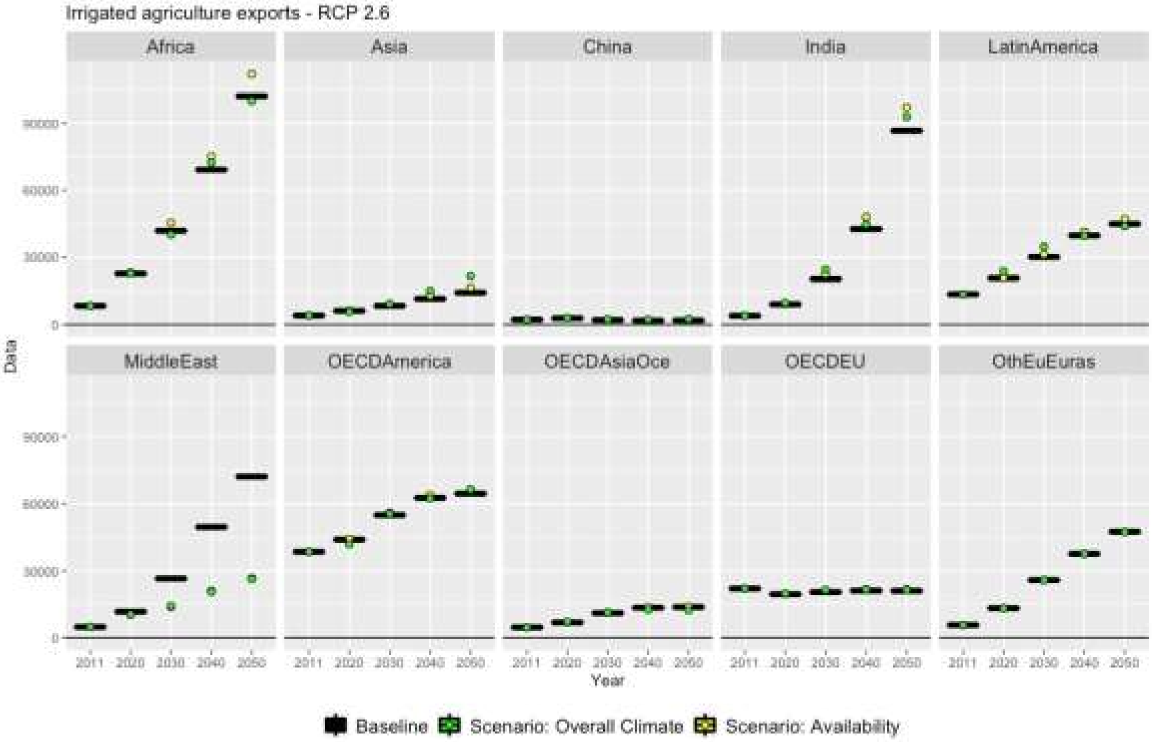
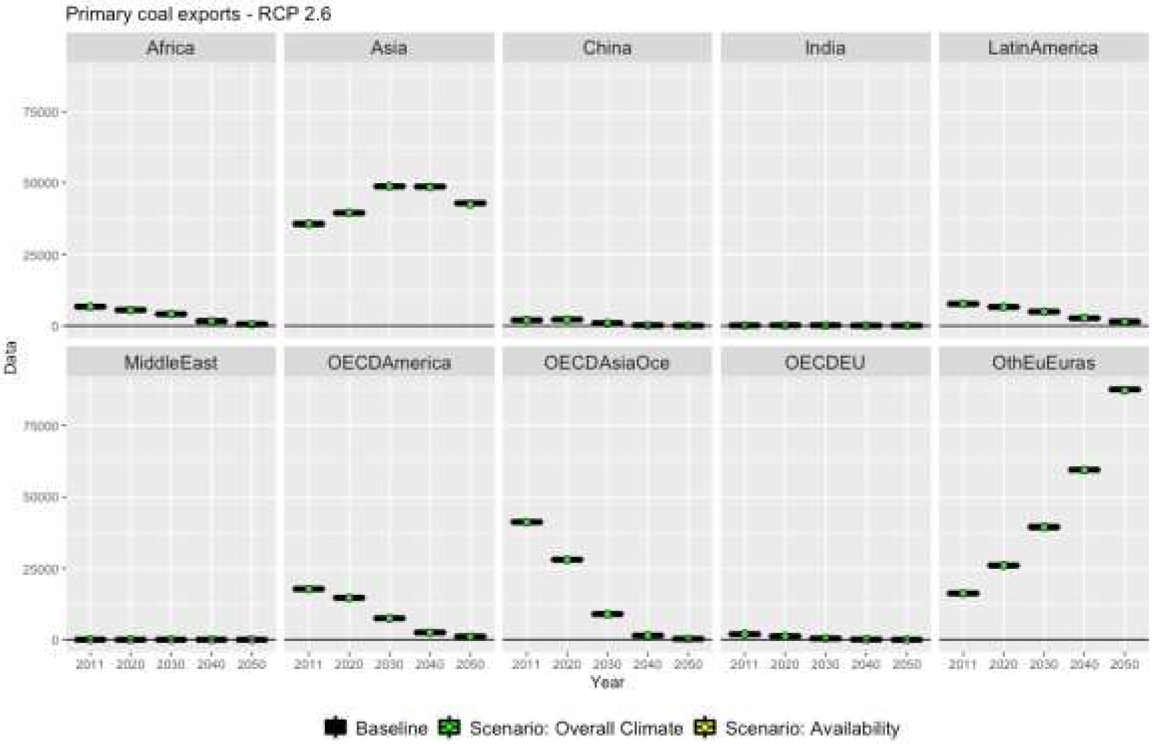
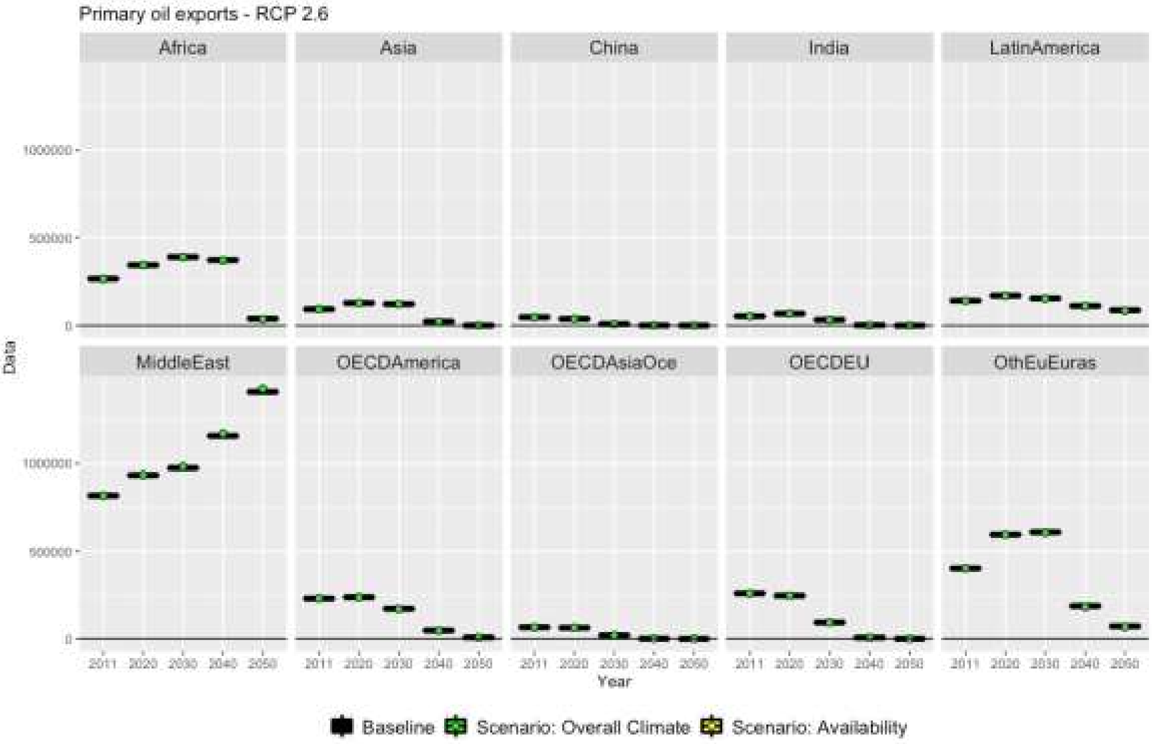
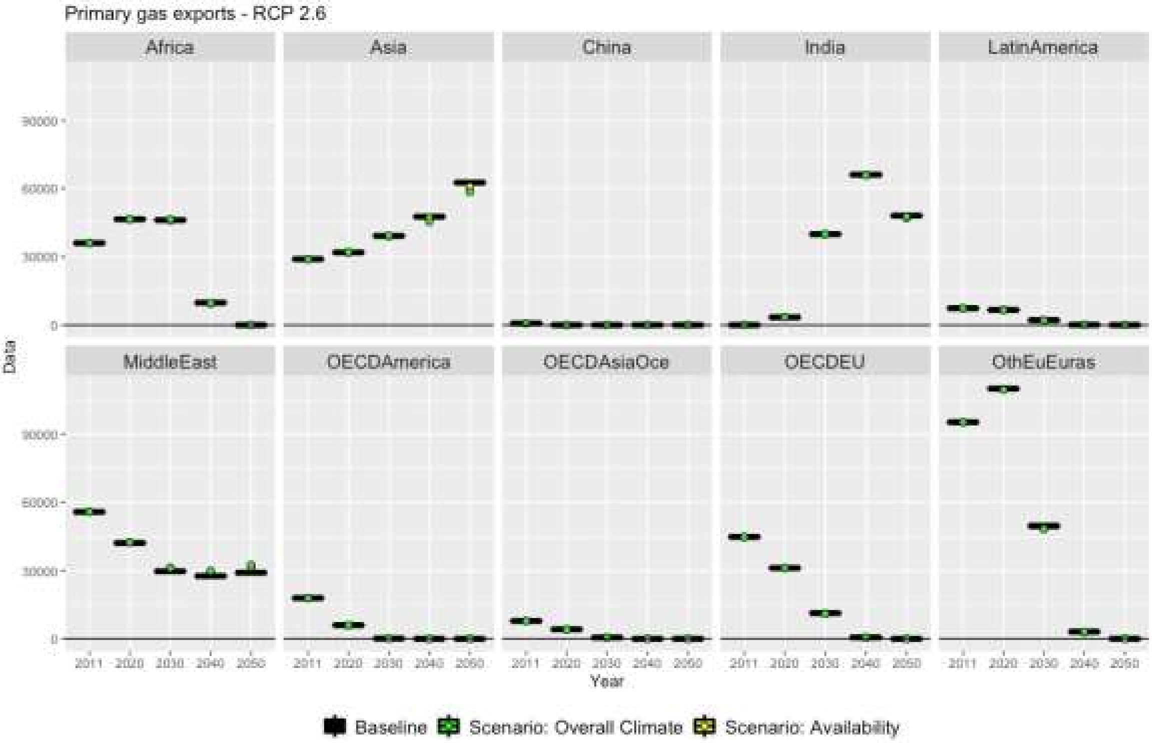

Hydro imports - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
8000
6000
4000
2000
0
Year
2011
2020
2030
2040
2050
Baseline
Scenario: Overall Climate
Scenario: Availability

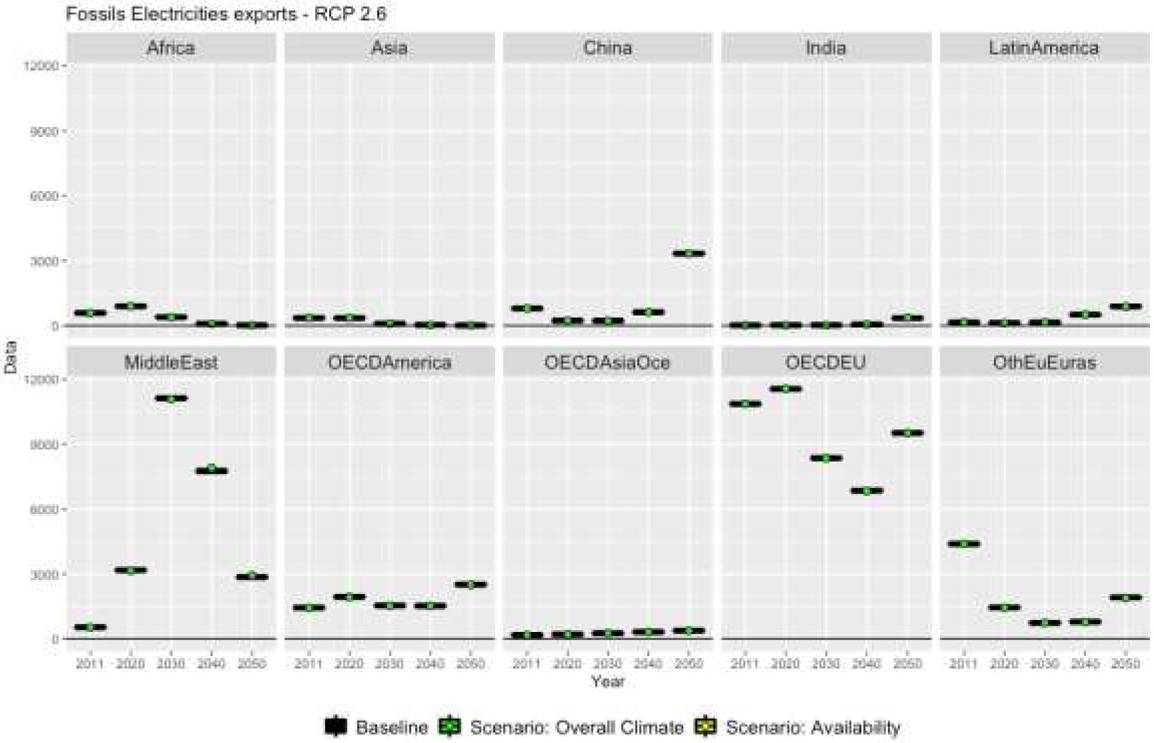
Figure S9. Irrigated Agriculture and Energy Exports in RCP 2.6 Baseline and Scenarios, Million US$

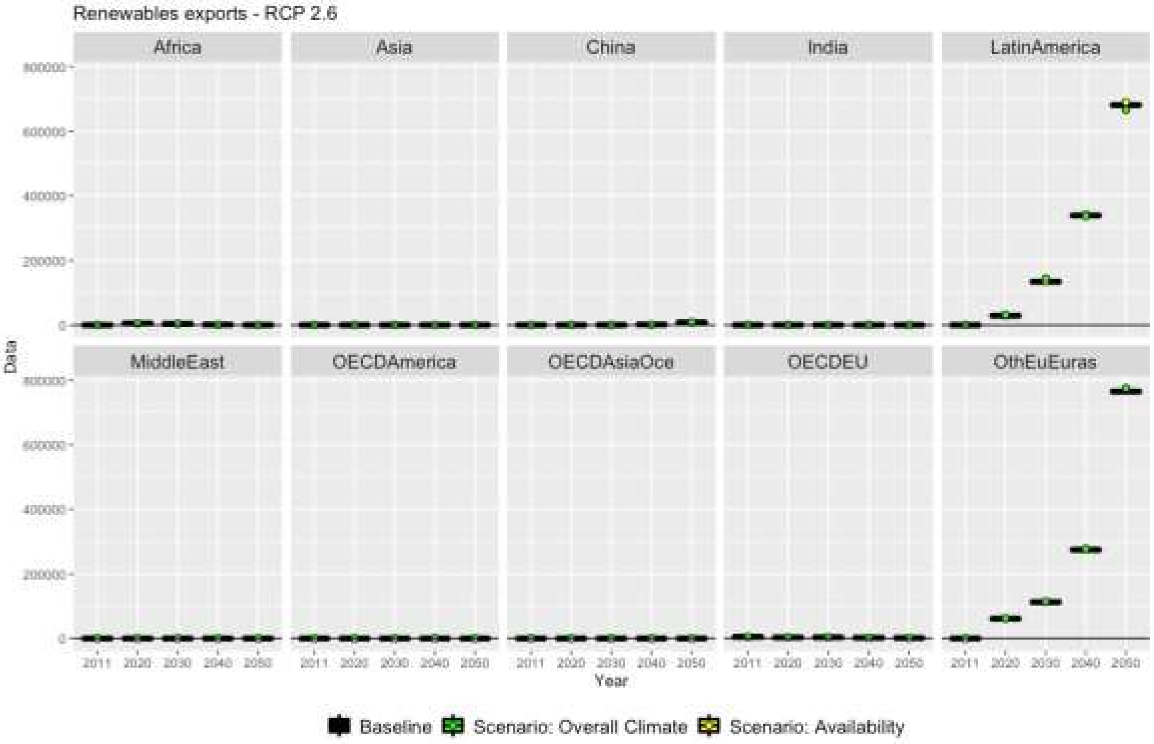


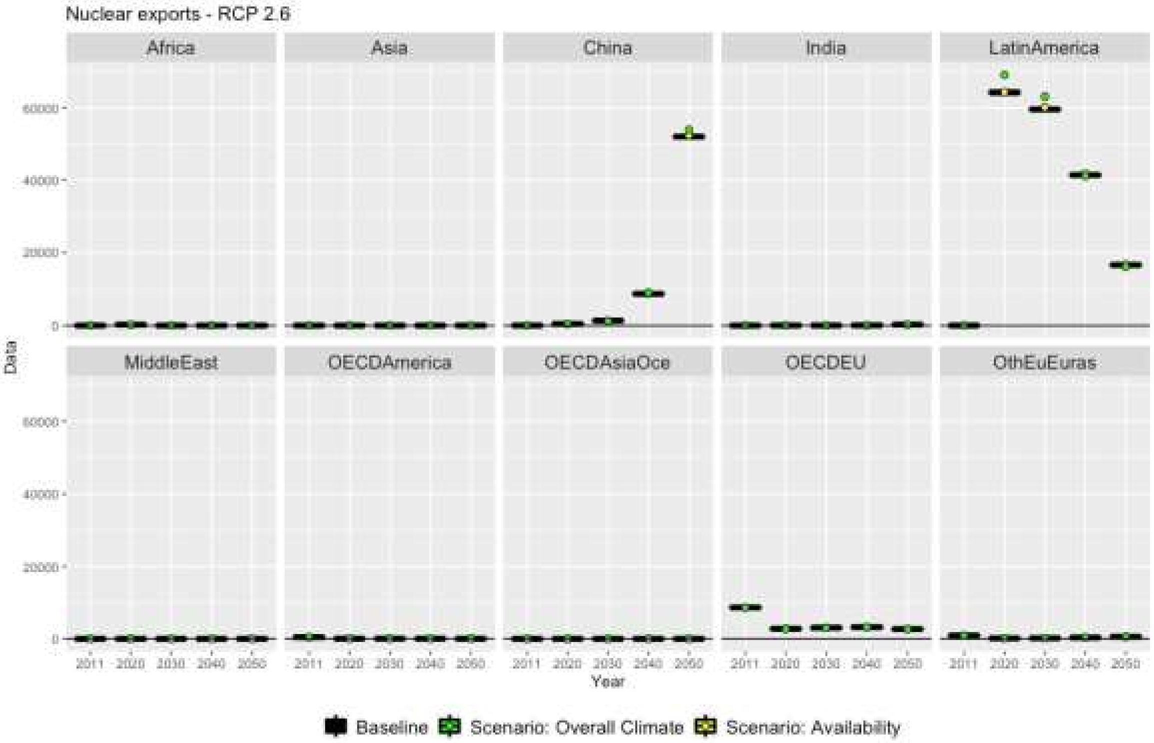



Primary oil exports - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
1000000
500000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Primary gas exports - RCP 2.6
Africa
Asia
China
India
LatinAmerica
MiddleEast
OECDAmerica
OECDAsiaOce
OECDEU
OthEuEuras
Data
90000
60000
30000
0
2011
2020
2030
2040
2050
Year
Baseline
Scenario: Overall Climate
Scenario: Availability


Fossils Electricities exports - RCP 2.6


Renewables exports - RCP 2.6


Nuclear exports - RCP 2.6

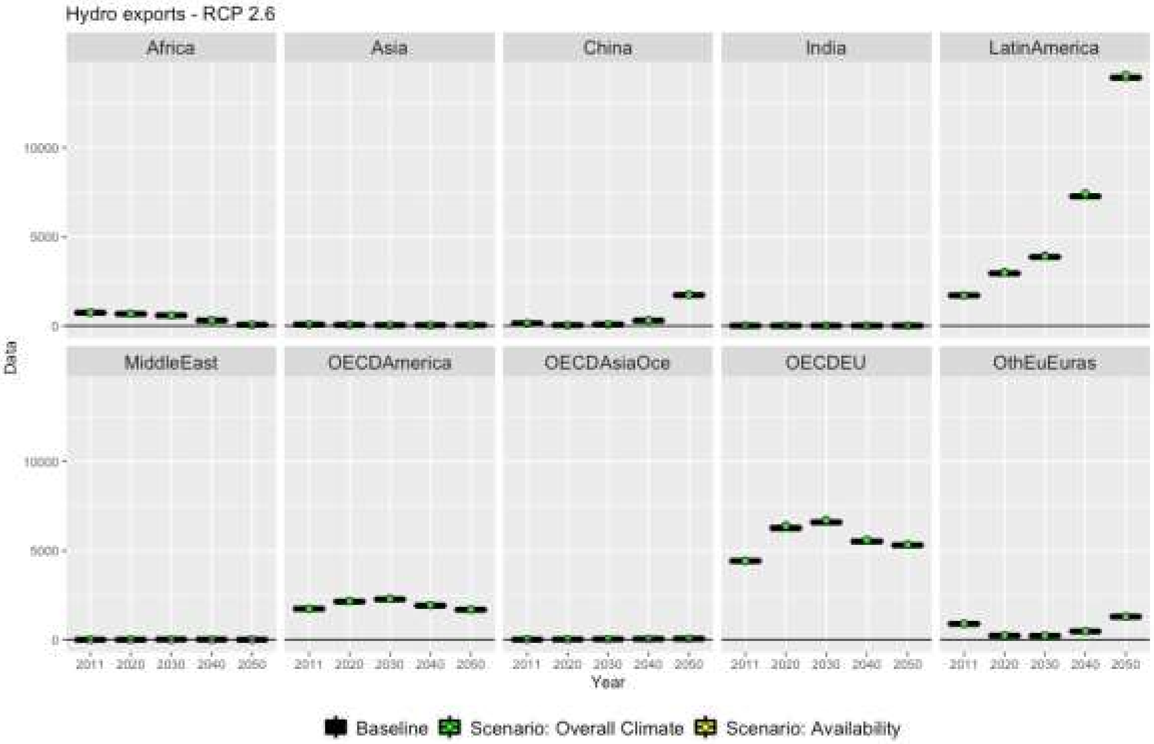
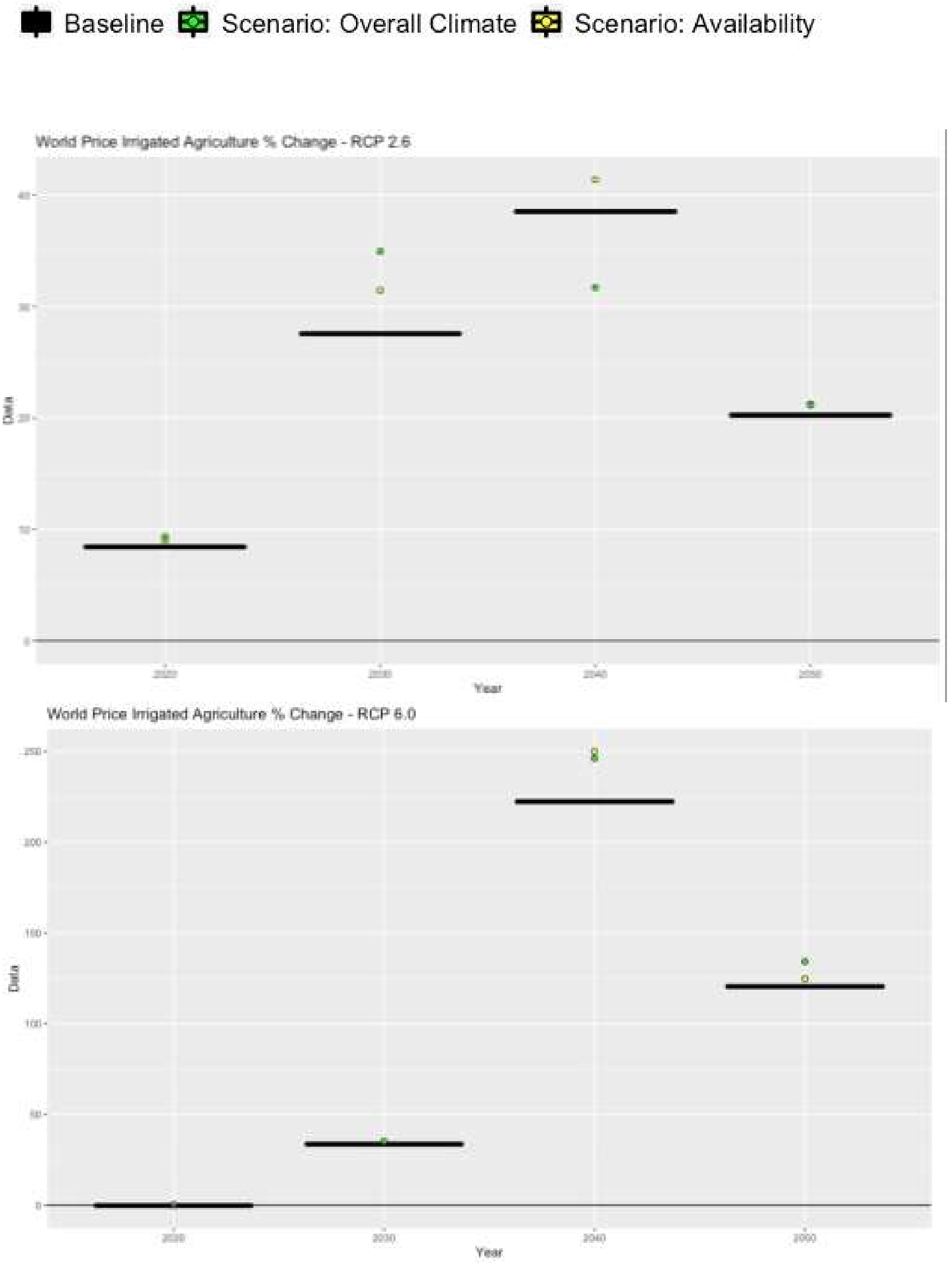

Hydro exports - RCP 2.6

Figure S10. % Change World Price Irrigated Agriculture, Baseline and Scenarios



Acknowledgements

This thesis would not have been possible without the guidance and support of my supervisors, Prof. Francesco Bosello and Dr. Garbiele Standardi and the contribution of Prof. Alvaro Rivera Calzadilla. To their teachings, I owe being the researcher I am today. I am also grateful to the institutions that hosted me during my journey, starting from Ca’ Foscari University, the Euro-Mediterranean Centre on Climate change, the Wegener Center for Climate and Global Change of Graz, and the University College of London. The people I met and the conversations I had within their walls were a continuous source of inspiration every single step of the way. I thank my fellow PhD candidates and the ones I met on the way, that shared and understood the pain of this specific challenge, and my family that always supported me. A special thanks goes to my partner, Stefano, which was my rock during the bad times and one of my greatest supporters in celebrating my achievements. I thank all the friends I made during this journey and the ones that have always been there. Last but not least, I need to thank my housemates. In that house I leave a piece of my heart. These few words will never express the feelings I would like to express, but I hope each one of the persons I am thinking of in writing these few lines will know how much they meant to me.

To Venice, and its eternal beauty, I dedicate the final line of this thesis.

Estratto per riassunto della tesi di dottorato

L’estratto (max. 1000 battute) deve essere redatto sia in lingua italiana che in lingua inglese e nella lingua straniera eventualmente indicata dal Collegio dei docenti.

L’estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: Bardazzi Elisa **Matricola**: 956408

Dottorato: Science and Management of Climate Change

Ciclo: XXXIV

Titolo della tesi : A Macroeconomic View of the Water-Energy-Food (WEF) Nexus Implications Under a Changing Climate

Abstract:

English: This thesis studies the most relevant dynamics relative to the Water-Energy-Food (WEF) Nexus, using an innovative modelling approach, and advancing the state of the art of Computable General Equilibrium (CGE) models. It begins with a critical review of the CGE literature, finding that CGEs have specific advantages in representing the Nexus, though they still need improvements, particularly in addressing the Water-Energy link. Thus, it proposes a method to explicitly model water uses for both sectors of the Nexus. Then, this framework is applied to assess the implications of Nexus water withdrawal pathways under two climate scenarios, which highlights that a) water projections will regionally differentiated, but globally negative, GDP impacts b) a resource distribution/coordination mechanism generally improves the macroeconomic conditions, though it does not eliminate the benefits of reducing climate change c) the GDP damages are particularly reduced when it leads to a low carbon/low water energy mix. All in all, this thesis evaluates Nexus implications in a “limits to growth” perspective, enhancing the ability of CGEs to assess in which conditions sustainable development paths will be possible under climate change.

Italiano: Questa tesi studia le maggiori dinamiche del Nexus Acqua-Energia-Cibo (WEF), utilizzando un innovativo approccio modellistico e progredendo lo stato dell'arte dei modelli Computazionali di Equilibrio Economico Generale (CGE). Essa inizia con una revisione critica della letteratura CGE, sottolineando che essi presentano vantaggi specifici nella rappresentazione del Nexus, sebbene necessitino ancora di miglioramenti, in particolare per quanto riguarda il legame Acqua-Energia. Pertanto, propone un metodo per modellizzare esplicitamente gli usi dell'acqua per entrambi i settori del Nexus. Quindi applica questo quadro alla valutazione delle implicazioni dei percorsi di uso idrici del Nexus in due scenari climatici, evidenziando che a) le tendenze indriche avranno impatti differenziati a livello regionale, ma globalmente negativi sul PIL b) un meccanismo di distribuzione/coordinamento delle risorse migliora in generale le condizioni macroeconomiche, anche se non elimina i benefici della riduzione dei cambiamenti climatici c) i danni sul PIL sono particolarmente ridotti quando si arriva a un mix energetico a basso contenuto di carbonio/basso contenuto di acqua. Nel complesso, questa tesi valuta le implicazioni dei Nexus in una prospettiva di "limiti alla crescita", migliorando la capacità dei CGE di valutare in quali condizioni saranno possibili percorsi di sviluppo sostenibile in presenza di cambiamenti climatici.

Firma dello studente

Elisa Bardazzi