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Water Use in a Sustainable Net Zero Energy System: What are the Implications of Employing Bioenergy with Carbon Capture and Storage?

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ABSTRACT

Net zero emissions of the global energy and land systems are needed to keep the temperature increase to the 1.5 degrees limit by 2100 as per the Paris Agreement (PA). Furthermore, updated Nationally Determined Contributions (NDCs) now include a net zero target by 2050 or until 2070. These climate policies require rapid technological development towards renewable energy and low carbon emission technologies like nuclear and carbon capture and storage. However, this transition is water intensive as water is needed in power plants cooling, gasification, carbon capture, hydroelectricity, or emission control. In this study, the focus is done on the first three by using an integrated assessment model TIAM-FR. It is based on techno-economic linear optimization and includes a water allocation module. Under two climate scenarios, the energy mixes of the world energy system are scrutinized. The results show that achieving net zero requires renewable energy mainly but would use bioenergy with carbon capture and storage. For the 2018-2100 period, water consumption increases by 100.5% for a 1.5-degree pathway whereas a NDC pathway increases it by 135%. The comparative analysis asses the choice of mitigation solutions with respect to regional water scarcity. At the end, a discussion on the relevant sustainable development goals (2, 6, 7, 13, 15) is presented.

Keywords

Net zero emissions;
Nationally Determined Contributions;
Bioenergy with carbon capture and storage;
Water;
Integrated Assessment Model

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1. INTRODUCTION

By the middle of this century, our global energy and land system must have reached neutrality in terms of carbon dioxide emission with efforts towards reaching this goal for the remaining greenhouse gas emissions in the following decades. This is necessary to keep the temperature increase in the 1.5 degrees limit by 2100, reducing the impact of climate change and the probability to cause irreversibility in the climate system. To do so, countries have elaborated Nationally Determined Contributions (NDC) in the framework of the Paris Agreement (PA), for climate change mitigation and adaptation. An increasing number of countries pledged (politically or through their NDCs) to meet a Net Zero (NZ) target [1,2], where the target year ranges between 2050 and 2070. This entails moving towards a low-carbon economy and requires the use of Carbon Dioxide Removal (CDR) to compensate for the residual emissions. [3,4]. This would include Bioenergy carbon capture and storage (BECCS) between other solutions like afforestation and direct air capture and storage [5]. Nevertheless, BECCS have the potential of contributing to emission reduction while providing energy services [6].

Alongside mitigation targets, the integration of sustainable development through the UN 2030 Agenda, adopted the same year as the PA, is reflected in

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Abbreviations

ANNCOST	Total Annualized cost
AR6	Assessment Report 6
BAU	Business as usual
BECCS	Bioenergy Carbon Capture and Storage
BW	Brackish Water
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CDR	Carbon Dioxide Removal
CH4	Methane
CLEW	Climate Land Energy and Water
CO2	Carbon Dioxide
CSA	Central and South America
EEU	Eastern Europe
EJ	Exajoule
ETSAP	Energy Technology Systems Analysis Program
FAO	Food and Agriculture Organization
FW	Fresh Water
FWW	Fresh water withdrawal
GAEZ	Global Agro-ecological zones
GCAM	Global Change Analysis Model
GDO	Global Drought Observatory
GDP	Gross Domestic Product
GHG	Greenhouse gases
GIS	Geographical Information System
GW	Ground Water
IEA	International Energy Agency
IGCC	Integrated Gasification combined Cycle
IGCCC	Integrated Gasification combined Cycle consumption
IGCCW	Integrated Gasification combined Cycle withdrawal
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
MAGGIC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MW	municipal water
N_2O	Nitrous Oxide
NDC	Nationally Determined Contribution
NPV	Net Present Value
NZ	Net Zero
NZE	Net Zero Emission
OCDE	Organisation for Economic Co-operation and Development
PA	Paris Agreement
PBL	Planbureau voor de Leefomgeving
PJ	Petajoule
RES	Reference Energy System
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathways
SW	Saline Water
TIAM-FR	French version of TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
USA	United States of America
WEU	Western Europe
WGIII	Working Group 3

NDCs [7]. It would ensure a larger and sustainable portfolio of mitigation solutions, helping in their success considering aspects of the economy and society This is essential to the resilience and adaptation of societies face of climate change [8]. It impacts lead to persisting and definitely increasing problems like water and food security, mental and physical health, reducing economic growth in some regions creating additional disparities and contributing to conflicts and humanitarian crises.

In fact, some countries are facing severe water issues putting people's lives at stake. Somalia is facing the worst drought year following 5 consecutive seasons of low rain [9], affecting the agriculture sector, creating food insecurity and economic losses, and the health sectors leading to "higher-than-normal deaths". In 2023, France faced a drought summer with 80% of its water reserves at lower levels than the usual amount, involving some stringent measures on water use [10]. According to [11], Greece faces pressure on water supply for crops (wheat and barley) because these plants' water needs are not met due to drought. These issues can be exacerbated when failure in reaching the Sustainable Development Goal 13 (SDG13) on climate action occurs [12,13].

The Food and Agriculture Organization (FAO), the custodian agency for 21 indicators of SDGs 2, 5, 6, 12, 14 and 15, tracks the water relevant indicators. SDG6 is about "*clean water and sanitation for all*" and compromises 6 different targets and 11 indicators [14]. The fourth target discusses water use efficiency and withdrawals of freshwater.

Water stress has been increasing since 2015 for some regions, especially in Northern Africa which already has a 120% level of water stress surpassing all other regions (Figure 1). Globally, it has increased by 0.3% with a small improvement in Central and Southern Asia and a safe and maintained levels in Europe and Northern America.

In the main axes of national strategies for sustainable development, it became important to bring a radical transformation in the policies related to the water, energy and agriculture sectors while considering food security. In the energy sector, almost all electricity production and fuel extraction processes require large amounts of water. The water sector also needs electricity to extract, treat, transport, desalinate, pump and heat water. In agriculture, energy and water are needed to provide food. The linking between sectors is consistent with the 2030 Agenda for Sustainable Development, paragraph 5 of the declaration of its adoption. [16].

Although the strategies related to emissions neutrality and the urgency of the climate situation impose an accelerated phase-out of fossil fuels, the world's consumption still relies massively on them [17]. In the Net Zero Emissions (NZE) scenario of the International Energy Agency (IEA) [18], fossil fuels are still used in 2050 in the production of non-energy goods and in "hard-to-abate sectors" like food production, long-haul aviation and heavy industry such as steel and cement [19]. Hence, as part of the decarbonization of the energy sector, power plants can be equipped with carbon capture and storage (CCS) which increases water consumption immensely. Indeed, water is used in the capture phase, where CO2 is separated and captured from process emissions [20].

Furthermore, another use of water is energy crops to produce bioenergy and biofuels. Traditional biomass provides 7% of energy use and biofuels accounts for 1% but the former would fall to zero leaving place to modern biomass (for example from agriculture and forest residues, solid waste) by 2050 according to the IEA-NZE scenario [18]. In fact, sustainable production and use of biomass are needed for addressing both the reduction of the CO_2 emissions and the competition and pressure on land and hence food security. The future plausible impacts of energy crops regarding water needs and/or irrigation has been identified for 6 global energy scenarios in [21] by accounting for the evapotranspiration from the energy crop production. It was noted that a "high growth" in population and economic activity scenario with rapid technological development in nuclear and renewable energy replacing the conventional electricity production, would require the highest volumes of water. Only in this scenario, energy crop evapotranspiration surpasses the average estimates of evapotranspiration from global cropland (6800 km^3 per year) by around 13% at the end of the century. When combined to a food sector scenario, [22] found that water use is sixfold higher than current levels, and when applying stringent constraints on water and land availability the global supply of irrigated biomass is reduced by 25%.

The evolution of the energy system and setting the relevant boundary conditions can be done with Integrated Assessment Models (IAMs) that allow multi-lateral connections with other sectors [23]. For instance, in the

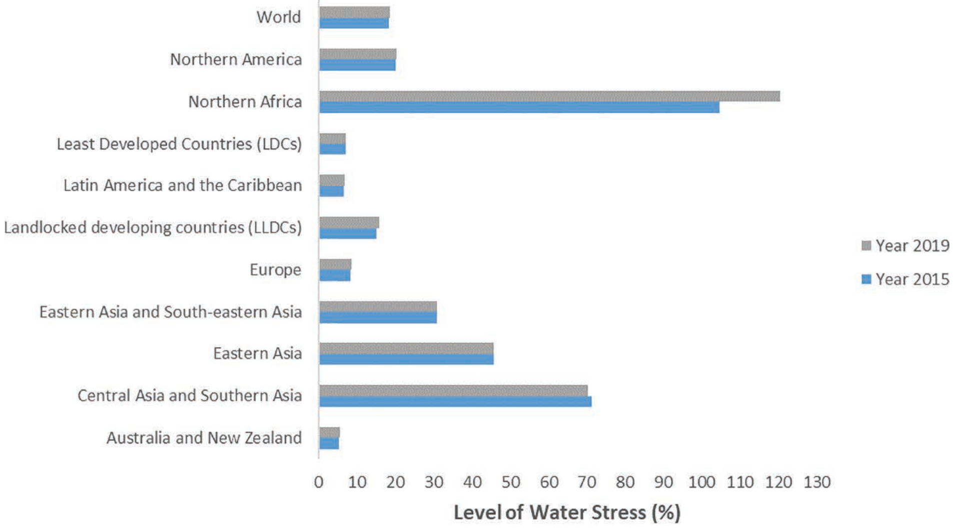


Figure 1: Evolution of the level of water stress: fresh water withdrawal as a proportion of available water resources by region in % related to the indicator 6.4.2 (Based on data from [15])

electricity generation sector, studies on TIAM-FR [24,25] and MESSAGE [26] models, implemented power plant cooling technologies to evaluate future water withdrawals trajectories. In a cost minimization approach with TIAM-ECN [27], the authors considered the water-energy nexus and demonstrated that the type of cooling technology impacts the water needs as much as the type of technology used. Also, in [28], GCAM model is used to assess future water demand under different cooling technologies adoption. However, these studies did not focus on water use with negative emissions technologies which role is being increasingly recognized in net zero emission pathways. In this context, the focus here is made on BECCS contribution in decarbonization and water consumption alongside CCS technologies.

Nevertheless, techno-economic optimization can be enriched by technical studies on energy and water like the assessment of the water footprint of bioenergy or the change in water availability. In [29] a GIS tool assesses Croatia's biogas potential from lignocellulosic biomass. This can be used to account for water needs if hydrological data is considered, hence choosing the correct time and space that reduces water consumption while preserving biogas production. Moreover, water and energy models can be linked like in [30], allowing analysis of hydroelectric changes and the impact of water supply and economic growth on hydropower under different scenarios. Currently, adopting an integrated framework on Climate, Land, Energy, Water (CLEW) in models is gaining momentum due to their usefulness in better assessment of strategies to achieve SDGs [23,31].

The energy and water sectors transition to low emissions is deeply intertwined, more water would be needed to achieve the energy transition while more energy would be needed for water supply with the increase of water demand given the climate change impacts. In this context, this study fills some research gaps regarding the consideration of water needs given both net zero emission targets and the future use of negative emission technologies as complementary solutions to renewable energy.

First, this study aims to address the new climate commitments NDCs and the PA focusing on the mitigation solutions in the energy sector such as BECCS and power plants equipped with CCS and the associated water use in these processes. This highlights the long-lasting and additional role of this natural resource as part of the water-energy nexus. For these purposes, it was necessary to describe the set of equations related to allocation of water withdrawal and consumption by type of power plant and cooling technology. The water allocation module is used to account for water uses in the extraction of fossil fuels (coal, oil, and gas) and in power plant cooling, gasification, and carbon capture. Water consumption from hydropower, which comes from evaporation, is not considered here because of the uncertainties for such accounting. Indeed, dams are used for other purposes than electricity like for agriculture and flood control. Also, the representation of the bioenergy sector presents the possibilities of decarbonization through biomass and CCS. In consequence, the influence of adopting net zero emission policies is investigated by considering carbon removal in the bioenergy sector (electricity and biofuel). The changes in the energy sector under these constraints denote that switching to electrification through nuclear, renewable energy and the use of CCS requires high volumes of water. Second, and a novelty of this research, would be in identifying the water-energy linkages according to sustainable development. More explicitly, relevant SDGs are explored with respect to the linkages between water and energy that are analyzed in this study.

The paper is organized as follows: the method section includes the explanation of TIAM-FR representing the global energy system and the main assumptions regarding bioenergy and water in this model. The results section focuses on the energy and electricity mixes, and the carbon capture in the bioenergy sector. Water use is then showcased with a regional overview including, but not limited to, regions with intense water stress. An analysis on the water-energy nexus is developed in the discussion before concluding on the main outcomes of this study.

2. METHOD

This section presents the bottom up, long-term energy system model TIAM-FR used for the analysis. Then, a focus is made on the representation of biomass in this model. The water allocation is described on the level of cooling technologies, gasification, and CCS. The scenario development related to climate policies, biomass potential and economic growth are elaborated.

2.1 Modelling Framework

Long-term energy optimization models rely on mathematical techniques, representing techno-economic systems and the interactions with the environment, hence their impact on the climate. Through energy system analysis, it is possible to plan future investments and determine the related emissions which are in this case CO2, CH4 and N2O. Based on these results, policy recommendations can be provided.

TIAM-FR, the French version of the TIMES Integrated Assessment Model, representing the world energy system is used, TIMES being a methodological corpus developed under the IEA's Energy Technology Systems Analysis Program (ETSAP) [32]. This bottom-up, perfect foresight and partial equilibrium optimization model gives a detailed description of technologies and end-uses constituting the Reference Energy System (RES) linking the different sectors (residential, transport, agriculture, industrial, commercial) constituting the world energy system in 15 regions (Figure 2). TIAM-FR is vertically and horizontally integrated model where the technologies are linked together by their inputs and outputs to constitute the energy system. For example, in oil extraction, the ground reserves are represented as processes and have heavy oil from the ground as output commodities. In turn, heavy oil is the input of the production process of crude oil.

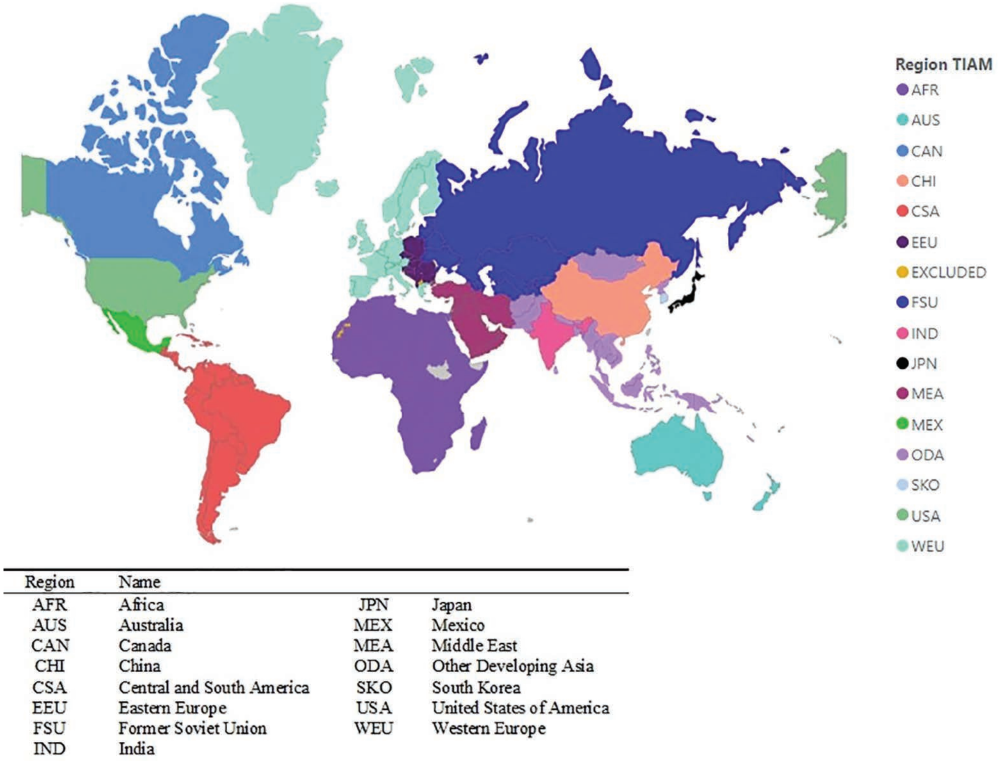
The model is driven by end-use demand. To determine exogenous projection of service demands in the different sectors, the Shared Socioeconomic Pathways (SSP) are used as drivers. These are narratives to examine how the global society, demographics and economics might evolve.

Through linear programming, the model uses cost minimization described in Eq. (1) through the horizon and perimeter of the study, determining the combinations of technologies and policies considered [33].

$$min\left(NPV\right) = min\left(\sum_{r\in R}\sum_{y\in Y}\left(1+d_{r,y}\right)^{T_{0-y}} \cdot ANNCOST\left(r,y\right)\right) \tag{1}$$

Where:

- NPV: net present value of the total cost for all regions (the TIMES objective function)
- ANNCOST: total annual cost in region ***r*** and year ***y***
- D: general discount rate
- $T_{0:}$ reference year for discounting (2018 for TIAM-FR)
- Y: set of years for which there is a cost



Region	Name		
AFR	Africa	JPN	Japan
AUS	Australia	MEX	Mexico
CAN	Canada	MEA	Middle East
CHI	China	ODA	Other Developing Asia
CSA	Central and South America	SKO	South Korea
EEU	Eastern Europe	USA	United States of America
FSU	Former Soviet Union	WEU	Western Europe
IND	India		

Figure 2: TIAM-FR regional representation

The annual cost, $ANNCOST(r, y)$, is linked to each year of the horizon and even for some years outside the horizon. These costs (in some cases revenues) include capital costs from investing into or dismantling processes, maintenance, and operation of processes, and delivery costs for commodities. Other economic parameters are the economic life of a process and its discount rate, both used to determine the annualized payments on the process investment cost [33].

2.2 Biomass

Biomass can be used as primary resource or transformed: feedstock and fuel in the chemical sectors, resource for the fuel in transport (aviation, cars etc…), and replacing natural gas by biomethane when buildings cannot be renovated [34]. Furthermore, in the power sector, biomass coupled to carbon capture and storage (BECCS) provides negative emissions.

Several energy crops are available as resources alongside their potential found by estimating the land available and retrieving crop productivity. The GAEZ [35] provides land resources by type of land cover (cropland, grassland…) and agro-climatically attainable yields by country and crop. To determine the potential for energy crops, land availability is estimated under different considerations [36]. First, priority is given to food production to avoid eventual food security issues. Second, the exploitation of forest wood is limited to a level below the natural increase of forests defined by the Gross Annual Increment [37], and no deforestation for bioenergy purposes is set by maintaining forest areas to their level in 2010.

Some of the biomass available accounted for in the model are wood and forest residues from transformation activities, agricultural residues from harvesting and from transformation activities. Biomass trade across regions is also possible representing the possibilities to deploy bioenergy to reduce the emissions and achieve the climate targets.

The parameters related to the potential of biomass land occupation, transformation and conversion to electricity and fuel, and 3 biomass expansion assumptions are available as Supplementary Materials. The assumption for biomass expansion used here assumes maximum technological progress and rapid technological uptake for both scenarios detailed in section 2.4.

2.3 Water

In TIAM-FR, water is integrated in the energy sector through “water withdrawal”, the quantity of water that is “withdrawn” from a water source to be used, temporarily or permanently as “water consumption”. Note that water consumption is the part of water that is not returned to the source after being withdrawn. It could be evaporated or incorporated into a product.

The updated “water module” [25] is used to identify upstream water consumption and withdrawal using a “commodity” driven approach. The “process” approach is a second way to determine the water use only in electricity production.

2.2.1 “Commodity” driven approach

The amount of used water (consumed and withdrawn) is modelled as output per unit of energy produced (in m^3/PJ). Water uses in the downstream electricity generation are for cooling systems, heat transfer fluid, emission control and gasification processes. In the cooling part, open loop systems can use brackish water (BW), fresh water (FW), ground water (GW), municipal water (MW) and saline water (SW). For other processes, only FW is considered. It was necessary to allocate water factors to account for water uses necessary to release the heat from the technologies in TIAM-FR while using information of water uses in the literature. To do so, the required parameters to be known are:

- The power plant efficiency ρ which depends on the type of the plant and the fuel used. Also, this parameter is related to the cooling system flow of the power plants that determines the amount of water withdrawn and consumed.
- Share of cooling systems (open, dry, wet closed) according to the installed capacities of types of power plants in different world regions where they are put in place. The shares are obtained from Platts database and [38] and the installed power generation capacities are from [39].
- Parameters as the allowed temperature increase of the water between upstream and downstream of the power plant.

1. For open loop Cooling systems: water withdrawal needed to release the heat.

The heat Q to be released from power generation is calculated according to eq (2). Water is part of the cooling system, but it is modelled as output commodity resulting from the power generation processes which allows obtaining the related uses as a result. To facilitate this accounting, water factors are allocated to these processes in TIAM-FR.

$$Q = \omega_{circulating}.c_P \Delta T = \frac{1-\rho_{th}}{\rho_{th}} W_M \tag{2}$$

Where $\omega_{circulating}$ is the water flow, Q is the heat to be released by the cooling system related to the efficiency ρ_{th} and the mechanical work W_M.

$$\frac{\omega_{withdrawal}}{W_M} = \frac{1-\rho_{th}}{\rho_{th}} \cdot \frac{1}{c_P \Delta T} \tag{3}$$

Where $\omega_{withdrawal}$ is the water flow in the cooling system, c_P is the water specific heat and ΔT the authorized increase of temperature.

Consumption of open loop systems accounts for 1% of the withdrawal.

2. For wet closed loop cooling systems, withdrawals are needed to maintain a constant flow in the system whereas water is consumed as losses from evaporation and by blowdown.

$$\frac{\omega_{consumption}}{W_M} = \frac{1-\rho_{th}}{\rho_{th}} \cdot \frac{f_{latent}}{h_{fg}} \tag{4}$$

h_{fg} is the water latent heat and f_{latent} rate of the heat transfer made by evaporation. A portion of the cooling water need to be replaced by make-up water for conservation of the concentration n of minerals and avoiding damages to the condenser and cooling system due to the minerals.

$$\frac{\omega_{withdrawal}}{W_M} = \frac{n}{n-1} \cdot \frac{\omega_{consumption}}{W_M} \tag{5}$$

c. For Dry closed loop: no consumption or withdrawal.

In power plants with integrated gasification, the water need is for the cooling system and the gasification process. Then different water factors are calculated. First, the water flux needs is required for a set of 4 representative plants found in [40] and the average water quantities used Integrated Gasification combined Cycle withdrawal (IGCCW) and consumption (IGCCC) are calculated. To do so, for cooling in the power plants, the average water factor is obtained by multiplying the water quantities by $\frac{1-\rho_{th}}{\rho_{th}}$ while applying a simple arithmetic mean and for the gasification part, it is set proportional to the efficiency of the power plant (multiplying by ρ_{th}).

The actual water factors of the technologies in TIAM-FR are obtained from the equations below:

$$Withdraw\ IGCC_{i,l} = IGCCW\ \ cool \times \frac{1-\rho_{th}}{\rho_{th}}_{i.l} + \frac{IGCCWg}{\rho_{thi,l}} \tag{6}$$

$$Withdraw\ IGCC_{i,l} = IGCCW\ \ cool \times \frac{1-\rho_{th}}{\rho_{th}}_{i.l} + \frac{IGCCWg}{\rho_{thi,l}} \tag{7}$$

Where i represents the type of combustible (coal or biomass) and l the region.

Hence, two water factors (withdrawal and consumption) of different kinds of water are allocated to each power generation processes for each region of the model (as an example for BECCS, Figure 3). Note that CO_2 emissions from bioenergy are captured up to 90% due to the efficiency of the capture process and the remaining are not considered as emissions since they are biogenic emissions.

2.2.3 "Process" driven approach

The second way is a "process" approach where the output commodity Q is allocated as input for cooling technologies, representing the amount of heat that must be discharged in the cooling system by type of power plant (combined cycles operating with gas, steam

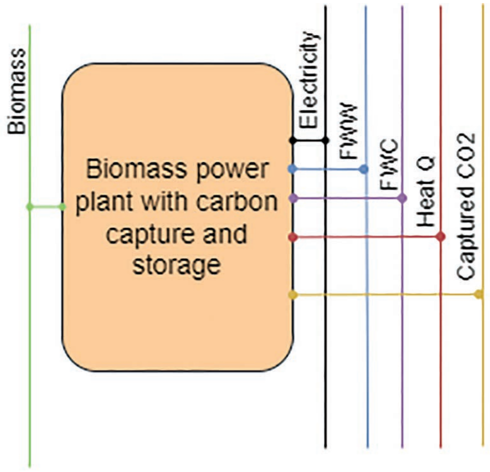


Figure 3: BECCS reference energy system with water module. FW* = Fresh Water, *C = Consumption, *W = Withdrawal, Q = heat to be discharged

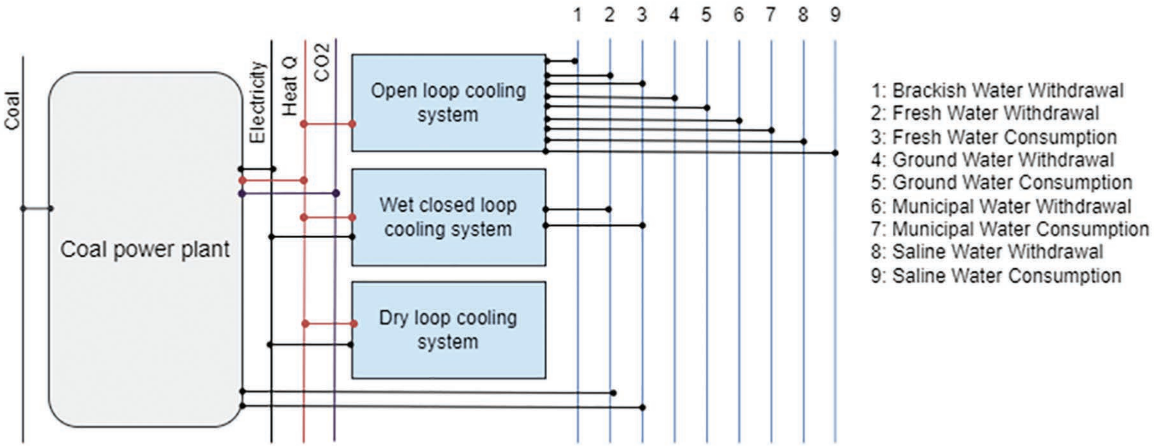


Figure 4: Example of RES representing the process approach.

turbines using subcritical coal etc.). Figure 4 represents a RES of this approach which is only used for investments in new power plants.

The commodity Q corresponds to the quantity of residual heat to be evacuated at the level of the condenser. Then Q can be determined according to the activity of the power plant *i* which uses the resource *k* in region *l*.

$$Q_{i,k,l} = \frac{1-\rho_{th\ i,k,l}}{\rho_{th\ i,k,l}} \times W_m i,k,l \tag{8}$$

In this method, the amount of waste heat Q is set to be zero in form of a constraint. The heat values are set in a similar way to the commodity approach, for each region. It should be noted that wet and dry closed loop cooling systems require electricity related to the heat discharged which is made possible in this approach. This approach also leaves the choice to the model to choose the cooling system by setting upper and lower bounds on the cooling type. This allows the implementation of a policy support for example for closed loop cooling systems...

2.4 Scenarios development

This study includes one scenario following the NDCs emission pathways and one following the Paris Agreement. The description of each scenario design is as follows:

NDC scenario: The updated NDCs [41] as of November 2022 were gathered and aggregated according to the 15 TIAM-FR regions. The total emissions expected in 2030 are calculated by using the targets obtained from the NDC documents. Also emission datasets [42,43] to obtain the base year emissions. After calculation, the emission values for 2030 are set as the upper limit for emissions till the end of the century. Net zero targets are included in NDC for countries and regions that align their actions with the Paris Agreement's goal of limiting global warming to well below 2°C above pre-industrial levels, aiming for 1.5°C. Net zero countries considered in the modelling are found in table 1. Note that their commitment to net zero might be more recent than November 2022. Also, for non-annex I parties, it is possible to use the base year emissions found in their Biennial Update Reports (BURs) [44] or National Communications (NCs) submissions [45] for more updated values.

The shared socio-economic pathway SSP4-3.4 as implemented in the GCAM4 model [46] is chosen as driver of the demand projections. According to the summary on CMIP6 [47], this scenario tries to "*explore the space between scenarios that generally limit warming to below 2C (RCP2.6 / SSP1-2.6) and around 3C (RCP4.5 / SSP2-4.5) by 2100. It will help scientists better assess the impacts of warming if societies rapidly reduce emissions but fail to mitigate fast enough to limit warming to below 2C*". This is coherent as the emissions pathways under current commitments and actions are far from achieving this temperature growth limitation [48].

PA scenario: A stringent climate scenario denoted "PA" is developed in this study and aims to be compliant with the Paris agreement. In that sense and according to the IPCC, net zero carbon emissions must be reached around mid-century for a temperature increase of 1.5°C, with a 50% probability of respecting this limit, the remaining carbon budget would be 500 GtCO2 from 2020 and 1,150 GtCO2 for a 67% probability of a temperature increase limited to 2°C [8]. However, IPCC states that the impact of the remaining global warming forcers on the CO_2 budget also depends on the related human mitigation choices in non-CO_2 reduction and present uncertainties related to the Earth's physical processes and systems. For that reason, the carbon budget is not implemented here. Instead, a constraint on a 1.5 degrees temperature change by the end of the century is used in the TIAM-FR climate module. Note that for this scenario the SSP1-26 economic and climatic driver is chosen. The model's climate module uses a linearized approximation of the forcing equations of the radiative forcing from the atmospheric CO_2, CH_4 and N_2O [49]. In addition, the processes for non-CO2 emissions follow an emission pathway of RCP2.6 calibrated according to MAGGIC [50] climate emulator. Table 1 provides a summary of the main assumptions for these scenarios.

3. RESULTS

This section presents an overview of the main results regarding the energy supply, electricity production and emissions removal through BECCS. It provides a comparison between different emissions pathways represented by the NDC and PA scenarios. Water use on a global and regional scale for these two scenarios has been also presented.

3.1 Energy supply, emissions, and removals

In the NDC scenario, primary energy supply is dominated by oil, gas, and coal in 2030 and 2050 representing 75% and 60% of the energy supply respectively whereas it reaches 35% in 2050 for the PA scenario. The demand in NDC scenario is filled by natural gas mostly while the bioenergy sector supply peaks between 2060 and 2080 (figure 5). This is not the case for the PA scenario, where biomass supply is stable at around 260 EJ and drops to 212 EJ by the end of the century (figure 6).

Table 1: Summary describing the developed scenarios' climate and economic assumptions.

Scenario name	**Narrative**	**Climate policy assumptions**		**Demand Drivers (GDP, growth of sectoral energy demand)**
		2030 strategy	**Long-term strategy**	
NDC	Emissions to 2030 are constrained according to NDCs. Only countries with NZ targets are assumed to reduce their emissions after 2030. The remaining regions are stabilized at 2030 levels.	Constraints on emission evolution as declared in the NDC registry till 2030 for all countries.	Net zero emissions by 2050 for USA, Australia, Europe, Brazil, Canada, Japan, South Korea. China and India have carbon neutrality target by 2060 and 2070, respectively.	SSP4-3.4
PA	Limitation on temperature to keep warming below 1.5°C.	Emission evolution up to 2030 and net zero emissions are kept as upper constraint.	Global temperature increase by 2100 is limited to 1.5°C	SSP1-2.6

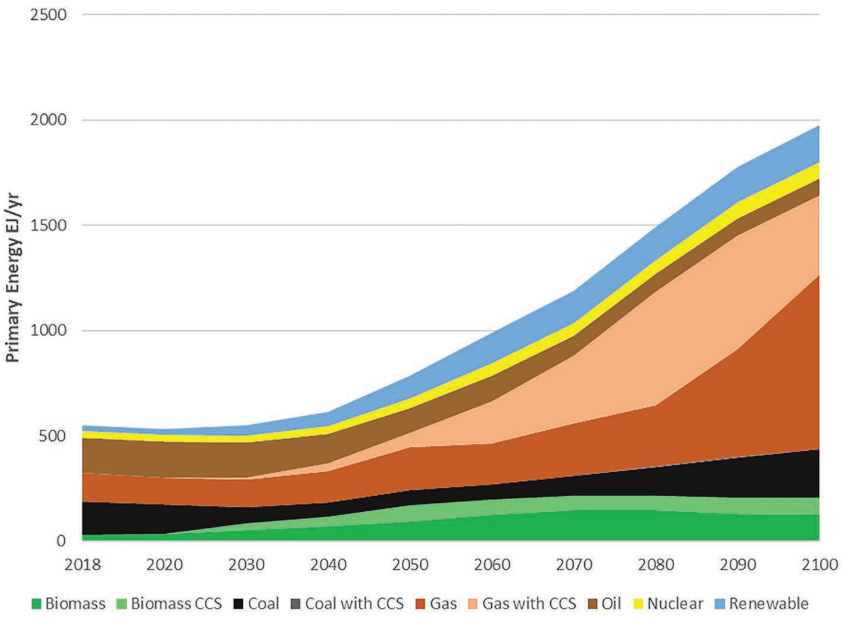


Figure 5: Primary energy supply - NDC scenario.

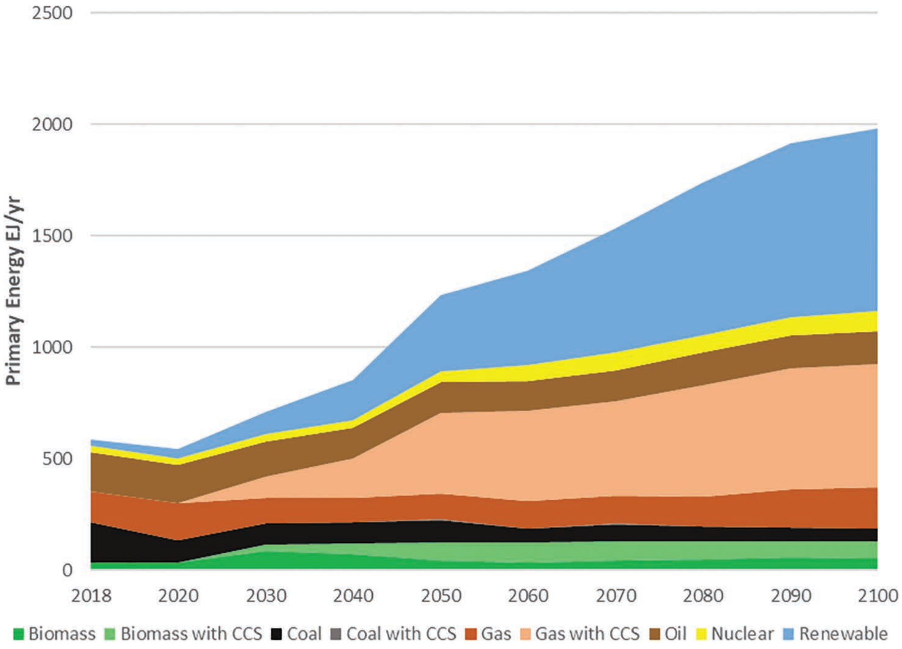


Figure 6: Primary energy supply - PA scenario

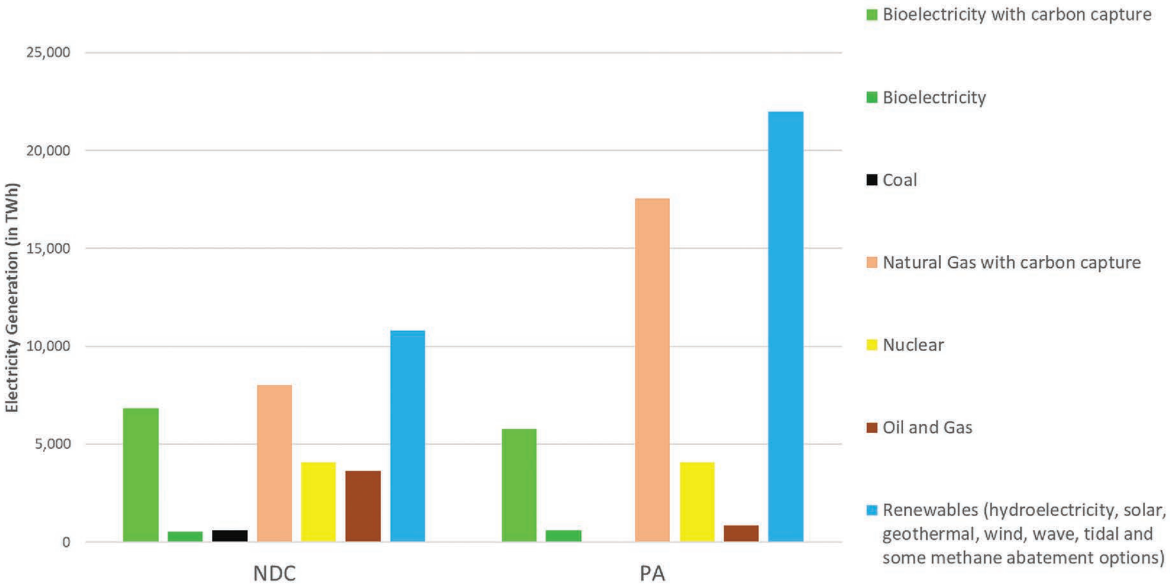


Figure 7: Electricity generation in 2050 for the two studied scenarios.

In all scenarios, the electricity sector shows a switch to gas coupled to CCS and a substantial increase of BECCS. Certainly, renewable energy plays a prominent role in the transition to low emissive power generation sector but develops the fastest in the PA scenario for the electricity mix in 2050 (Figure 7). Coal use in electricity generation almost disappears from this mix whereas it remains in both scenarios representing current policies while oil and gas electricity generation remain present in all three scenarios by 2050. Its share remains the lowest in the PA scenario.

The bioenergy sector profits from negative emissions by CCS with 2nd generation biofuels. Biodiesel is produced through fast pyrolysis with logging residues (lignocellulosic biomass) with CO2 capture. In both scenarios, biodiesel with CCS, however, appears around 2050 at a higher level in the most constrained scenario than in NDC scenario (figure 8) where biodiesel without capture is deployed. Bioethanol with wheat straw technology also appear starting 2030 including CCS. First generation ethanol continues to be present using corn crops, with carbon capture and two technologies for second generation bioethanol are invested. Biofuels with CCS represent 31% of the total BECCS in 2050 while this negative emission technology accounts for 11% of the total carbon capture in the PA scenario. Biomass for electricity dominates the carbon capture development in the bioenergy sector.

Note that biomass also contributes to the decarbonization of the industrial sector through biogas (with or without carbon capture) and biochar (in combination with the use of coal for the latter) but are not represented here.

3.2 Water

Until 2050, water consumption growth similarly in NDC and PA scenarios with a total consumption being of 71.4 km^3 and 69.25 km^3 respectively. From 2050 onward, the consumption keeps rising in PA scenario but at slower rate than for NDC (Figure 9). Indeed, an increasing requirement is determined in 2100, with respect to the base year, of 132.5% and 100.5% for NDC and PA, respectively.

The main differences in freshwater consumption of the energy sector are first due to the IGCC power plants (up to 6.4 km^3 in NDC and 3.36 km^3 for PA in year 2100). Biomass prevails in the NDC trajectory until the end of the century whereas it is dominated by renewable energy in the PA alongside natural gas with CCS. The fossil fuel primary energy represents 25% of the total water consumption in the NDC scenario compared to only 20% in PA. Global water consumption in 2030 from IEA NZE [51] amount for 66 km^3 are comparable to these values (figure 9).

Considering the energy mixes at global level, the switch to electrification anticipated in both scenarios will have different regional water uses. The reduction in

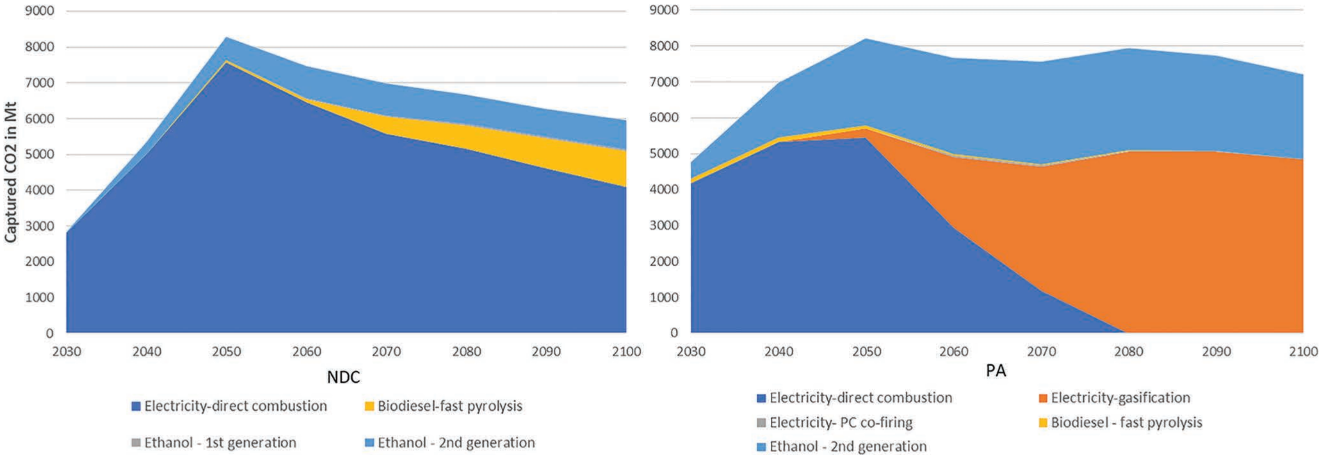


Figure 8: Carbon capture evolution in the bioenergy sector

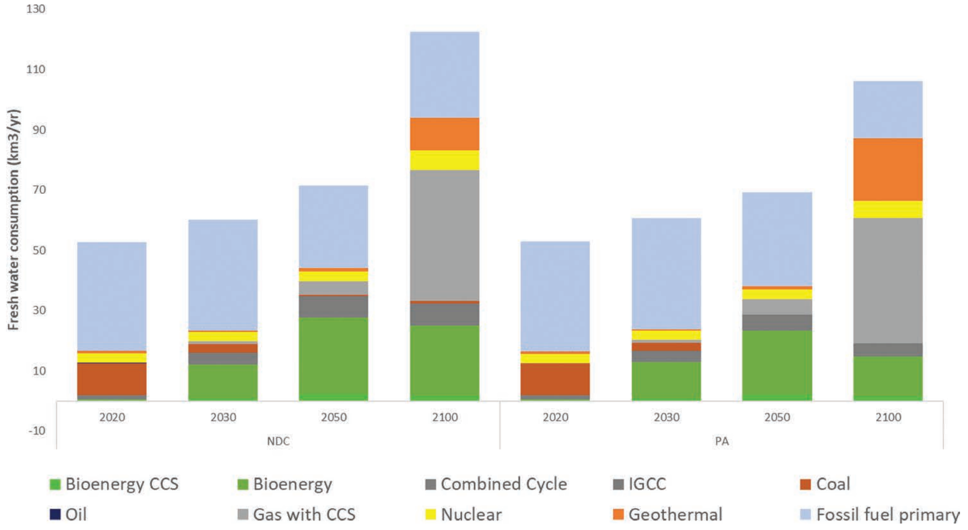
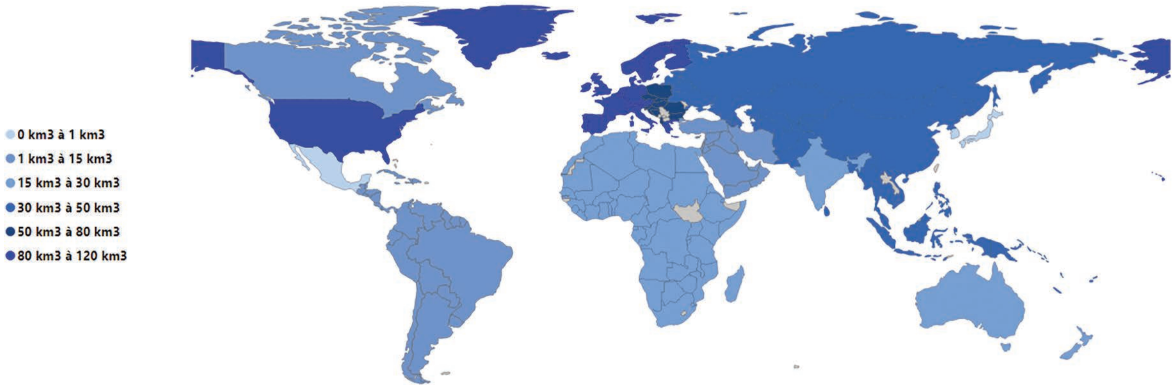


Figure 9: Global Fresh water consumption evolution in the energy sector

a)- Fresh water withdrawals in 2050 for NDC scenario



b)- Fresh water withdrawals in 2050 for PA scenario

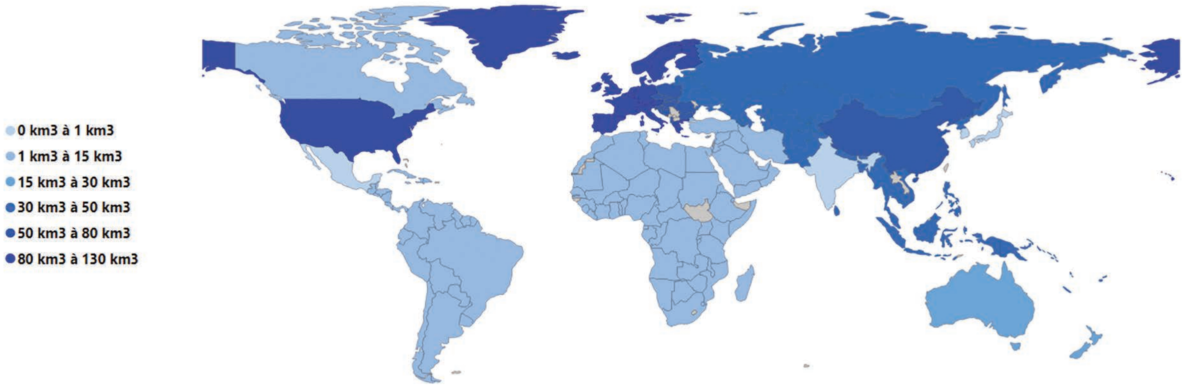


Figure 10: Regional Fresh water withdrawals in 2050.

freshwater withdrawal (FWW) is noticeable between NDC and PA in Canada, Russia, and Western Europe whereas it remains similar for the USA and Eastern Europe and increases for China (Figure 10).

Emission reduction actions impact the water use across regions differently (Figures 10, 11) Africa, India and Middle East are three regions with water scarcity. The results of the PA scenario in 2050 show a decrease, with respect to NDC scenario, in water withdrawal from around 26 to 13 km^3 and 37 to 15 km^3 for Africa and India, respectively. Water consumption shows a similar pattern. For the Middle East, the water consumption and withdrawal rise in the PA scenario. The difference is most significant at the end of the horizon (Figure 11) where water withdrawal attains around 16 km^3 in the PA compared to 2.5 km^3 in NDC. The freshwater consumption in the upstream sector in this region decreases in the PA but is compensated by an increase in consumption in electricity generation to reach around 10 km^3 in 2100. The results are comparable with the data found in [52].

4. DISCUSSION

Based on these results, several points can be raised. The Paris Agreement involves an electrified energy system dominated by renewable energy and relying on carbon capture technologies inducing a significant increase in water use. In fact, starting mid-century, a sudden change in withdrawals and consumptions patterns suggests that climate change mitigation must consider the use and

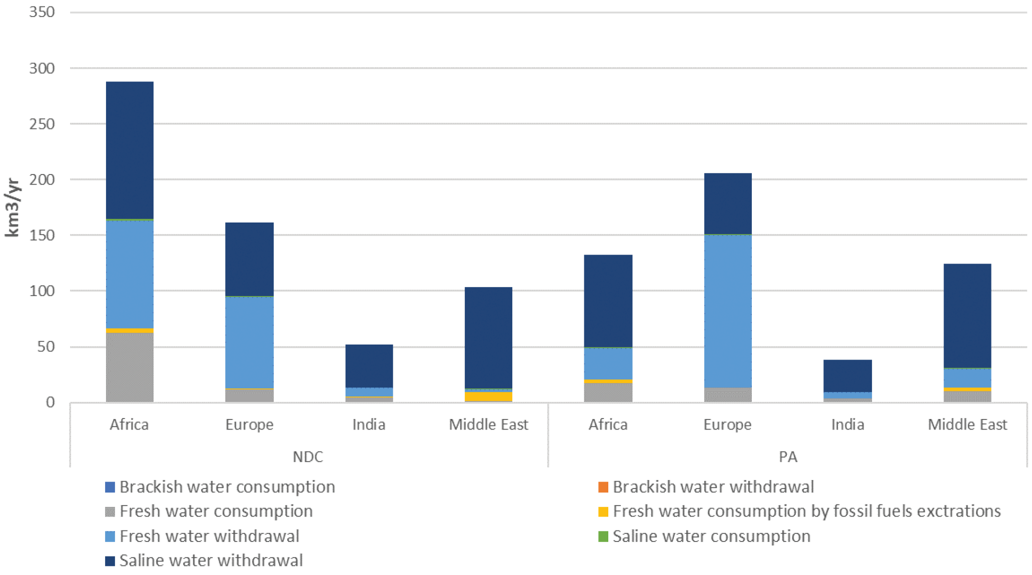


Figure 11: Water use in km^3 across TIAM-FR regions in 2100 for NDC and PA scenario.

availability of natural resources such as biomass and water, that can become harder to manage. Bioenergy provides a complementary opportunity to reduce emissions especially in the PA scenario from the beginning of 2030, in electricity and transport sectors where investments shift towards higher efficiency technologies (gasification) and using harvest residues in 2nd generation ethanol production.

Limiting the emission reductions to the NDCs trajectory, the situation of water use might be less critical than a Paris Agreement scenario for some regions like Middle East (Figure 11). In fact, water consumption in this oil and gas rich region is mainly due to the inevitable investments in carbon capture to decarbonize the energy system. Nonetheless, the PA scenario for Africa, where renewable energy is leading compared to CCS, results in less freshwater withdrawals. Regions with net zero emission targets including, but not limited to, Northern America, Europe (which water stress increased from 2015 to 2019, figure 1) and China would require attention to reduce water withdrawals since the use of this resource is needed in their transition to lower emission from electricity, fuel, and heat production. For instance, the strategies for China do consider the reduction of coal use but consider the case of energy saving and renovation of these power plants [53,54]. In regions such as Africa, India and Middle East, better policies that support the use of efficient water technologies in the energy sector are recommended. An important remark was identified through the results (Figures 7, 9, and 11) concerning the impact of switching to an electricity-based system based on low-emission technologies. Such system implies less variability across consumption scenarios when compared to withdrawal.

The interlinkages of the goals of the UN 2030 Agenda must be considered and could guide the choices and validation of solutions in relation to SDG13 reducing the negative impact on the other goals of the agenda, namely SDG6. Implementing SDGs in the national climate commitments would ensure a comprehensive transition to low-emission energy systems. As carbon dioxide removal will take an important part of the decarbonization of the energy system, these processes are water intensive and would pose pressure on land use (SDG15) and food security (SDG2). For example, bioenergy and BECCS contributes to access to energy (SDG7) while reducing the emissions (SDG13). However, they require massive use of lands and enter in competition with food crops. The solution would be to switch to sustainable practices like limiting land use to already exploited parts and resorting to using residues from forestry and agriculture sectors. However, CDR can involve natural climate solutions like reforestation, biochar in agriculture, agroforestry, coastal restoration. All these solutions would improve elimination of GHG emissions while having additional benefits. Indeed, these measures would restore ecosystems, while providing up to 37% by 2030 and 20% by 2050 of GHG mitigation [55]. For example, coastal methods can improve the situation of wetlands where ecosystems monitoring through SDG 6.6.1 shows that 21% of the world's basins are experiencing rapid changes in the area covered by surface waters. A study using a bottom-up type energy system model evaluated the attainability of net zero by 2050 without CCS for Thailand. It showed the requirement of rapidly increasing renewable energy (wind, solar, biomass), the installed capacities and the role of the land sector as carbon removal solution to this target [56]. In parallel, studies focusing on life cycle assessment like [57] would be very useful for the choices in clean energy projects. Indeed, a multi-objective optimization model is able to arbitrate between profit and environmental maximization for an algal biorefinery by arbitrating. It appears that the transesterification process is the most water-intensive part of this process. Impacts on water-related categories are found such as water consumption (human heath, terrestrial and aquatic ecosystems), freshwater (eutrophication, ecotoxicity) and global warming (freshwater ecosystems).

5. CONCLUSION

Climate change mitigation imposes drastic measures related to decreasing greenhouse gases emissions so that the global warming is kept within the 1.5°C limits. This is translated into net zero carbon emissions by mid-century. The current commitments put in place through NDCs implement net zero targets for some regions but are still not well aligned with the Paris Agreement goal. In this study, the key issues related to water were underlined in context of the transition to a low-emission energy sector. The relation between the energy sector and water is eminent in the electricity sector, but also in bioenergy and in negative emissions technologies. While comparing the NDC and the Paris Agreement scenarios, it seems that 2nd generation biofuels would be used keeping in mind that land use constraints were included in the scenarios. These biofuels present a low water footprint. Carbon capture is necessary in power generation to provide enough emission reduction, but it increases the pressure on the water supply. Water withdrawals impose a major limiting factor for electricity and fuel production when water resources are scarce. The water consumption would reduce the overall amount of water that is available for different users and sectors. Thus, water use from this sector is a challenge that impacts the plausibility of future mitigation solutions deployment. Considering Sustainable Development Goals became essential to ensure the feasibility of these mitigation policies and actions and the preservation of different resources and people's resilience to climate change at a broader level. Nonetheless, this study presents some limitations related to accounting for water use in the renewable energy sector, for example in hydropower and solar (the case of concentrated solar power). Moreover, the biomass supply (from agriculture, forestry, and other land use sectors) which is disaggregated in all available crops for bioenergy does not incorporate water consumption. This is under development and allows expanding the evaluation and assessment of water linked to energy by including other water uses like water for irrigation.

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REFERENCES

[1] United Nations. The race to zero emissions, and why the world depends on it. UN News 2020. https://news.un.org/en/story/2020/12/1078612 (accessed March 30, 2022).

[2] Climatewatch. Net-Zero Tracker 2022. https://www.climatewatchdata.org/net-zero-tracker?indicator=nz_year&search=&showEUCountries=true (accessed March 29, 2022).

[3] Creutzig F, Breyer C, Hilaire J, Minx J, Peters GP, Socolow R. The mutual dependence of negative emission technologies and energy systems. Energy Environ Sci 2019;12:1805–17. https://doi.org/10.1039/C8EE03682A.

[4] IPCC. AR6 Climate Change 2022: Mitigation of Climate Change 2022. https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (accessed April 8, 2022).

[5] Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, et al. Negative emissions—Part 1: Research landscape and

synthesis. Environ Res Lett 2018;13:063001. https://doi.org/10.1088/1748-9326/aabf9b.

[6] Bauer N, Klein D, Humpenöder F, Kriegler E, Luderer G, Popp A, et al. Bio-energy and CO2 emission reductions: an integrated land-use and energy sector perspective. Climatic Change 2020;163:1675–93. https://doi.org/10.1007/s10584-020-02895-z.

[7] Chlela S, Selosse S. Carbon Dioxide Removal in SDGs and Nationally Determined Contributions. In: Leal Filho W, Dinis MAP, Moggi S, Price E, Hope A, editors. SDGs in the European Region, Cham: Springer International Publishing; 2022, p. 1–20. https://doi.org/10.1007/978-3-030-91261-1_100-1.

[8] IPCC, 2022: Summary for Policymakers. In: Climate Change 2022: *Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

[9] Somalia: $2.6 billion appeal to support millions amid historic drought and famine fears | UN News 2023. https://news.un.org/en/story/2023/02/1133272 (accessed March 24, 2023).

[10] Le Monde. France faces threat of a new drought. Le MondeFr 15 March, 2023. https://www.lemonde.fr/en/environment/article/2023/03/15/france-faces-threat-of-a-new-drought_6019427_114.html (accessed April 01, 2023).

[11] Greece is not spared by the drought ongoing in Europe | Copernicus n.d. https://www.copernicus.eu/en/media/image-day-gallery/greece-not-spared-drought-ongoing-europe (accessed April 1, 2023).

[12] Barkdull J. Transformational Adaptation to Climate Change 2022. https://www.academia.edu/80327994/Transformational_Adaptation_to_Climate_Change

[13] Filho WL, Wall T, Salvia AL, Dinis MAP, Mifsud M. The central role of climate action in achieving the United Nations' Sustainable Development Goals. Sci Rep 2023;13:20582. https://doi.org/10.1038/s41598-023-47746-w.

[14] Goal 6: Clean Water and Sanitation - SDG Tracker. Our World in Data n.d. https://sdg-tracker.org/water-and-sanitation (accessed April 1, 2023).

[15] Progress on the level of water stress. FAO and UN Water; 2021. https://doi.org/10.4060/cb6241en.

[16] United Nations. Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs 2015. https://sdgs.un.org/2030agenda (accessed May 30, 2022).

[17] Global direct primary energy consumption. Our World in Data n.d. https://ourworldindata.org/grapher/global-primary-energy (accessed January 15, 2023).

[18] IEA. Net Zero by 2050 – Analysis. IEA 2021. https://www.iea.org/reports/net-zero-by-2050 (accessed April 24, 2022).

[19] IEA. CCUS in clean energy transitions. Energy Technology Perspectives 2020:174. https://www.iea.org/reports/ccus-in-clean-energy-transitions

[20] Global CCS Institute. Water Use in Thermal Power Plants equipped with CO2 capture systems 2016. https://www.globalccsinstitute.com/resources/publications-reports-research/water-use-in-thermal-power-plants-equipped-with-co2-capture-systems/

[21] Berndes G. Water Demand for Global Bioenergy Production: Trends, Risks and Opportunities 2008. https://www.wbgu.de/fileadmin/user_upload/wbgu/publikationen/hauptgutachten/hg2008/pdf/wbgu_jg2008_ex02.pdf

[22] Jans Y, Berndes G, Heinke J, Lucht W, Gerten D. Biomass production in plantations: Land constraints increase dependency on irrigation water. GCB Bioenergy 2018;10:628–44. https://doi.org/10.1111/gcbb.12530.

[23] Vinca A, Riahi K, Rowe A, Djilali N. Climate-Land-Energy-Water Nexus Models Across Scales: Progress, Gaps and Best Accessibility Practices. Frontiers in Environmental Science 2021;9 https://doi.org/10.3389/fenvs.2021.691523.

[24] Bouckaert S, Selosse S, Assoumou E, Dubreuil A, Maïzi N. Analyzing Water Supply in Future Energy Systems Using the TIMES Integrating Assessment Model (TIAM-FR). Journal of Systemics, Cybernetics and Informatics 2012;10:89–94.

[25] Bouckaert S, Assoumou E, Selosse S, Maïzi N. A prospective analysis of waste heat management at power plants and water conservation issues using a global TIMES model. Energy 2014;68:80–91. https://doi.org/10.1016/j.energy.2014.02.008.

[26] Fricko O, Parkinson SC, Johnson N, Strubegger M, Vliet MT van, Riahi K. Energy sector water use implications of a 2 °C climate policy. Environ Res Lett 2016;11:034011. https://doi.org/10.1088/1748-9326/11/3/034011.

[27] van der Zwaan B, Halstead M, Kober T. Water Stress Implications of Energy Scenarios for the Middle East: An Assessment of Risks and Uncertainties. In: Doukas H, Flamos A, Lieu J, editors. Understanding Risks and Uncertainties in Energy and Climate Policy: Multidisciplinary Methods and Tools for a Low Carbon Society, Cham: Springer International Publishing; 2019, p. 143–60. https://doi.org/10.1007/978-3-030-03152-7_6.

[28] Davies EGR, Kyle P, Edmonds JA. An integrated assessment of global and regional water demands for electricity generation to 2095. Advances in Water Resources 2013;52:296–313. https://doi.org/10.1016/j.advwatres.2012.11.020.

[29] Lovrak A, Pukšec T, Duić N. A Geographical Information System (GIS) based approach for assessing the spatial distribution and seasonal variation of biogas production potential from agricultural residues and municipal biowaste. Applied Energy 2020;267:115010. https://doi.org/10.1016/j.apenergy.2020.115010.

[30] Melo LB, Costa AL, Estanislau F, Velasquez CE, Fortini A, Moura GNP. Water-energy-emissions nexus – an integrated analysis applied to a case study. International Journal of Sustainable Energy Planning and Management 2022;36:19–32. https://doi.org/10.54337/ijsepm.7349.

[31] Ramos EP, Howells M, Sridharan V, Engström RE, Taliotis C, Mentis D, et al. The climate, land, energy, and water systems (CLEWs) framework: a retrospective of activities and advances to 2019. Environ Res Lett 2021;16:033003. https://doi.org/10.1088/1748-9326/abd34f.

[32] IEA-ETSAP | Times n.d. https://iea-etsap.org/index.php/etsap-tools/model-generators/times (accessed January 16, 2022).

[33] Loulou R, Goldstein G, Kanudia A, Lettila A, Remme U. Documentation for the TIMES Model-Part I 2016. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf (accessed March 25, 2021).

[34] IRENA. World Energy Transitions Outlook: 1.5°C Pathway (Preview) 2021. https://www.irena.org/publications/2021/March/World-Energy-Transitions-Outlook (accessed March 15, 2021).

[35] Fischer G. Global Agro-Ecological Zones v4 – Model documentation. Rome, Italy: FAO; 2021. https://doi.org/10.4060/cb4744en.

[36] Kang S, Selosse S, Maïzi N. Contribution of global GHG reduction pledges to bioenergy expansion. Biomass and Bioenergy 2018;111:142–53.https://doi.org/10.1016/j.biombioe.2017.05.017.

[37] FAO. FRA 2015 | Global Forest Resources Assessments 2015. https://www.fao.org/forest-resources-assessment/past-assessments/fra-2015/en/ (accessed January 24, 2024).

[38] Cooling Tower Fundamentals. SPX Cooling Technologies 2019. https://spxcooling.com/library/cooling-tower-fundamentals/ (accessed May 4, 2023).

[39] IEA. World Energy Balances - Data product. IEA 2020. https://www.iea.org/data-and-statistics/data-product/world-energy-balances (accessed February 12, 2024).

[40] DOE (US. Departement of Energy) / NETL (National Energy Technology Laboratory). Power plant water usage and loss study. 2007 update 2007.

[41] IPCC. All NDCs 2022. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx (accessed January 23, 2022).

[42] UNFCCC. Greenhouse Gas Inventory Data - Time Series - Annex I 2021. https://di.unfccc.int/time_series (accessed May 20, 2022).

[43] Climatewatch. | Greenhouse Gas (GHG) Emissions | Climate Watch 2022. https://www.climatewatchdata.org/ghg-emissions?end_year=2019&regions=&start_year=1990 (accessed February 1, 2023).

[44] Biennial Update Report submissions from Non-Annex I Parties | UNFCCC n.d. https://unfccc.int/BURs (accessed March 5, 2024).

[45] National Communication submissions from Non-Annex I Parties | UNFCCC n.d. https://unfccc.int/non-annex-I-NCs (accessed March 5, 2024).

[46] Calvin K, Bond-Lamberty B, Clarke L, Edmonds J, Eom J, Hartin C, et al. The SSP4: A world of deepening inequality. Global Environmental Change 2017;42:284–96. https://doi.org/10.1016/j.gloenvcha.2016.06.010.

[47] harrisson thomas. CMIP6: the next generation of climate models explained. Carbon Brief 2019. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/ (accessed February 1, 2023).

[48] UN Environment. Emissions Gap Report 2022. UNEP - UN Environment Programme 2022. http://www.unep.org/resources/emissions-gap-report-2022 (accessed November 2, 2022).

[49] Loulou R, Lettila A, Kanudia A, Remme U, Goldstein G. Documentation for the TIMES Model-Part II 2016. https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-II_July-2016.pdf (accessed March 25, 2021).

[50] MAGICC n.d. https://magicc.org/ (accessed February 19, 2024).

[51] IEA. Energy and water – Topics. IEA n.d. https://www.iea.org/topics/energy-and-water (accessed May 4, 2023).

[52] Terrapon-Pfaff JC, Ortiz W, Viebahn P, Kynast E, Flörke M. Water Demand Scenarios for Electricity Generation at the Global and Regional Levels. Water 2020;12:2482. https://doi.org/10.3390/w12092482.

[53] Circular of the National Energy Administration of the National Development and Reform Commission on carrying out the transformation and upgrading of national coal-fired power units_SMM | Shanghai Non ferrous Metals n.d. https://news.metal.com/newscontent/101652936/circular-of-the-national-energy-administration-of-the-national-development-and-reform-commission-on-carrying-out-the-transformation-and-upgrading-of-national-coal-fired-power-units (accessed May 8, 2023).

[54] Fan J-L, Li Z, Huang X, Li K, Zhang X, Lu X, et al. A net-zero emissions strategy for China’s power sector using carbon-capture utilization and storage. Nat Commun 2023;14:5972. https://doi.org/10.1038/s41467-023-41548-4.

[55] Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. Natural climate solutions. PNAS 2017;114:11645–50. https://doi.org/10.1073/pnas.1710465114.

[56] Pradhan BB, Chaichaloempreecha A, Chunark P, Rajbhandari S, Pita P, Limmeechokchai B. Energy system transformation for attainability of net zero emissions in Thailand. International Journal of Sustainable Energy Planning and Management 2022;35:27–44. https://doi.org/10.54337/ijsepm.7116.

[57] Solis CMA, San Juan JLG, Mayol AP, Sy CL, Ubando AT, Culaba AB. A Multi-Objective Life Cycle Optimization Model of an Integrated Algal Biorefinery toward a Sustainable Circular Bioeconomy Considering Resource Recirculation. Energies 2021;14:1416. https://doi.org/10.3390/en14051416.