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Climate actions effects on ressource sustainability in a carbon constrained world

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Working paper

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ABSTRACT

This paper analyzes carbon dioxide removal (CDR), with a focus on Bioenergy Carbon Capture and Storage, as climate actions related to the Sustainable Development Goal 13. It examines this goal's interlinkage to other UN goals such as SDG6 (water) and SDG7 (energy) in accordance with the concept of the water-energy-land nexus. To align the Nationally Determined Contributions (NDC) to the Paris Agreement long-term goal of net-zero emissions, the global energy system's evolution is studied, using the global and regional outputs of the techno-economic optimization of TIAM-FR that incorporates various mitigation options including a disaggregated biomass representation. In addition, a water module is used to assess water withdrawals and consumptions. The analysis is made under three climate scenarios. Results show that bioenergy with carbon capture and storage (CCS) contributes to decarbonizing the energy mix (SDG7) even with sustainability constraints. Also, carbon capture and storage technologies are a plausible solution to keep the temperature limit at 1.5 degrees, but impact water use due to their use of water-intensive resources and technologies (SDG13 in trade-off with SDG6). The analysis shows that the Paris Agreement scenarios, both with and without temperature overshoot, increase global water use by 65% and 62%, respectively, by 2050 compared to 2020. Regionally, water-scarce areas like the Middle East and India exhibit similar patterns, whereas Africa shows lower water use compared to an NDC scenario by leveraging its renewable energy potential.

1 Introduction

The 17 Sustainable Development Goals (SDGs), established by the United Nations in 2015, aim to address economic, social, and environmental issues. Key environmental goals include climate change mitigation and biodiversity preservation. However, progress is slow, with only 15% of targets likely to be met, particularly lagging in environmental and poverty-related areas [1]. One related concept to sustainability is the water-energy nexus [2]. It highlights the mutual dependencies between water and energy sectors and extends to include the food sector due to its significant water and energy usage and environmental impact. The nexus concept incorporates strategies like integrated water management and sustainable agriculture, aiming for sustainable consumption and production.

The nexus approach, guided by human rights and climate change considerations, aims to balance its elements equally. Central to this are SDGs 2 (food security), 6 (water and sanitation), and 7 (energy), focusing on long-term resource management and accessibility. Thus, choosing sustainable climate action (SDG13) has a central role for setting the policies where multiple SDGs from socioeconomic objectives, environmental quality and sustainable resource management targets can be achieved simultaneously.

Integrated assessment models (IAMs) can capture the feedback between sectors like water, energy and agriculture. Moreover, the climate system is being represented in addition to the other three giving more credibility and comprehensiveness to the studies [3]. Indeed, the effectiveness of climate policies are influenced by uncertainties related to climate sensitivity and the level of decoupling between energy demands and economic growth [4].
For the mitigation of climate change, the IPCC report [5] reminds that removing anthropogenic emissions from the atmosphere is part of the portfolio of strategies to attenuate climate change. Deploying carbon dioxide removal (CDR) is found in vetted scenarios and includes afforestation/reforestation and bioenergy carbon, capture, and storage (BECCS). Technological options also exist in these scenarios like direct air carbon capture and storage (DACCS) and enhanced weathering (EW). The CDR solutions in climate scenarios run from different IAMs in [6], indicate a rapid achievement of the net zero target in the Agriculture, Forestry and Other Land use (AFOLU) sector compared to energy supply. Some models however rely on BECCS heavily like REMIND-MAgPIE, or on nature-based solutions or rely on a balance between CDR solutions like WITCH, POLES and MESSAGE-GLOBIOM models. The magnitude of the sinks in the assessed models at the year of net zero ranges between 5 GtCO2/year for REMIND-MAgPIe and GEM-E3 models to more than 10 GtCO2/year for POLES and WITCH in a 1.5 °C pathways with low temperature overshoot. In such a scenario, CO2 emissions globally reach net zero around 2050–2075. In this paper, BECCS are analyzed as the CDR solution as well as part of energy system decarbonization with the use of biomass. In fact, biomass has historically played a crucial role in energy production and security, providing heat through wood and biofuels for transportation, especially during petroleum crises and geopolitical tensions [7]. Additionally, as a renewable energy source, it supports the UN Agenda 2030, particularly Sustainable Development Goal 7 (SDG7), which focuses on affordable and clean energy. Furthermore, it can provide a renewable source to produce hydrogen, which is getting attention to replace fossil fuels and provide a sustainable energy solution [8].

The interconnection between water and land systems plays a crucial role in sustainable development pathways. In fact, integrated assessment models emphasize the complexity and uncertainty of climate change impacts on water, energy, and land systems, stressing the importance of coordinated strategies to achieve SDGs. MESSAGEix-GLOBIOM and IMAGE provide valuable insights into the interconnections between water, energy, and land systems in the context of sustainable development pathways [9]. These models highlight the significant impact of climate change on water availability, affecting agriculture, hydropower potential, and power plant cooling technologies, with water sector changes being a major source of uncertainty. Also, implementing water accounting in demand sectors like industries, a major contributor to greenhouse gas emissions, highlights the need for reducing water and energy usage to lower carbon footprints [10]. In this work, water use is applied to the energy production sector and allows its replication for other sectors.

Moreover, the report [5] also provides a qualitative assessment of synergies and trade-offs for the sectoral mitigation options (like BECCS, CCS) with respect to SDGs. The challenge involves balancing the benefits of large-scale GHG emission reductions and enhanced removals against potential risks and barriers. For example, implementing land-based mitigation strategies, such as reforestation or bioenergy crop cultivation, can compete with agricultural land, potentially affecting food security (SDG2) and the livelihoods of local communities (SDG8, Decent work and Economic Growth), especially in areas where land is scarce or highly valuable for agricultural production.

Furthermore, BECCS, but also CCS technologies used in fossil-based power plants, can be water-intensive. In fact, the process of converting biomass into energy, whether through combustion or gasification, can also consume water, primarily for cooling purposes. Water is also used in the capture phase, where CO2 is separated and captured from process emissions [11]. Water use in CCS can vary significantly depending on the capture technology, the cooling system, and the plant's overall efficiency. For instance, using a life cycle assessment on four types of carbon capture power plants, [12] found that primary energy demand increased by 21–46% and water resources depletion by 59–95%. Water-energy constraints are implemented in [13] where an energy and water models are linked, highlighting the impact of managing resources for power generation under emissions reduction pathways. The transition to low emissions energy sector is intertwined with water consumption and land use. This was also demonstrated in [14], where GCAM-USA model is used to identify, among other, the future energy supply and land use considering the net zero emission target of the United States of America, under stringent water availability limitation. Nevertheless, other types of models exist that could tackle these topics. The study of [15] uses system dynamics models, to examine the linkages between the evolution of the energy system, water, emissions in addition to food. The outcomes involved policy considerations for balancing between synergies and tradeoffs of the evaluated scenarios. To promote greener practices and sustainable development in power generation and industries in China, economic profits and environmental benefits of integrating CCS were evaluated in [16] for a set of scenarios compromising renewable energy and CCS.

This paper addresses several critical environmental issues related to climate actions and resource sustainability. First, it emphasizes the interdependencies between water and energy sectors, highlighting how climate actions can impact water availability and usage. This nexus is crucial for understanding the sustainability of electricity and fuel production and emission reduction methods, particularly those involving carbon capture technologies like BECCS and CCS. Second, the research focuses on strategies for reducing greenhouse gas emissions, with an emphasis on carbon dioxide removal (CDR) methods. This is done through energy system optimization, using the French version of TIMES Integrated Assessment Model (TIAM-FR). More explicitly, net zero emissions pathways are investigated in terms of techno-economic feasibility and sustainability. Third, it assesses the effectiveness of these pathways while considering their environmental impacts such as water use. It investigates the deployment of BECCS under sustainability constraints on land use like no deforestation and "food first" approach. Owing to the disaggregated biomass representation and complete value chain from land occupation to transformation and energy production, the evaluation covers the plausible future roles of different feedstocks. Additionally, it examines water use in the energy system, including BECCS and low-emission technologies, and compares water consumption and withdrawals for these climate policies. Fourth, the paper presents the results of climate policies and their impact on water resources, revealing challenges from a regional variability perspective. Water-scarce regions, such as the Middle East and India, may face significant challenges under different climate scenarios, while Africa could harness its renewable energy potential with lower water use. Fifth, the study connects climate actions to the broader framework of the SDGs, particularly those related to water (SDG6), energy (SDG7), and climate action (SDG13). It highlights the need for policies that balance environmental quality with socioeconomic objectives. The research underscores the importance of integrated resource management strategies to ensure that climate actions do not exacerbate existing environmental issues, such as water scarcity and land degradation.

The paper is structured as follows: the main assumptions related to bioenergy, land and water use in energy and CCS approaches are presented. The results segment focuses on energy and electricity, as well as carbon sequestration efforts in the bioenergy sector. It then presents data on water use and withdrawal, providing a geographical analysis that includes areas experiencing significant water stress among others. The discussion offers insights into the nexus between water, energy, and land, before concluding with an interpretation of the results in light of the SDGs.

II The integration of biomass and water in the energy modelling framework

2-1 Modelling framework

Prospective modeling, especially in energy systems, allows for in-depth exploration of potential futures, aiding strategic decision-making in both private industries and public sectors for policy development. This approach supports selecting cost-effective investments that align with net zero emission goals. The model generator TIMES is a methodological corpus developed under the IEA's Energy Technology Systems Analysis Program (ETSAP). Its global incarnation was initially presented and explained by [17] as ETSAP-TIAM.

This analysis is carried out with TIAM-FR, the French version of TIAM, representing the global energy system in 15 regions (fig.1).

Like other TIMES models, it is a partial equilibrium model with perfect foresight, technology-rich, and tracks the evolution of the energy system until the end of the century. The TIAM-FR model is calibrated for the start year 2018 and allows investments in new technologies according to their characteristics while accounting for the present and future resources and their potential. It interconnects 5 end-uses (residential, transport, agriculture, industrial, and commercial sectors).

In TIAM-FR model, the future energy services demand across various sectors can be anticipated by using key economic indicators such as Gross Domestic Product (GDP) and population growth rates. The SSP database of IIASA is used to obtain these values which are incorporated in the model as fundamental drivers through sector-specific elasticities. The model covers CO_2, CH_4 and N_2O emissions and allows the calculation of the global temperature by a climate module.

Region	Name	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		

Fig 1. TIAM-FR regional representation

2-2 Biomass representation in TIAM-FR

In TIAM-FR, biomass feedstocks are represented covering all sorts of crops including energy plantation, agriculture and forest residues, waste (industrial and municipal). For the energy plantations, short rotation crops, miscanthus, switchgrass, soja etc. were modelled based on a land-based approach to account for the competition between these crops and to estimate the availability of land based on a food-first approach [7]. The GAEZ [18] provides data about land resources from which the land cover types "cropland", "grassland" and "tree cover land" are set as allowed exploitable land in the model. In other terms, forests are maintained at their actual level, hence no deforestation is projected for the purpose of bioenergy. Protected areas on grassland are also conserved. Then another sustainability condition is imposed concerning food security. The land available for bioenergy, through the horizon of the study, is obtained after estimation of the food and feed demand where the relative future demand is taken from [19] and population projection from [20]. Hence, the change in agricultural land is estimated for each region and projected year, using crops yields and food demands. For crop productivity projections, GAEZ provides agro-climatically attainable yields for each crop and country.

The areas designated for each crop are then translated into units of energy. This is done by considering each crop's specific productivity levels, assumed market prices, and energy conversion rates, which vary according to the water and energy content of each crop. The model specifies the use of selected sugar and starch crops in various energy transformation processes, including their use as solid biomass, except for first-generation biodiesel production. Conversely, oil-bearing crops are considered for all applications except first-generation bioethanol production.
The model also includes the conversion of agricultural residues, wood, logging and processing wood residues, short rotation crops, miscanthus and switchgrass as lignite biomass to be used as 2nd generation feedstock. Wood supply can also be produced into pellets, torrefied pellets, used in pyrolysis for charcoal, or converted into solid biomass. Energy plantations are also used in biogas production by anaerobic digestion which can also have agricultural residues as inputs.

Three primary sources exist for forestry biomass estimates including roundwood derived from both (1) forest areas and (2) other woodland, as well as (3) trees located outside of forest boundaries (TOF). The wood supply potential from these sources is evaluated based on the Gross Annual Increment (GAI), derived from the Net Annual Increment (NAI) [21] and natural loss data obtained from [22], with regional variations considered. The GAI represents natural forest growth thus respects the sustainability of wood consumption for bioenergy. Its value is multiplied by the area of forests and other woodland to obtain the offer surplus of wood in volume. The volume is converted to energy value using the Biomass Conversion and Expansion Factor (BCEF) and the wood's energy content of 18.3 MJ/kg dry matter [23]. TOF also represent an important source of biomass hence their potential estimation followed a similar way for where data is available [24]. Additionally, agricultural and forestry residues were categorized into harvesting (logging) residues and processing residues. Agricultural residues are calculated by multiplying region and crop specific residue to product (RPR) [25] and recovery factor to the amount of primary production thus estimating the collectable crop residues. Parameters related to the potential of biomass, land occupation, transformation and conversion to electricity and fuel are found in the Supplementary Material.

For the forest biomass these include the deduction of industrial wood demand and the elaboration of an economic potential of biomass where the GAI is combined with the rate of commercial forest species. This choice was made in [7] rather than using technical potential because the production costs are based on the market prices of [26]. Also, capital, labour, land, and transport are the four elements that constitute the total cost of production of an agricultural resource. After deducting the industrial roundwood consumption and adding the residues and TOF potential, the forestry biomass potential at year 2050 is estimated at 61.2 EJ/year and 107.5 EJ (technical). A medium technical progress is assumed and expansion of biocrops on other surfaces outside the surfaces cultivated in year 2010 is not allowed. Under such conditions, 0.47 Mm2 of land can be exploited by bioenergy crops which is the level of year 2010. The regions with the highest biomass potential are the USA, Canada, Western Europe, Africa, India and the lowest are for Japan, South Korea, Mexico.

2-3 Water accounting in TIAM-FR

The water module described in [27] is applied to facilitate the identification of water consumption and withdrawal in the upstream sector (extraction of oil and gas) and electricity generation. First, a commodity-driven approach is used to assess the water use in the upstream sectors and the existing power generation plants by allocating water factors depending on the process and region. Water use is modelled as output per unit of energy produced (m3/PJ). The information about existing power plants production by type and region are extracted from the IEA energy balances for the reference year [28]. It allows determining the according load factors and efficiency. This is important to allocate the water factors by type of the cooling system and by source and regions. Water use in liters/MWh can be obtained from [29] for consumption and withdrawal.

Additionally, in a process-driven approach, new technologies are allocated an output commodity Q. It represents the heat to be discharged and is set as an input of a cooling technology for power plants (thermal, using coal or gas) with or without carbon capture and storage (CCS), nuclear, bioenergy (fuel and electricity) again with or without CCS. Note that the assessment of water use here does not include hydropower. Water consumption may occur due to evaporation in reservoirs, but it is difficult to assess the share related to electricity production since dams are also used for agriculture, flood control and navigation [30]. Figure 1 describes the water use for cooling in a biomass gasification power plant equipped with CCS. Here, heat from cooling and gasification is discharged into the different cooling systems. Using this approach allows accounting for the electricity used to power these systems.

To obtain the heat discharged from the condensers, the efficiency of the new power plants and their mechanical work are used to calculate it for each type of technology by region. For closed loop systems, the temperature variation (ΔT) between inlet and outlet of the power plant, specific heat of water (4.18 kJ/kg), the motor mechanical work are needed to calculate the heat discharge. Since the climate is different by region, distinct (ΔT) have been considered. Consumption in this case represents 1% of the withdrawals. In the case of wet closed loop systems, the water latent heat and the coefficient for heat transfer made by evaporation f_{latent} = 0.9 [31] are used to calculate Q from consumption. Water losses from evaporation and blowdown are compensated by withdrawals to keep a constant flow in the system. Then the concentration of minerals in the water needs to be constant, which allows the relation between withdrawn water and evaporated (consumed) water.

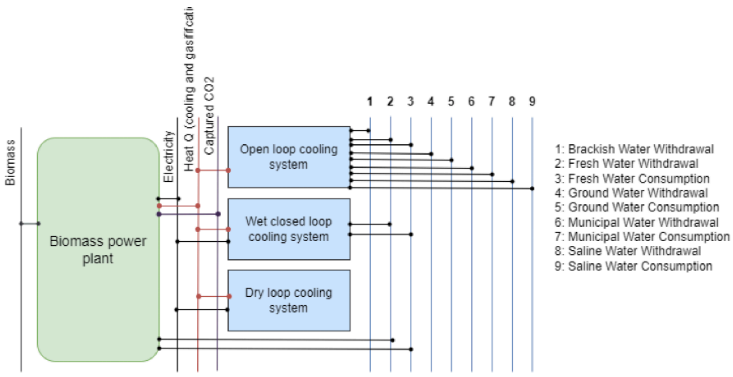


Fig 2. Example of a RES representing water use by a BECCS power plant

In the carbon capture, the main capture approaches considered in the model for the power sector are post-combustion for thermal power plants using coal, biomass, and gas turbines where the capture the technology would treat the output gases. Precombustion is included with gasification power plants for syngas production where the capture process acts before the combustion of the gas as suggested by its name. Oxycombustion is used for the case of retrofitting power plants like coal.

The water needs for carbon capture varies depending on the cooling technology like in the case of power plants without carbon capture and on the CCS technology (absorption, adsorption, membrane). Post-combustion can be applied to existing energy and industrial infrastructure and thus it is considered an economically viable approach. Amine based absorption present the highest water withdrawals across all cooling techniques studied in [32] but are currently the most reliable and used liquid sorbent. In TIAM-FR, the capture technologies in the power sector are amine-based chemical absorption (liquid solvent) for post-combustion processes with their techno-economic properties found in [33] and [34]. CCS costs in the last study are assumed to decrease due to the influence of policy and regulatory frameworks aimed at achieving net zero emissions. Water factors for the CCS are based on [11,29].

Using solid sorbent is the subject of many studies where it was shown that it requires lower energy for regeneration and CO2 release than liquid sorbents whereas it presents lower rates of CO2 uptakes. [35]. Nevertheless, these technologies like temperature swing, pressure and vacuum swing adsorption are used in Direct Air Carbon Capture (DACC). Indeed, they present benefits water use compared to liquid sorbent and require less energy because their heat requirement is lower as per the [36]. This study provides the techno-economic parameters used in TIAM-FR. The assessment is for the temperature swing adsorption and/or in combination with vacuum swing.

Capture method and technology	Purpose of water use
Post-combustion using liquid solvent	• Regulating the concentration of the amine solvent at the washing loop • Water is released from condensation and make-up water needs treatment before re-use
Precombustion	• Water use in the water gas shift (WGS) to process syngas • Steam is required to hold the shift reaction • (water-intensive method compared to post-combustion)
Oxycombustion	• Water is needed for cooling in the cryogenic air separation unit (ASU) and in the flue gas purification (FGR) systems

Note: in this model, the carbon capture is done by absorption (use of liquid sorbent) or atmospheric pressure oxyfuel technology

2-4 Scenarios development

Three scenarios regarding climate policy are used to analyze the evolution of the energy system.

The first scenario describes the GHG emissions reduction according to the updated or second NDCs (as of October 2022) and is denoted "NDC" hereafter. In this analysis, the Agriculture, Forestry and Land Use (AFOLU) sector emissions were excluded. To quantify these commitments, computational methods and the use of emissions datasets [37,38] are required. The emissions at the base year are obtained and multiplied by the reduction target of year 2030. The NDC documents of all parties are obtained from [39] were reduction targets are extracted. For few cases, the NDC document lacks emissions values hence [40] was used to complete the assessment.
This scenario follows a SSP4-3.4 (see fig 3) since 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 [41]. This is coherent as the emissions pathways under current commitments and actions are far from achieving this temperature growth limitation [42]. This scenario also assumes that post-2030 the emissions will be maintained at the same level of 2030 for regions without net zero commitments. For countries or regions with the net zero targets, i.e Brazil (2050), China (carbon neutrality 2060), India (carbon neutrality 2070), United States of America, Canada, Australia, Europe all in 2050, net GHG starting the net zero year will be capped at zero as maximum till 2100.

The second explored scenario "PA" is the Paris Agreement compliant scenario where the limit is set for respecting a temperature increase of 1.5 by 2100. It features high emissions in the beginning of the century that leads to temperature overshoot corrected using negative emissions before the end of the century [43].
The third scenario "PA no-os" is the does not allow the temperature variation to surpass 1.5 at any period of the horizon. It means that temperatures stay below the global temperature goal throughout the century with no overshoot. This scenario features more immediate emissions reductions. To include the effect of all climate forcers and follow the temperature variation, the climate module is used taking the CO2 concentration variation obtained from MAGICC [44] for a SSP4-45 and SSP1-2.6 for the NDC and PA, PA no OS scenarios, respectively.

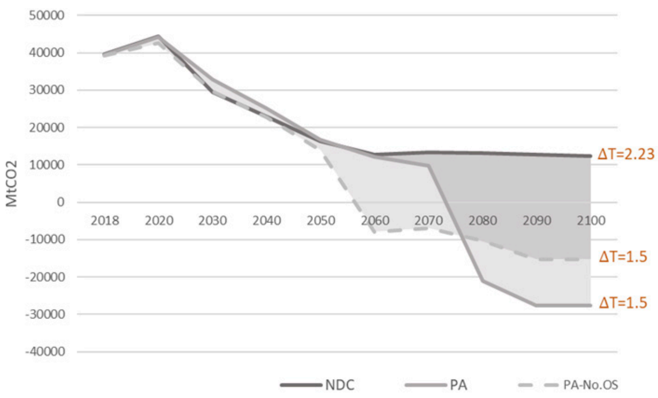


Fig 3. Global net CO2 emissions evolution

III Further growth in energy and water consumption with climate mitigation efforts

3-1 Energy panorama

The primary energy in 2050 is dominated by coal, oil, and gas in the NDC scenario (fig 4). Biomass, renewables, and gas are the main energy carriers in the "PA no OS" scenario starting mid-century with coal almost phased out in 2100 whereas it remains in the "PA" scenario. The high values of natural gas in the energy supply are due to two reasons: the negative emissions at the end of the century, used with CCS and for DACCS supply and the increasing Gross Domestic Product (GDP) of the African continent. Despite this requirement of negative emissions, the "PA no OS" shows the highest reduction of fossil fuels consumption in 2100.

In 2050, bioenergy accounts for 18% of the primary in the NDC scenario, representing higher shares than what is observed in the PA (9%, figure 5) and PA no-OS (14%, figure 6) energy supply. Nevertheless, renewables in mid-century are at 25% in "PA no OS" compared to 15% in the NDC. They are mostly constituted from wind, solar, hydro, and geothermal energy. Furthermore, bioenergy keeps increasing till the end of the century in the "PA no OS" which is facilitated by the decrease of fossil fuels due to strict and rapid emission reductions compared to the "NDC" and "PA" scenarios.

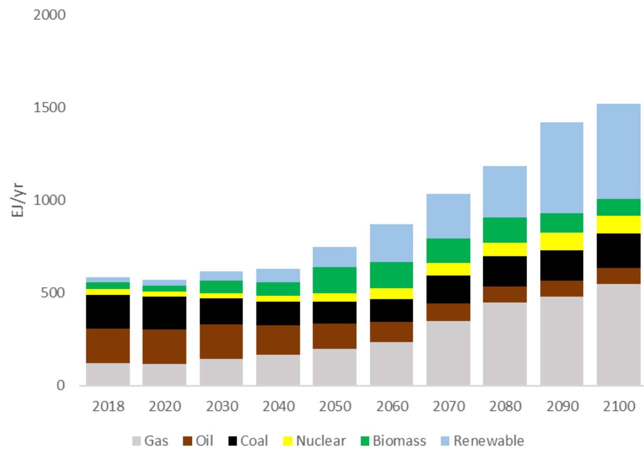


Fig 4. Primary energy supply for the NDC scenario

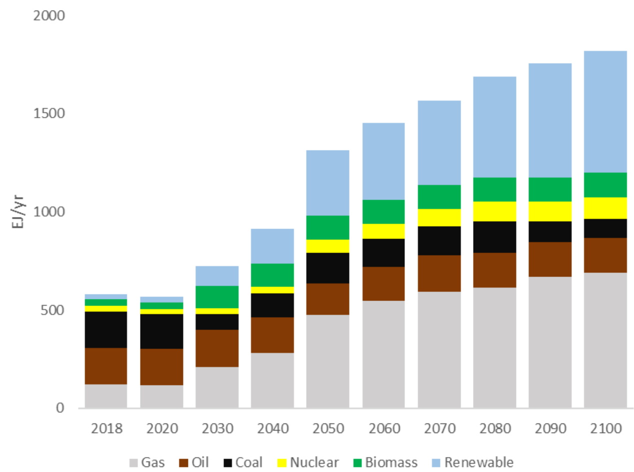


Fig 5. Primary energy supply for the PA scenario

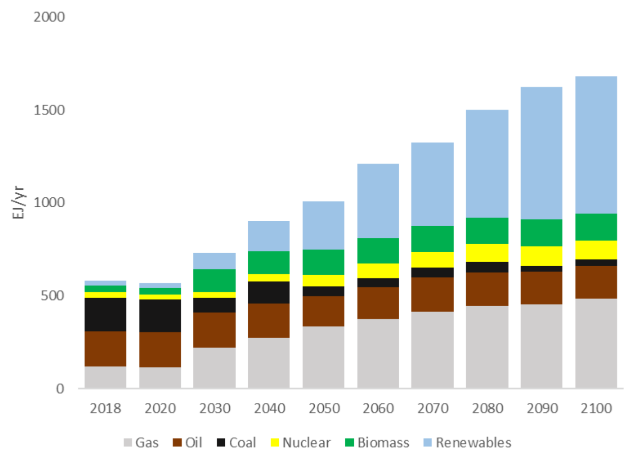


Fig 6. Primary energy supply for the PA no OS scenario

The global electricity generation system in both cases shows a significant increase in the natural gas with carbon capture starting where it amounts to 28.9%, 45% and 47% by 2050 in NDC, PA, and PA no overshoot, respectively. The share continues increasing for the case of NDC at the end of century to reach 60% of the total electricity mix. A drop to 39% is noted in the PA and PA no overshoot scenarios, while the renewables share increases from 33% in 2050 to 48% and 50% in 2100 in PA and PA no overshoot, respectively. Higher electricity production is observed in both PA scenarios denoting the transition to an electrified energy system. These two changes would facilitate SDG7. The Renewables category, in these graphs, incorporates hydroelectricity, solar, geothermal, wind, wave, tidal, and specific methane reduction options from farm-scale digesters that produce both electricity and heat. For the electricity production from BECCS, its share decreases throughout the horizon of the study, starting mid-century for the NDC and earlier (around 2040) for the PA case.

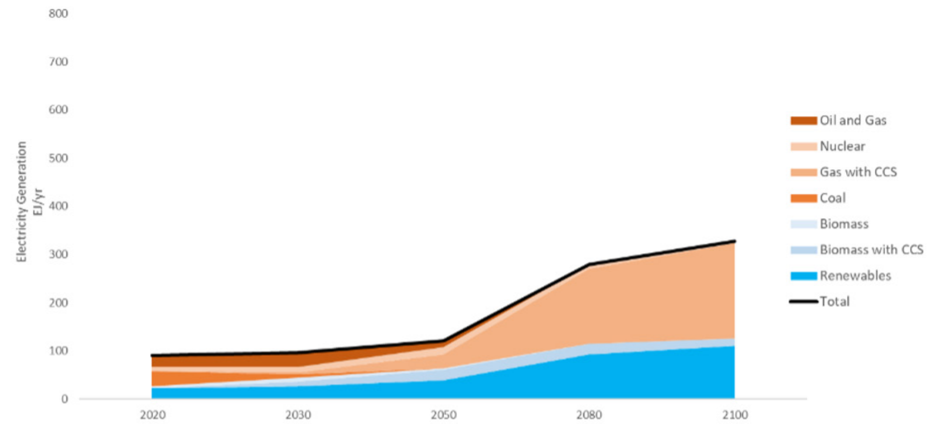


Fig 7. Electricity generation for the NDC scenario

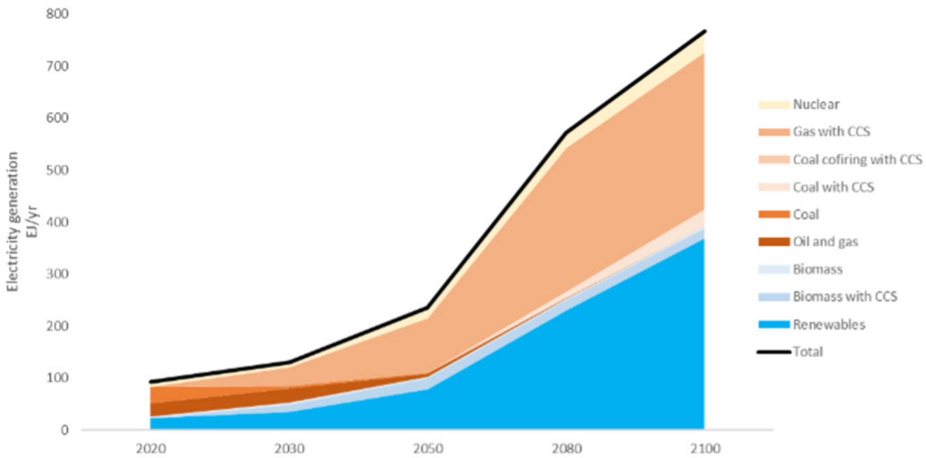


Fig 8. Electricity generation for the PA scenario

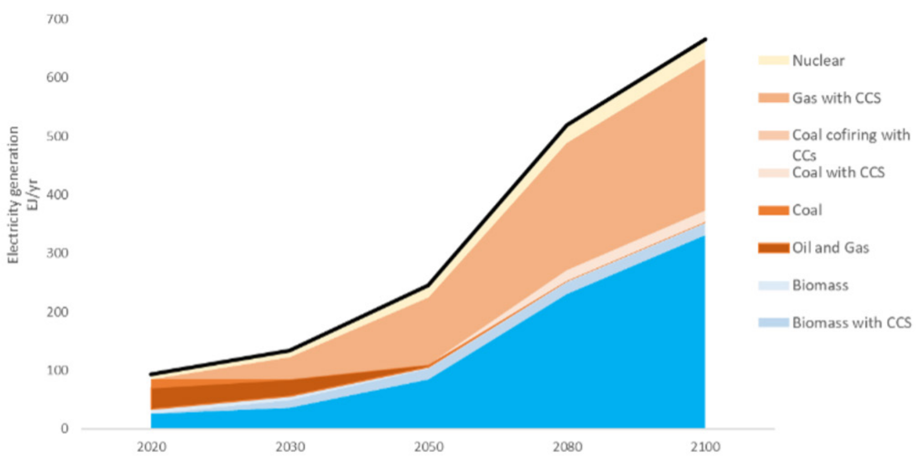


Fig.9. Electricity generation for the PA no overshoot scenario

Across regions, renewable energy has a consistent trend of increasing with PA and PA no OS by 2050. Bioenergy with CCS is a significant part of electricity generation in the USA and Europe (Eastern and Western) under the PA and PA no-OS scenarios (figure 10), which indicates reliance net negative emissions to achieve the climate goals. Natural Gas with CCS shows a reduction in use by 2050, especially in the PA no-OS scenario, which reflects an emphasis on reducing reliance on fossil fuels, even when coupled with CCS.

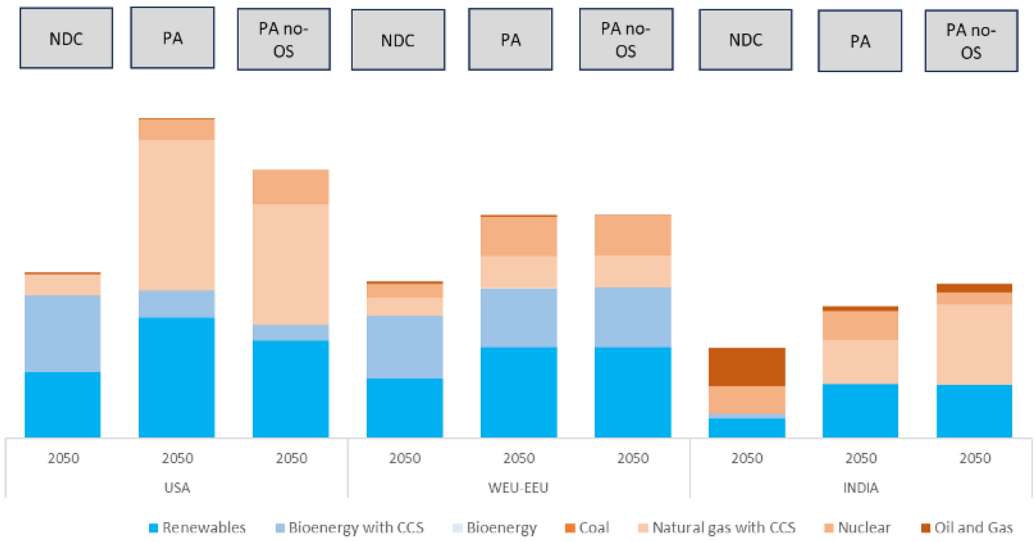


Fig 10. Comparison of the electricity generation mix for USA, Europe and India in 2050 between the NDC and PA scenarios.

3-2 Carbon removal via BECCS is needed for a net zero energy system

Electricity coming from BECCS plays an important role in all scenarios starting 2030. Electricity is generated by bioenergy plants, through direct combustion in NDC, and direct combustion and gasification in PA, using pellets processed from saw industry side stream, agricultural residues (from the agricultural sector and from biocrops) and pellets from forestry biomass. In 2050, 86 EJ, 62.3 EJ and 57 EJ of pellets are used in the NDC, PA, and PA (no overshoot) scenarios, respectively. In the IEA Net Zero Emission (NZE) scenario solid bioenergy, considered as modern i.e using high efficiency conversion technologies often relying on processed biomass such as pellets, accounts for 70 EJ. For the whole bioenergy sector, the land occupation by energy crops reaches its maximum of 47 million ha in 2050 for PA and PA no OS earlier than for NDC (reached in 2060).

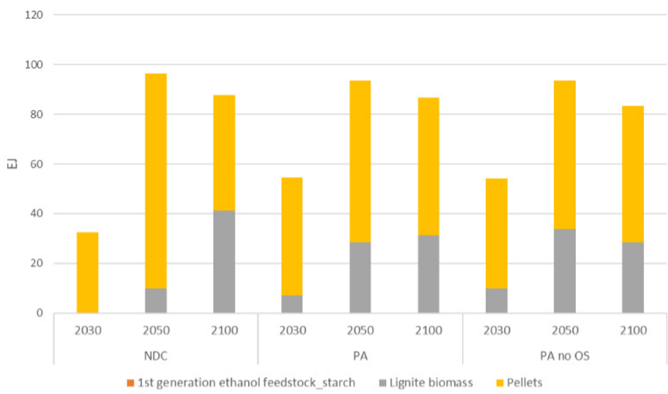


Fig 11. Comparison of the biomass feedstock for BECCS

Some capture is done from the co-firing power plants in the PA scenario. In that case, the biomass is from industrial waste, municipal waste, and other solid biomass (wood, wood and agricultural residues converted to solid biomass). The biodiesel production through fast pyrolysis (and CO2 capture with 91% availability factor) is a 2nd type that uses lignocellulosic biomass transformed from short rotation crops, miscanthus, wood etc. by the appropriate conversion processes modeled in TIAM-FR.

Bioethanol 2nd generation with carbon capture is mostly used in the PA scenarios at the end of century and use wheat straw as input commodity. This leads to a production of 2.7 EJ, 8.5 EJ and 9.3 EJ of ethanol for the NDC, PA and PA no overshoot in 2100.

Fig 12. Carbon capture in the bioenergy sector of TIAM-FR for the "NDC" scenario.

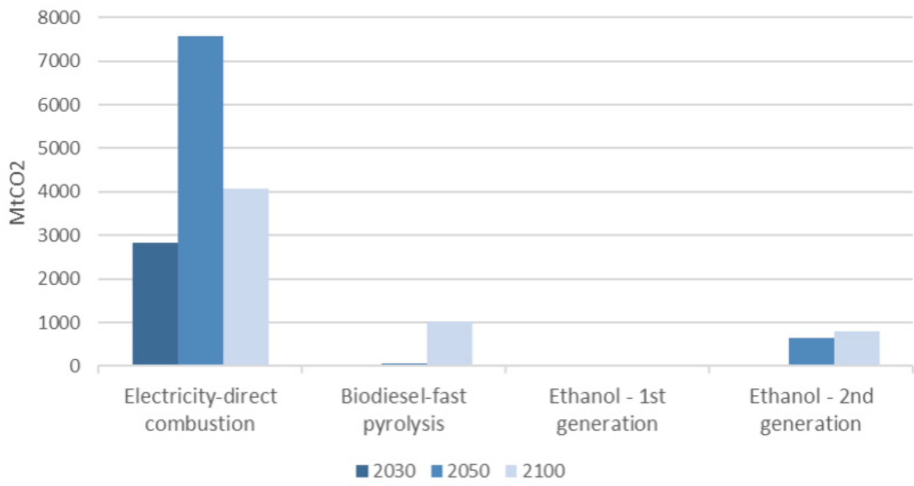
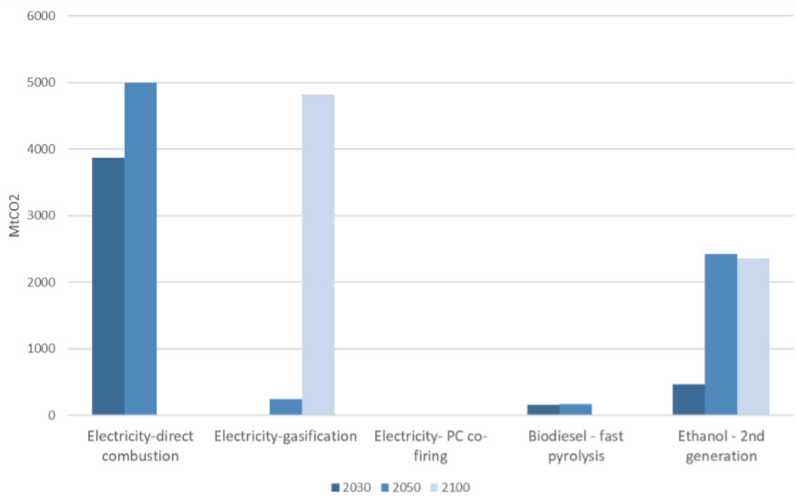


Fig 13. Carbon capture in the bioenergy sector of TIAM-FR for the "PA" scenario.



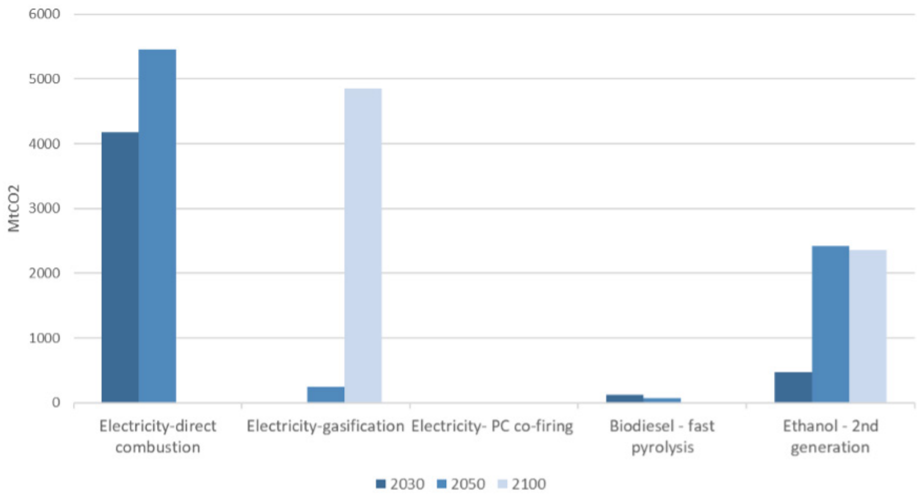


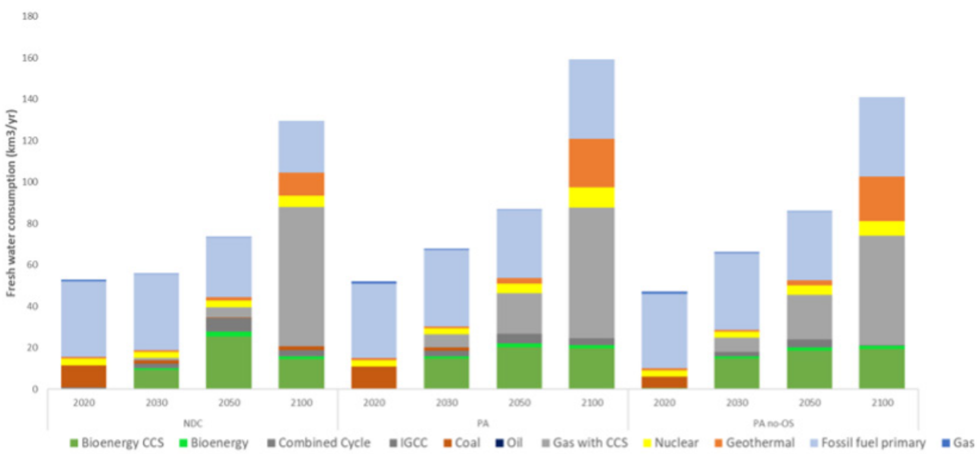
Fig 14. Carbon capture in the bioenergy sector of TIAM-FR for the "PA no OS" scenario.

3-3 Implication of climate policies on Water use

3-3.1 Global overview of Water consumption

The results of the water consumption from electricity generation and fossil fuels extraction (indicated as fossil fuel primary in figure 15) describe an increasing trend and shows that the PA scenario is the most water intensive. This is explained by the acute dependence on negative emissions technologies at the end of the century required to bring down the temperature increase back to 1.5 degrees temperature in 2100. At 2050, water consumption for PA and PA no OS is higher by 13% and 15%, respectively than in NDC scenario. In this scenario, BECCS have a greater share, but have less impact than nuclear and geothermal water consumption in the PA and PA no OS as these scenarios have a more electrified energy supply (figures 7, 8 and 9). Water resources are highly at risk when deploying massive amounts of negative emissions noticed in the PA scenario. It is significantly influenced by gas power plants with CCS demands. In fact, the upstream sector water consumption would reach 25% of the total water consumption in the PA scenario due to natural gas, a large consumer of water in extraction.

Fig 15. Water consumption from the electricity and upstream sectors



3-3.1 Regional focus on water use

The water withdrawal is disparate across regions and its impact depends on the water availability of the region. Regions like the Middle East and India are water scarce. Climate policy imposes more pressure on water resources where the water withdrawals in India increase from 3.5 km3 (NDC) to 4.5 km3 (PA no OS) in 2050 and from 9 km3 (NDC) to 17 km3 (PA no OS) in 2100 for India (figure 16). As for the Middle East, the increase in water withdrawal is the highest in PA no OS in mid-century at 6 km3/yr whereas at the end of century it reaches 10 km3/yr versus 20km3/yr for the PA scenario. However, for Africa water withdrawals drop from 8 km3 in NDC to 5.6km3 and 5.5 km3 in PA and PA no OS, respectively in 2050. In fact, the region is expected to harness its vast and cost-effective renewable energy resources, which would reduce the water use levels within the energy sector. A similar pattern in water withdrawal between the three scenarios is noted for Western Europe whereas an increase in regions like Canda, Russia and Eastern Europe is observed. This is explained by the utilization of CCS with both gas and bioenergy. In contrast to water consumption, water withdrawal is returned to its source, but it imposes constraints on its availability and quality for utilization by other sectors such as agriculture. Water stress indicators rely on the water withdrawal values and water availability [45]. These values can be implemented in the model as constraints and are currently part of an ongoing project.

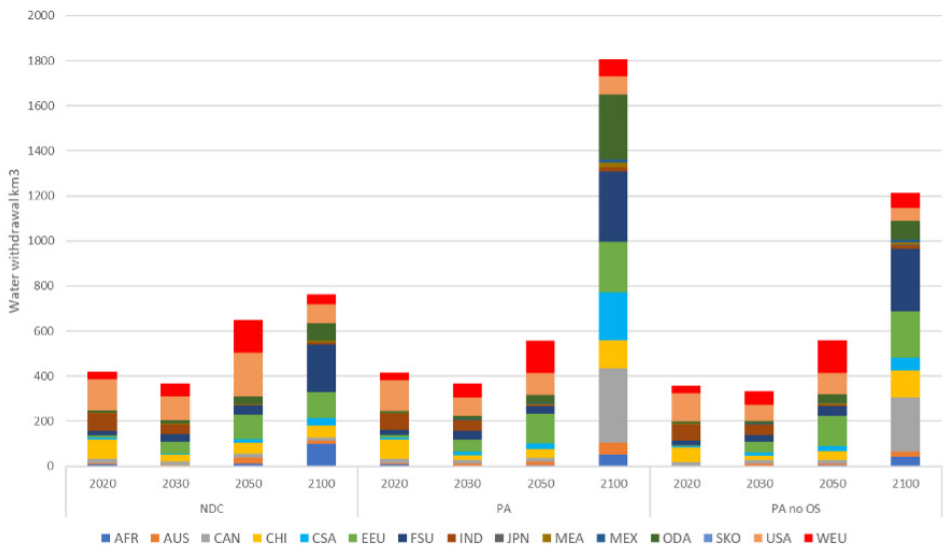


Fig 16. Water withdrawal by region

IV Conclusion and policy implications

The results suggest that the bioenergy sector will provide the opportunity for clean energy access within the scope of SDG7 through electrification but also negative emissions. First, modeling new technologies and using techno-economic optimization in the case of bioenergy and CCS power plants which projects are currently limited, promotes the development of these infrastructure and technologies on a larger scale. Although their deployment for climate change mitigation is indispensable, it must complement renewable energy. In addition to energy security, water availability needs to be integrated in the optimization analyses and policies. This is essential in terms of resource management and considering the energy-water nexus.

Also, optimizing biomass source selection is essential to overcome the challenges of land occupation and degradation issues related to bioenergy. The implemented potential of agricultural residues and residues from forest harvesting and wood processing and biomass from waste is designed to provide modern biomass supply. This is to deal with the trade-offs of BECCS with SDG2, which concerns displacing productive agricultural land dedicated to food production. Also, it reduces the impact of N-fertilizers run-off used in large-scale agriculture that would contaminate drinking water resources (SDG6) and rivers, oceans (SDG14). Nevertheless, all CDR would reduce ocean acidification by removing CO2 [46].

Another important aspect of sustainable bioenergy and land use is the effect on the social aspect. The social dimension of sustainable development is concerned primarily with poverty reduction, social investment, and the establishment of safe and resilient communities. Although these parts are missing in the energy modeling, this study prioritized food availability in applying the "food first" approach when it comes to biomass demand, preventing deforestation and respecting the biomass natural growth in the potential assessment. Social sustainability issues include health and wellness thus respecting the food demand helps prevent such problems. As for economic livelihoods, bioenergy would include job creation, for example in processing and transporting biomass [47]. Nevertheless, regions with larger land availability as mentioned in the scenario description (section 2.4) would have more opportunities than others in switching to bioenergy. This represents a trade-off of this solution. This is also the case for water where arid and semi-arid regions are faced with the climate change mitigation challenge and human rights in water access (SDG6) and food security (SDG2). The above analysis on synergies and trade-offs has significant policy implications. They suggest that clear guidelines related to the conservation of land, water and energy need to be established so that climate actions do not affect socioeconomic growth or lead to the loss of valuable ecosystems. Here comes the role of regulations and governance in the land sector to ensure the sustainable cultivation and harvesting of biomass with an emphasis on protecting natural habitats and biodiversity. For instance, the cultivation of bioenergy crops could be focused on degraded or marginal lands to avoid competition with food production and preserve natural habitats, supporting SDG15 [48]. Other carbon removal options like afforestation/reforestation have similar issues when it comes to land use hence DACCS present an opportunity with smaller land occupation. Potential impact on land use would be perceived in natural gas pipelines for energy supply [46].

For water use, climate policy in line with the Paris agreement (SDG13) leads to higher water consumption in the energy sector. This variation is noted especially in systems that transition from using fossil fuels to electrified systems. This is the case of the USA and Europe (Eastern and Western Europe) which switch towards renewables and gas with carbon capture power plants as well as BECCS and some coal with CCS for the case of Europe at the end of the century. With the implementation of the NDCs, the situation of water use would be less critical than a Paris Agreement scenario for some regions like the case of the Middle East and India. It represents one trade-off that countries need to evaluate in their climate actions. Moreover, the study highlighted the relation between water use and the carbon capture method and technology i.e post combustion vs oxy combustion, absorption, and adsorption respectively. The impact of these options is substantial in terms of water use when delaying climate change mitigation till the end of the century. Investments and sustainability measures related to climate action would strengthen the remaining pillars of sustainable development. Furthermore, the choice of the capture technology can consider environmental parameters like in [49] Specifically parameters like acidification potential can be used to assess the amount of acid pollutants deposited in water, soil, and organisms, and Global Warming Potential to indicate the amount of CO2 released into the atmosphere. However, water related analysis remains limited in IAMs due to the regional disaggregation and on-ground effect.

For example, the water scarcity in Northern Africa is high compared to the south which are both aggregated in one region in TIAM-FR. Also, according to [50], reduction in water abstraction attained 15% in Europe between 2000 and 2019 but did not show any overall reduction in the area affected by water scarcity conditions.

Mitigating climate change necessitates significant measures aimed at reducing greenhouse gas emissions to limit global warming within the 1.5°C threshold. Despite the ambitious nature of this goal, its attainment appears challenging given the current commitments outlined in Nationally Determined Contributions (NDCs) and the governance that needs understanding to support the global goal. The integration of Sustainable Development has become crucial to ensure the effectiveness of mitigation policies and actions like CDR deployment. This alignment aims to preserve various resources like land and water and requires studying the interlinkages with the water-energy-land nexus considering the environment. In fact, one of the main conclusions was that this aligns with the SDGs and that ratcheting mitigation imposes further pressures on the environment and society.

In this study bioenergy emerged as one of the important drivers of realizing the transition to a low-emission energy sector with BECCS and biofuel. The modeling approaches allowed the integration of sustainability constraints on biomass. Still, the exploitable potential of biomass for BECCS, technologies, CO2 transport and storage, BECCS costs require transparency especially for stakeholders outside the IAM community [51]. The analysis of updated emission reduction targets and Paris Agreement scenarios suggests a shift towards using second-generation biofuels with a low water footprint. While carbon capture becomes imperative for power generation, it introduces challenges by increasing pressure on water supplies. Scarce water availability poses a significant constraint on energy production through water withdrawals, impacting various users and sectors. Further development on TIAM-FR is to include the land system represented by a land use model GLOBIOM [52] which allows for a more comprehensive evaluation emissions and sinks from the land sector linked to energy, encompassing additional considerations like water for irrigation.

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Data and code availability

The TIMES code is available at IEA-ETSAP GitHub (https://github. com/etsap-TIMES/TIMES_model) as open-source. A supplementary material file is provided containing the technologies representing the biomass and bioenergy in the model. It also includes their techno-economic parameters. Other information or data is available upon request.

References

[1] Masood E. Bucking the system: the extraordinary story of how the SDGs came to be. Nature 2023;621:247–8. https://doi.org/10.1038/d41586-023-02807-y.

[2] Brusseau ML. Chapter 32 - Sustainable Development and Other Solutions to Pollution and Global Change. In: Brusseau ML, Pepper IL, Gerba CP, editors. Environmental and Pollution Science (Third Edition), Academic Press; 2019, p. 585–603. https://doi.org/10.1016/B978-0-12-814719-1.00032-X.

[3] 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.

[4] Panos E, Glynn J, Kypreos S, Lehtilä A, Yue X, Ó Gallachóir B, et al. Deep decarbonisation pathways of the energy system in times of unprecedented uncertainty in the energy sector. Energy Policy 2023;180:113642. https://doi.org/10.1016/j.enpol.2023.113642.

[5] 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).

[6] Riahi K, Bertram C, Huppmann D, Rogelj J, Bosetti V, Cabardos A-M, et al. Cost and attainability of meeting stringent climate targets without overshoot. Nat Clim Chang 2021;11:1063–9. https://doi.org/10.1038/s41558-021-01215-2.

[7] Kang S. La place de la bioénergie dans un monde sobre en carbone : Analyse prospective et développement de la filière biomasse dans le modèle TIAM-FR. phdthesis. Université Paris sciences et lettres, 2017.

[8] Machhirake NP, Vanapalli KR, Kumar S, Mohanty B. Biohydrogen from waste feedstocks: An energy opportunity for decarbonization in developing countries. Environmental Research 2024;252:119028. https://doi.org/10.1016/j.envres.2024.119028.

[9] Awais M, Vinca A, Byers E, Fricko O, Frank S, Krey V, et al. Leveraging Integrated Assessment Models to access climate feedbacks on Water, Energy, and Land Systems: An Evaluation of Regional and Sectoral Transformations for Achieving the Sustainable Development Goals Copernicus Meetings; 2023. https://doi.org/10.5194/egusphere-egu23-16585.

[10] Naing PM, Babel MS, Karthe D, Stamm J. Analysis of the water-energy-carbon nexus for sustainable development of the selected industries. Sustainable Development n.d.;n/a. https://doi.org/10.1002/sd.2994.
[11] Global CCS Institute. Water Use in Thermal Power Plants equipped with CO2 capture systems 2016.
[12] Wang J, Yu Z, Zeng X, Wang Y, Li K, Deng S. Water-energy-carbon nexus: A life cycle assessment of post-combustion carbon capture technology from power plant level. Journal of Cleaner Production 2021;312:127727. https://doi.org/10.1016/j.jclepro.2021.127727.
[13] Wang P, Huang R, Zhang S, Liu X. Pathways of carbon emissions reduction under the water-energy constraint: A case study of Beijing in China. Energy Policy 2023;173:113343. https://doi.org/10.1016/j.enpol.2022.113343.
[14] Licandeo F, Flores F, Feijoo F. Assessing the impacts of economy-wide emissions policies in the water, energy, and land systems considering water scarcity scenarios. Applied Energy 2023;342:121115. https://doi.org/10.1016/j.apenergy.2023.121115.
[15] Liu G, Du S, Gao Y, Xiong X, Lombardi GV, Meng F, et al. A study on energy-water-food-carbon nexus in typical Chinese northern rural households. Energy Policy 2024;188:114100. https://doi.org/10.1016/j.enpol.2024.114100.
[16] Chu B, Lin B, Tian L, Zheng C, Ye N, Zhu Y, et al. A long-term impact assessment of carbon capture (storage) investment conducted by conventional power company on sustainable development. Applied Energy 2024;358:122567. https://doi.org/10.1016/j.apenergy.2023.122567.
[17] Loulou R, Labriet M. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. CMS 2008;5:7–40. https://doi.org/10.1007/s10287-007-0046-z.
[18] Fischer G. Global Agro-Ecological Zones v4 – Model documentation. Rome, Italy: FAO; 2021. https://doi.org/10.4060/cb4744en.
[19] Alexandratos N, Bruinsma J. World Agriculture Towards 2030/2050: The 2012 Revision. 2012.
[20] United Nations. World Population Prospects - Population Division - 2022. https://population.un.org/wpp/ (accessed January 24, 2024).
[21] FAO. FRA 2015 | Global Forest Resources Assessments 2015. https://www.fao.org/forest-resources-assessment/past-assessments/fra-2015/en/ (accessed January 24, 2024).
[22] Pérez-Soba M, Petit S, Jones L, Bertrand N, Briquel V, Omodei-Zorini L, et al. Land use functions — a multifunctionality approach to assess the impact of land use changes on land use sustainability. In: Helming K, Pérez-Soba M, Tabbush P, editors. Sustainability Impact Assessment of Land Use Changes, Berlin, Heidelberg: Springer; 2008, p. 375–404. https://doi.org/10.1007/978-3-540-78648-1_19.
[23] Erb K-H, Haberl H, Krausmann F, Lauk C, Plutzar C, Steinberger J, et al. Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely – a scoping study 2009.
[24] 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.
[25] Kang S, Selosse S, Maïzi N. Methodological long-term analysis of global bioenergy potential. report. Chaire Modélisation prospective au service du développement durable, 2016.

[26] Buongiorno J, Zhu S, Raunikar R, Prestemon JP. Outlook to 2060 for world forests and forest industries: a technical document supporting the Forest Service 2010 RPA assessment. Gen Tech Rep SRS-151 Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station 119 p 2012;151:1–119. https://doi.org/10.2737/SRS-GTR-151.
[27] 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.
[28] IEA. World Energy Balances - Data product. IEA 2020. https://www.iea.org/data-and-statistics/data-product/world-energy-balances (accessed February 12, 2024).
[29] IEA. WEO-2016 Special Report: Water-Energy Nexus – Analysis. IEA 2017. https://www.iea.org/reports/water-energy-nexus (accessed January 23, 2024).
[30] 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.
[31] thompson luke. Cooling Tower Fundamentals. SPX Cooling Technologies 2019. https://spxcooling.com/library/cooling-tower-fundamentals/ (accessed January 22, 2024).
[32] Rosa L, Sanchez DL, Realmonte G, Baldocchi D, D'Odorico P. The water footprint of carbon capture and storage technologies. Renewable and Sustainable Energy Reviews 2021;138:110511. https://doi.org/10.1016/j.rser.2020.110511.
[33] IEAGHG. Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS 2017. https://ieaghg.org/component/content/article/49-publications/technical-reports/784-2017-02-smr-based-h2-plant-with-ccs (accessed January 23, 2024).
[34] Global CCS Institute. Global Cost of Carbon captue and storage 2017.
[35] Williams NJ, Custelcean R. CO2 Capture Going BIG. Carbon Capture Journal 2019;68.
[36] National Academy of Sciences NA of. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press; 2019. https://doi.org/10.17226/25259.
[37] UNFCCC. Greenhouse Gas Inventory Data - Time Series - Annex I 2021. https://di.unfccc.int/time_series (accessed May 20, 2022).
[38] 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).
[39] IPCC. All NDCs 2022. https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx (accessed January 23, 2022).
[40] den Elzen M, Dafnomilis I, van Soest H. The PBL Climate Pledge NDC tool. The PBL Climate Pledge NDC Tool 2021. https://themasites.pbl.nl/o/climate-ndc-policies-tool/ (accessed February 1, 2023).
[41] 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).
[42] UN Environment. Emissions Gap Report 2022. UNEP - UN Environment Programme 2022. http://www.unep.org/resources/emissions-gap-report-2022 (accessed November 2, 2022).

[43] Tandon A. Avoiding temperature 'overshoot' reduces multiple climate change risks, say scientists. Carbon Brief 2021. https://www.carbonbrief.org/avoiding-temperature-overshoot-reduces-multiple-climate-change-risks-say-scientists/ (accessed February 15, 2024).
[44] IIASA. MAGICC: A reduced complexity Earth system model. IIASA - International Institute for Applied Systems Analysis n.d. https://iiasa.ac.at/models-tools-data/magicc-reduced-complexity-earth-system-model (accessed February 19, 2024).
[45] UN Water. Progress on Level of Water Stress – 2021 Update. UN-Water 2021. https://www.unwater.org/publications/progress-level-water-stress-2021-update (accessed January 29, 2024).
[46] Fuhrman J, McJeon H, Doney SC, Shobe W, Clarens AF. From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better. Frontiers in Climate 2019;1:11. https://doi.org/10.3389/fclim.2019.00011.
[47] Press Release – How bioenergy contributes to a sustainable future – Bioenergy n.d. https://www.ieabioenergy.com/blog/publications/press-release-how-bioenergy-contributes-to-a-sustainable-future/ (accessed July 31, 2024).
[48] Vera I, Wicke B, Lamers P, Cowie A, Repo A, Heukels B, et al. Land use for bioenergy: Synergies and trade-offs between sustainable development goals. Renewable and Sustainable Energy Reviews 2022;161:112409. https://doi.org/10.1016/j.rser.2022.112409.
[49] Yagmur Goren A, Erdemir D, Dincer I. Comprehensive review and assessment of carbon capturing methods and technologies: An environmental research. Environmental Research 2024;240:117503. https://doi.org/10.1016/j.envres.2023.117503.
[50] EEA. Water scarcity conditions in Europe (Water exploitation index plus) 2023. https://www.eea.europa.eu/en/analysis/indicators/use-of-freshwater-resources-in-europe-1 (accessed January 29, 2024).
[51] Butnar I, Li P-H, Strachan N, Pereira JP, Gambhir A, Smith P. A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise. Environ Res Lett 2020;15:084008. https://doi.org/10.1088/1748-9326/ab5c3e.
[52] Integrated Biospheres, Futures, International Institute for Applied Systems Analysis (IBF-IIASA). Global Biosphere-ManagementModel (GLOBIOM) Documentation 2023- Version 1.0 2023.
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Les cahiers de la Chaire

Climate actions effects on ressource sustainability in a carbon constrained world

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Working paper