Observational Article

Climate change challenges and state fragility in the water, energy, food/land, raw material nexus and the position of hydrogen and Carbon Capture Utilisation and Storage for increasing resilience

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Abstract: Over the last decade, Europe has experienced a sharp increase in infrastructure expenditure due to the severe and frequent natural phenomena related to climate change. Local consequences, such as habitat destruction, finite freshwater availability and food scarcity exert significant pressure on the available ecological space. Therefore, there is a growing interest in assessing risks and vulnerabilities to climate change, which has already led to a wide range of impacts on environmental systems and society, including destabilising security. Increased environmental, social, and financial damage costs are expected in the future. Many of these imminent or ongoing challenges are related to the overexploitation of resources and the energy transition, requiring a more holistic approach to encouraging new technologies, that involves a whole-of-society approach and stakeholder participation. State-of-the-art CCUS and hydrogen energy technologies, offer sustainable solutions to mitigate the current situation, allowing a reduction in carbon emissions, a transition towards a low-carbon economy, and an increased overall resilience of the international community to climate change.

Keywords: water food energy nexus, hydrogen, CCUS, climate change, sustainability, resilience, raw materials, SDGs, CCS, stakeholders

1. Introduction

Climate change is one of the most pressing issues of our time. Its impact on the water, energy, food/land, and raw material nexus is immense, and the fragility that imposes is of significant concern. Rising temperatures, changing precipitation patterns, and more frequent and severe weather events can affect the availability and distribution of water, disrupt energy production and distribution, and negatively impact agriculture and food security. These impacts can exacerbate existing vulnerabilities and lead to political and social instability. Developing countries face increased poverty and inequality, a fragility that makes it even more challenging to develop adaptation and mitigation measures.

The transition from using fossil fuels to renewable energy sources has increased demands for water (hydropower), land (which requires 50 times more space than coal and 90 - 100 times more space than gas), and critical raw materials [1]. Increased temperatures have resulted in habitat destruction, acidification, and massive runoff of nutrients into the water. Past research [2] has shown that global warming has increased the oligotrophic ocean waters by 6.6 million km². Freshwater systems are even more vulnerable to climate change due to their isolation and physical fragmentation within the terrestrial landscape but, more importantly, to unsustainable human exploitation practices.

Changes in climate and precipitation patterns influence natural forests, agriculture, and food security. Droughts, for instance, increase the vulnerability of forests to wildfires and decrease arable land, which can force conversion of forests into agricultural land. This process emits substantial amounts of greenhouse gases and further contributes to global warming. Agriculture, forestry and other land use accounted for 24 % of the total anthropogenic emissions in 2010 [2]. This increases competition for natural resources while decreasing livelihood security.

The net result is a synergetic spiral degradation effect with fewer forests, reduced biodiversity and further deterioration of ecosystems and their services, with the danger of the spiral becoming self-perpetuated until the potential of deterioration is fully exhausted (Figure 1).

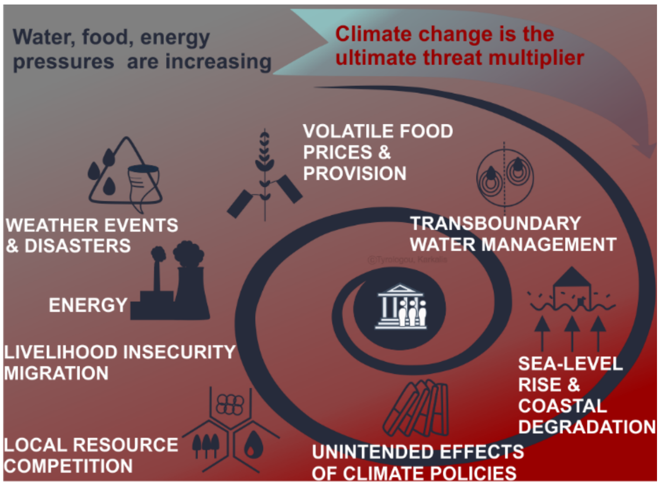

Figure 1: Water-food-energy synergetic degradation spiral, adapted from Wolfmaier et al. 2019 [3].

Adding to the equation of natural hazards (floods/droughts) as a direct consequence of climate change, the average annual economic losses in Europe are forecasted to be around €23.5 billion by 2050, compared to the €4.6 billion for the period of 2000 - 2012 [2]. The conditions have not been ameliorated. The consequences on environmental and social stability are expected to be vast and long-term.

Past research on how interactions between biophysical effects and climate change impact the water, energy, food/land, raw material nexus, including the social dimension, is limited due to insufficient relevant quantitative models. Additionally, the focus on socio-economic assessments linked to climate change in most countries is restricted to national boundaries without considering transnational issues. Consequently, any available results only address higher-order socio-economic impacts. International policy frameworks developed by the Paris Agreement, the United Nations Sustainable Development Goals (SDGs), and the Sendai Framework for Disaster Risk Reduction, highlight the importance of quantitative indicators and consider the approaches developed by stakeholders, as alternative or complementary measures to assessing vulnerability to climate change. Stakeholder engagement, through more collaborative and consultative approaches, requires meaningful participation of relevant stakeholders throughout the design, development and operational phases of projects. The benefits of public participation, particularly from communities that are directly and indirectly affected by the project, will strengthen both the design (by considering extraneous factors that might not be obvious to the technical teams) and the operational sustainability of the final product, given the community's ownership, ease of use, and added benefits.

This more participative approach ensures that adaptation actions devised today are robust for future biophysical determinants acting upon current social determinants. Carbon Capture Utilisation and Storage (CCUS) integration with hydrogen-related technologies can be part of a defensive solution against the climate change occurred by uncontrolled greenhouse emissions. Proper design of such methods can lead to social acceptance and financial maintenance while increasing resilience. A transition energy period of producing blue hydrogen with the use of CCUS can be replaced ultimately with green hydrogen, where geological hydrogen storage can be facilitated by deploying captured CO_2 as a cushion gas [4-6]. In addition, injection of captured CO_2 in ophiolites can induce serpentinisation to provide "orange hydrogen" [7]. The process significantly impacts the sustainable use of raw materials, energy and water. It removes volatility and brings energy security and socio-economic stability while delivering a mitigation/adaptation solution for climate change. Even in the transportation sector, which is hard to decarbonise, the production of e-fuels from green hydrogen and CO_2 captured from biomass energy, can contribute significantly to the sustainability of that particular sector. It is argued that during the early stages of a hydrogen economy, hydrogen will need to be mixed with CO_2 to produce methane or methanol to facilitate the transportation of vast amounts of hydrogen through the existing network of natural gas pipelines [8-10].

2. Challenges and impacts of the energy transition in response to climate change

To mitigate the effects of climate change and remain below the 1.5 °C scenario, the challenge [11] is to adapt society and businesses to ensure economic prosperity and sustainability. Rapid decarbonisation of the global economy is part of the solution [12]. The goal of a net-zero emissions energy system and the economic needs will merge the available technologies and solutions with new options that should gradually replace the older and (un)sustainable ones in the overarching rationale of the energy transition. This transition will be disruptive and must consider the inter-competitiveness and interconnections of the food, water and raw materials industries to ensure the integrity of the ecosystem. In addition, for any 'disruptive' transition to occur with the support of society, the process of introduction needs to be inclusive and transparent (per the SDGs), so that as many people as possible (including governments) understand why the adoption of these technologies is needed, and to encourage ownership of new technologies in the local communities. Technology alone will not provide the solution without widespread systems for encouraging adoption. A brief exploration of the inter-competitiveness is given below.

Climate change, may cause floods in some areas and droughts in others. The latter can cause an increase in the consumption of any available surface water and the over-extraction of groundwater for potable and agricultural reasons. Groundwater extraction is closely coupled with energy consumption, which is required to bring water to the surface. As shallow aquifers become exhausted, deep aquifers will be exploited, further increasing the energy demand particularly in places where water and energy supplies are limited. Thus, creating an endless cycle failing to solve the problem of sustainable resource use. Figure 2 depicts the global freshwater use over the last 113 years [13], with steep increases after 1950. This trend is closely linked with global population growth [14] and, subsequently, food production.

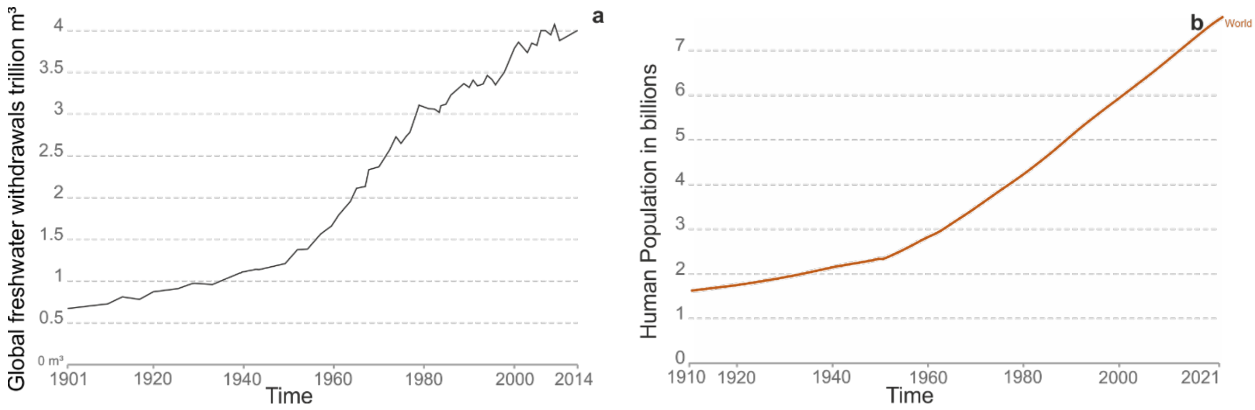

Figure 2 : a) Global freshwater withdrawals for agriculture, industry and domestic use since 1900, measured in cubic metres (m^3) per year [13], sourced: https://ourworldindata.org/water-use-stress, Global International Geosphere-Biosphere Programme (IGB), **b)** Population growth from 1910 to 2021 [14], CC BY

Food production, an absolute necessity to avoid famine, consumes between 70 - 90% of available water resources [15,16]. Figure 3 provides data on food production against water demands. The production of one kg of cheese requires an astonishing volume of 5605 litres of freshwater and one kg of tomatoes needs 370 litres of water [14]. In both cases, the water must be transported or withdrawn from underground reservoirs which, in turn, consumes energy. Furthermore, producing 100g of cheese emits 10 kg CO_2eq, whereas, for one kg of tomatoes, the respective emission is estimated at 2 kg CO_2eq [15,17]. The drive to lower agricultural costs, is leading to the adoption of super-intensive agriculture of high value products, such as avocados or cotton, with much higher level of water consumption and soil exhaustion than traditional agriculture practices.

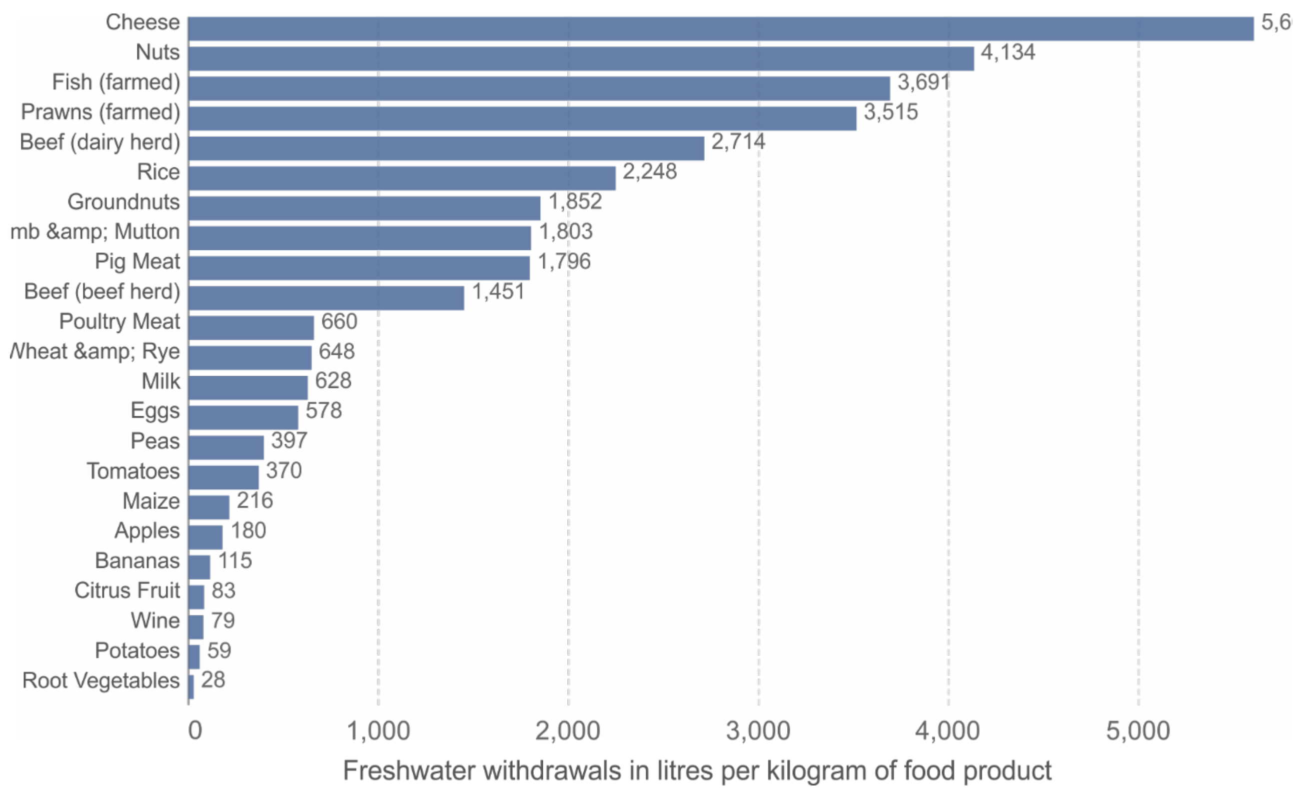

Figure 3: Freshwater withdrawals per kilogram of food product, adopted from Poore, J., & Nemecek, T. (2018) [15] and sourced from https://ourworldindata.org/grapher/water-withdrawals-per-kg-poore, CC BY.

Importing food to alleviate water shortages transfers the problem elsewhere, as demonstrated by the concept of virtual water [15], i.e. the hidden flow of water in food or other commodities traded from one place to another [16,18]. Food imports can make things worse for countries whose economies are agricultural-based and dependent on food export. Big economies with strong currencies can afford to import large quantities of food from poorer countries, thus depriving the latter of essential food resources and forcing them into energy and water overconsumption. The aforementioned challenge directly makes developing countries poorer and deprives them of resources available for economic development [18] . This over-exploitation can have a detrimental effect on local societies where water is scarce, especially in Asia, Africa, and South America. Under the compound influence of climate change and regional conflicts, affected inhabitants migrate to wealthier nations [19] which are part of the problem and see these immigrants as a social disturbance [20,21].

Society needs to invest heavily in using renewable energy to cover increasing demands for energy and move into a zero-emissions and later, negative emission era. This requires the exploitation of an unprecedented amount of raw materials that the world has ever seen [22] to build the necessary infrastructure and equipment [23-27] . For instance, solar panels for photovoltaic power require up to 40 times more copper than fossil fuel combustion, and wind turbines for harvesting wind power require up to 14 times more iron [28]. More importantly, mining requires fresh water to extract metals and minerals [24]. Thus, large-scale mining will require huge amounts of energy and water, which, as mentioned above, will become scarce due to climate change. The latter will strongly influence and erode the social acceptance of companies involved in mining [29].

In many developed regions, including Europe, mining is not socially acceptable under the "Not in My Back Yard" perception [24,30,31]. Most European needs for critical raw materials for renewable energy infrastructure and batteries are covered by imports from Africa and Asia [32]. Similarly, raw materials follow the same trend as the paradigm presented above on food imports, critical or not. They are imported from developing countries in exchange for hard currency. However, this practice leads to loss of opportunity for development, creating regional competition for available energy, food, water, and raw material resources. Climate change, further enlarges this competition, creating instability, social unrest and violent local conflicts [19,33]. Current research strongly indicates that rising food prices, due to climate change, have acted as catalysts for protests and political unrest [19]. With temperatures rising, the impacts of climate change will further destabilise already unstable areas [19]. Raw materials mining and renewable energy both require large surface areas, competing with the demand on land for food production or grazing. Additionally, arable land is decreasing, also under the influence of climate change [34]. To make things even more complex, agriculture, forestry, and changes in land use contribute to climate change by emitting 19.9 $GtCO_2eq$, while nitrogen fertiliser production, with the current technology, accounts for a further 0.4 $GtCO_2eq$ of emissions [35]. At the same time, it increases the dangerous dependency of developed regions on vital resources produced elsewhere. This dependency can become an economic weapon used by autocratic regimes, as recently demonstrated during the eruption of a full-fledged war in Ukraine.

Furthermore, new solutions proposed to meet the energy demands must consider potential conflicts with other economic sectors, such as agriculture. For instance, it is proposed that ammonia can be used as an alternative fuel as it is easy to transport and store compared other forms of hydrogen [36]. However, so far, the potential of ammonia as a fuel has not been adequately evaluated against any potential competing needs, such as its use as a fertiliser.

If our society replaces current fossil fuels with ammonia, the amounts required to fulfil our energy needs will be vast. Without a structured approach, such a transition will directly compete with the demands of the fertiliser industry. With an increasing human population [14], the need for food increases; thus, the required quantities of fertilizer will rise, as shown in Figure 4. Furthermore, ammonia is deployed in various industrial activities, such as cotton softening and synthetic fibres [37]. Notably, it is estimated that every kilogram of hydrogen produced from electrolysis requires 9 kg of water [38]. This is typically fresh water, as it is cheaper to clean and deionise. However, it should also be noted that conventional thermal power plants account for 41 % of all freshwater withdrawals in the USA [38].

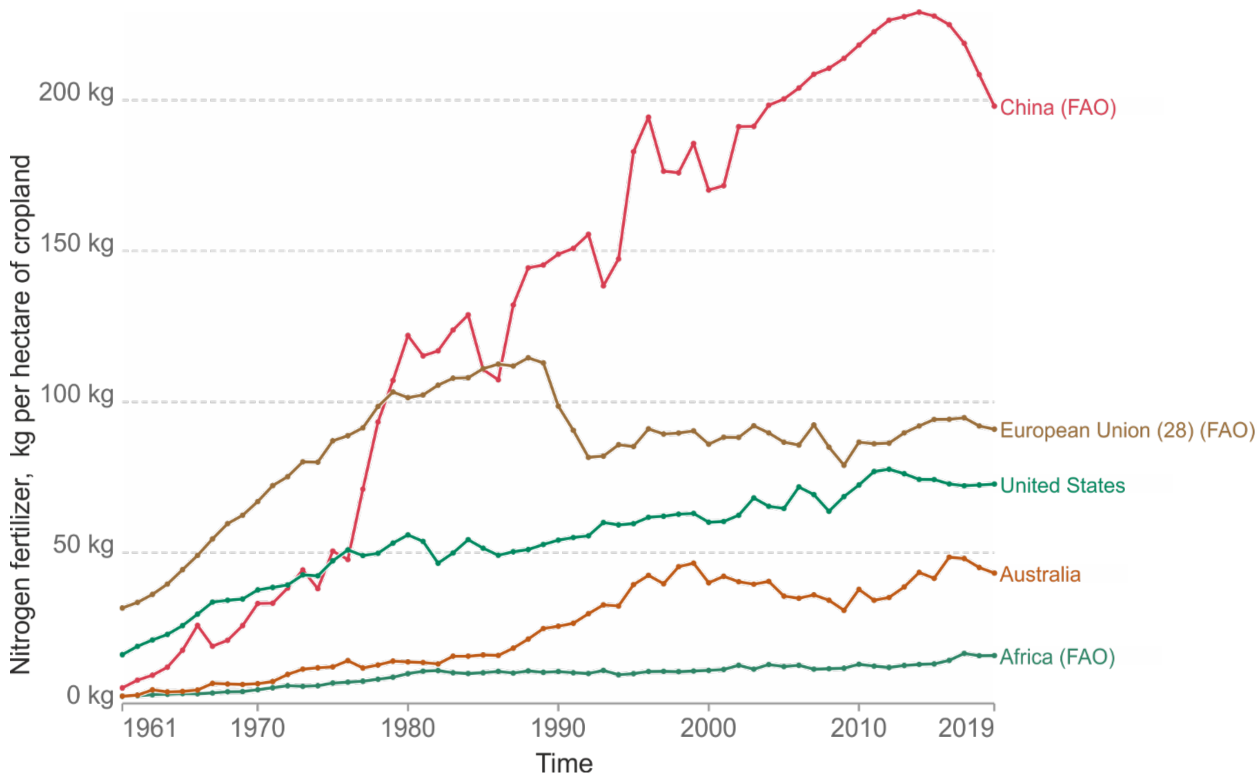

Figure 4: Application of nitrogen fertiliser, measured in kilograms of total nutrient per hectare of cropland, source: Food and Agriculture Organization of the United Nations [39], CC BY.

There is progress from the scientific community in understanding the processes described above and their interconnections, which affect our society. This is partially driven by the SDGs [40-43] and the Paris Agreement, which aims to reduce CO_2 emissions by 60 % [44]. A circular economy, together with capturing emissions technology from existing industrial and power generation processes combined with developing new clean energy sources can facilitate an emissions reduction pathway. Thus, one way to increase resilience to climate change and its effects is to increase the use of natural hydrogen, green hydrogen, and CCUS technologies.

These processes, elaborated further below, can achieve a non-disruptive energy transition while increasing sustainability and resilience, and minimising conflicts [45].

3. Opportunities, proposed solutions and mitigation measures of CCUS and hydrogen

To sustain the quality of life that has been achieved, a new era of energy consumption based on renewable energy is needed. To achieve this, an energy transition is required without compromising development. Current practices of energy conversion can be coupled with carbon capture, which can be (immediately) (re) utilised or stored.

3.1. CCUS - The steps to decarbonisation and net zero emissions

Carbon capture, utilisation, and storage (CCUS) is a technology that involves the capture of carbon dioxide (CO_2) emissions from industrial processes, such as power generation and manufacturing, pipelines for transportation, utilisation sites, and finally injecting the surplus into secure geological reservoirs. The technology helps reduce emissions by preventing CO_2 from entering the atmosphere, thus reducing the impacts of climate change. Deployment of CCUS allows for the current use of fossil fuels for energy conversion with no emissions. It offers the potential for a structured non-disruptive energy transition to renewable energy using current technologies and fossil fuels. The technologies used for CO_2 capture include chemical looping combustion, pre-combustion capture, and post-combustion capture. After being captured, CO_2 can be transformed into various goods and services, including fuels, chemicals, building materials made from waste or minerals, and CO_2 that increases the productivity of biological processes [46]. In addition, geological media can potentially store large quantities of CO_2 in deep saline aquifers, salt caverns, coal seams, abandoned coal mines and depleted hydrocarbon fields. CO_2-mineralisation is an additional option for CO_2-storage that involves the chemical reaction of several rock-types (such as basalts, sandstones and serpentinites) with supercritical CO_2. The same utilization and storage principles can be used for CO_2 from direct air capture (DAC), however, at the moment of writing, this technology is significantly more expensive. The process results in CO_2 sequestration by the formation of carbonate minerals and, under the right conditions, releases hydrogen [7]. This process will be explained further below. The potential uses of CO_2 are vast, with the possibility being converted into e-fuels, chemicals, polymers or applied as aggregates, in new types of cement, or in CO_2-cured concrete through a range of mineralisation techniques. Even direct uses of CO_2 has seen a boost in research, be it in the utilisation for greenhouses, algae growth, or as a heat transfer fluid in enhanced geothermal systems or supercritical power systems [47].

3.2 Reducing the footprint of hydrogen production through CCUS and transitioning to lower emission energy sources

Hydrogen can be burned in turbines or used in fuel cells to generate electricity. It can also be used in fuel cells to power electric vehicles, as a source of domestic and industrial heat, and as a feedstock for industrial processes [48]. Currently, hydrogen is produced using hydrocarbon reforming methods (primarily SMR) with associated CO_2 emissions on the scale of 10-20 tons per ton of H_2 produced (often referred to as "grey" hydrogen). The annual hydrogen production is 120Mt, with only 1% utilising CCUS technologies [48].

CCUS and hydrogen have become increasingly intertwined as a part of the world's efforts to reduce carbon emissions and move towards a low-carbon economy. Low footprint hydrogen production may be achieved by producing hydrogen a) from water electrolysis, b) from natural gas by separating hydrogen from CO_2 through Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR) and c) from coal gasification. Each method, must always be coupled with CCUS [21,48], which captures the CO_2 instead of emitting it into the atmosphere. The overall reduction of associated emissions could be on a scale of 5-10 times of the current reforming methods.

The Hydrogen Council estimates that demand for hydrogen could exceed 530 Mtpa by 2050. To meet this demand, an increase in productivity is a pre-requisite, and hydrogen produced with the aid of CCUS will be essential, at least in the first years [48], when renewable energy is still penetrating the market on a large scale. Current hydrogen production costs using SMR and CCS are reported to be around \$2/kg [48] benefiting from the advantage of existing infrastructure and assets, making it less expensive than alternative energy sources in the short term. Thus, these production methods may serve as a transitional energy source to achieve climate goals at a reasonable cost without compromising energy diversity and the objective of a low-carbon economy [21], leading to wide-spread usage of renewable energy.

3.3 Hydrogen from renewable energy sources

Hydrogen produced from renewable energy sources such as solar, wind, and hydropower (or "green" hydrogen) offers a further footprint reduction compared to traditional SMR. Electrolysers convert excess electrical energy into chemical energy in the form of hydrogen. When there is a strong demand for energy, fuel cells or engine generators convert chemical energy back into electricity [49]. Currently, the cost of hydrogen production by electrolysis ranges around \$6/kg [48]. Electrolysis is a key component for grid stability and renewable electricity production due to its ability to store energy for long periods of time with minimal losses. Large amounts of hydrogen are produced and subsequently stored either alone or in combination with other gases in underground formations. Hydrogen storage in geological media involves rock/salt caverns and, potentially, porous media such as saline aquifers and depleted oil and gas fields. Captured carbon dioxide can be employed as a cushion gas since it is much denser than hydrogen under typical reservoir conditions; the density segregation in this situation is relatively strong [49].

In a fully decarbonised energy sector, replaced with hydrogen produced with renewable-sourced electrolysis, the annual water use would be approximately 28kg per person per day [38]. Very often, the regions with a high potential for electrolysis, due to the availability of solar conditions, also have water scarcity problems, or they will develop due the effects of climate change. Water for electrolysis will not be transported from a large distance, posing a regional problem resulting from competition for water between electrolysis, agriculture and human consumption. To alleviate this, wastewater or sea water direct electrolysis for hydrogen production can be used. The kind of technology is under development and promising [50].

Furthermore, the use of hydrogen produces the same amount of water as was initially electrolysed. Thus, in large facilities water vapour can be condensed at the point of use and recovered as liquid water [38]. The potential use of treated wastewater for electrolysis may offset local competition for freshwater from other industries. Wastewater facilities offer close proximity to urban areas with easy access, thus facilitating the development of decentralised hydrogen hubs [38]. However, it should be noted that hydrogen production has consequences for climate change and does not provide an ultimate solution. However, it is part of the mitigation measures for climate change and a shift towards sustainable energy [51].

3.4 New and emerging technologies for hydrogen - Synergies with CCUS to retrieve energy and raw materials

In contrast to the previously mentioned technologies, which are energy vectors, hydrogen may also be liberated by inducing serpentinisation or through water coming into contact with geological formations that contain reduced iron, provided that the right conditions of temperature, fluid composition and pressure exist. This is performed by injecting water *in situ* in identified reactive formations and collecting the hydrogen-saturated water from recovery wells [52]. The process is often referred as “orange” and is similar to the production of natural hydrogen [53-55].

This production method has a great potential for synergy with CCUS since the same formations that naturally produce hydrogen are also the ideal places to store carbon [56]. The natural oxidation of iron and carbon mineralization works extremely well with saltwater or even wastewater. In contrast to electrolysis, which can only be used with high quality water compositions, this significantly reduces the water cost of producing hydrogen without counting the environmental benefits [7].

Geological target formations may also include minerals, such as Li, Ni, and Co, which are of interest to industry. Following the injection, minerals can dissolve, releasing these elements into the percolating fluids. These can then be recovered alongside hydrogen through fractional precipitation. Orange hydrogen does not require as many essential raw materials as electrolysis procedures do. On the contrary, orange hydrogen produces them and therefore differs significantly from its alternatives [7].

Hydrogen production technologies often referred as “gold hydrogen” have rapidly emerged in the recent years. Most commonly, and in this paper, the term “gold” refers to low-footprint hydrogen generated and produced from subsurface reservoirs, although other uses may be found in the literature.

An accumulation of recoverable natural hydrogen has been reported in Mali, with occurrences in other regions of the world being actively discussed [57,58].

On top of that, several technological companies are working on underground conversion of natural gas to hydrogen, using biological (Cemvita - www.cemvita.com) or chemical (Hydrogen Source - www.hydrogen-source.com) conversion of methane. Proton Technologies (https://proton.energy) is focused on gasification/pyrolysis processes to generate hydrogen from heavy oil deposits.

It is also important to remember that associated emissions for any type of hydrogen production will increase with the transportation distance to the end-user. Therefore, localised hydrogen production must be prioritised, with different production types being more advantageous in some regions than others.

3.5 Environmental trade commodities

Intelligent climate and water policies can be achieved by understanding complex interactions between water, food and energy production. The concept of virtual water is an important tool for better understanding how climate change can affect the above-mentioned nexus. Virtual water can also be defined as "the amount of freshwater used for producing goods or services that are exported from one country to another". By understanding how virtual water moves between countries, it is possible to identify where changes in temperature or precipitation may cause disruptions in supply chains. This insight can be used to inform policy decisions that aim to maximize synergies between managed resource sectors while minimizing their vulnerability to climate change impacts.

Given that major climate change is expected to alter the hydrological cycle, policymakers and planners will need to make changes in major practices related to climate change, such as water abstraction regulations, water rights, irrigation systems, land use planning and infrastructure upgrades. To ensure that resource management needs are met under a changing climate, cross-sectoral linkages between policy sectors must be established to maximize synergies while minimizing vulnerability. This paper argues for an integrated framework of policy innovations that considers both sector policies as well as cross-sectoral linkages, which can help decision makers identify how best to address the population's needs under a changing climate. This framework should include strategies for monitoring ecosystem processes, in order to identify early warning signs of resource depletion related to water, food, energy, raw materials and state destabilization.

Cross-sector ecosystem services should be integrated into assessments of policy decisions to ensure that they address climate change, demand for raw materials, food, energy and water resources. The nexus between agricultural food production, energy food and energy water resources is complex, requiring comprehensive consideration of the increasing water diversions and pollution caused by human demand [59]. The need for an integrated approach to managing the water, energy, food/land, raw material nexus is evident; providing water for agriculture while also maintaining wildlife habitats is a delicate balance that requires careful consideration of all systems involved. Policy makers must assess their decisions from a holistic perspective in order to consider the implications of their choices for both humans and the environment. Changes in land use, pollution levels, and resource availability must all be considered when deciding how to best manage these resources.

Climate change mitigation policies should be tailored to the context in which food is produced and how it is traded. Adaptive policy decisions should include new approaches to adaptive food trade that account for future virtual water flows. They must assess population changes, climate land use and estimated land use changes to assess the combined effect of climate change on food security. This would highlight future value of trade decisions and population trends in improving food security and reducing greenhouse gas emissions [60].

There is a strong need to direct the efforts towards developing methodologies to evaluate the environmental assets of natural capital resources related to the water, energy, food/land, raw material nexus. This includes the financial value of adopting nature-based solutions into ecosystem services based on stock and flow models [61-65]. Virtual water provides a conceptual framework for treating water as an internationally traded commodity [16]. Businesses and citizens can employ information and analytical support of natural capital and natural assets for deciding on ecosystem service management in a rapidly changing climate. Financial analysis of both natural capital and asset balance sheets can be aided by databases and maps of the areas of interest. This is achieved by setting an environmental profit-and-loss account to determine: “the cost of ecoservices provided to a company if nature were a business”, and “how much would it charge to clean up the ‘footprint’ left behind by the company?” Integrating these efforts into the nexus with security/disaster risk management, used by the finance sector, will provide the natural resources and ecological services with their insurance value.

To address the competition of resources, water markets are an efficient approach, as they allow for the allocation of limited water resources in an optimal way. The water demand of each consumption region should be calculated to determine the economic impact on the basin and its corresponding surpluses. Furthermore, land use change can significantly affect the availability and quality of water supply, so it should be considered when calculating economic impacts [66,67].

4. Conclusions and future trends

It is recognised that CCUS is the least costly and (in some cases) least disruptive option, but the full social and economic value of the investment require effective communication. It is essential to realise that CCUS provides multiple services: (1) To the emitter, especially for hard-to-abate industries like steel, cement and waste incineration - CCUS takes care of emissions; (2) To the public - CCUS contributes to mitigating climate change by facilitating the decarbonisation of multiple sectors and distributed emissions sources over the long term, through a balanced and equitable transition. CCUS does not only ‘deal with waste from industry’ but also deals with the side effects of the products that consumers are using. Utilisation allows stepping away from waste management to resource management, enabling more efficient use of resources and a more positive perception of the technology. This is a wider social and sustainability dimension that directly involves consumers. Therefore, placing the responsibility of consumers at the core of what CCUS provides, and communicating a business case and a narrative that explains what CCUS will deliver to the public, consistent with their expectations, is critical [45].

Increasing the use of locally produced natural hydrogen, electrolysis with renewable energy sources and CCUS technologies can help increase the resilience of countries to climate change and its effects. Hydrogen can be used to reduce emissions and store energy, while CCUS can be used to capture and store CO_2 emissions from industrial processes. By increasing access to clean water, energy, food/land and raw materials, the application these technologies can reduce poverty and inequality and increase the ability of countries to adapt to climate change.

Virtual water is an important resource management concept for the water, energy, food/land, raw material nexus in the context of climate change. It provides a framework to understand the sector-specific opportunities and threats in terms of adaptation, mitigation and sustainable development. When evaluating the impacts of CCUS on natural resource sectors, one must consider its role in sustainable climate change mitigation, including food-related ecosystem processes. Reviews of CCUS pathways have revealed potential opportunities for energy agriculture, energy water, and energy food. These pathways can be used to reduce emissions from energy sectors while helping to meet targets for mitigating climate change. Hydrogen has emerged as a crucial component of strategies for adapting to climate change. It provides an affordable alternative to traditional fuels like coal or oil and has the potential to reduce emissions from energy production and other sectors. Additionally, hydrogen provides a mechanism for storing renewable energy during periods of peak demand.

Ammonia production using renewable energy sources can provide an alternative fuel or fertilizer that does not rely on fossil fuels. Moreover, substitution of feedstocks for chemical production can help reduce emissions from methane and other greenhouse gases.

Inclusion of stakeholders in the process of major transitions to new technologies is not only limited to CCUS. Societal attitudes to concepts such as virtual water, the use of hydrogen as a replacement fuel, and the connection between groundwater management and sustainability, need to change. Policies that introduce new approaches require ownership by the communities, and investment in education, communication and visible demonstration sites are critical for getting people involved. Governments need to adopt the concepts with a more holistic approach, encouraging societal ownership and adoption.

The use of the described technologies and concepts can contribute to the mitigation of global climate change, by reducing carbon emissions and helping to reduce circular economy strategies. It can also facilitate carbon trading and create new economic opportunities for countries to transition their energy structures, to mitigate climate change. Applying circular economy strategies to raw materials and hydrogen can improve energy efficiency, transform energy structures and contribute to mitigating objectives related to climate change. The strategies also enable the transition from fossil fuels to electrification through the application of digital technologies. Electrification and fuel switching are also crucial components of the plans to transition away from a high-carbon intensity economy.

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