

Global Green Hydrogen Economy

Electricity Competition and Land-Use Change

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Abstract

Hydrogen is emerging at the center of the global energy discourse as an energy carrier with a great potential to reshape the global energy transition. Produced through the electrolysis process with renewable sources, green hydrogen provides a low-carbon alternative to decarbonize hard-to-electrify sectors and provides flexibility to be stored and transported across regions. An acceleration of the green hydrogen production is projected by 2050, which necessitates a significant amount of renewable sources and land endowment globally, bringing about considerable land-use and economic implications for sustainability. The objective of this study is to evaluate the impact of the expected expansion of solar electricity for the global green hydrogen production on land-use change, as well as the associated economic impacts on the electricity market and agricultural market. A global recursive-dynamic CGE model, CGEBox, with an extension of hydrogen energy, is employed to examine the interlinkages across the energy and agricultural sectors through land allocation. Additional disaggregated information of hydrogen production, the solar electricity sector, and solar land factor with the GTAP 11- Power datasets are used in the model. We apply scenarios on increased hydrogen demand and increased solar energy inputs by 2050 and compare this to a baseline. The baseline is constructed through GTAP-based Recursive Dynamic Economic Model with exogenous projections of Shared Socioeconomic Pathway 1. The analysis focuses on the dynamics and interlinkages of the land factor and the corresponding responses from the energy and agricultural sectors, led by the increasing demand for hydrogen products, alongside an evaluation of competitive dynamics between green hydrogen and renewable electricity. The anticipated results of this study could facilitate the knowledge of the sustainability implications of new energy technology and future strategies in green hydrogen development.

Keyword: Hydrogen, Green Hydrogen, Solar Electricity, Renewable Energy, Land-Use Change, Computable General Equilibrium Model

Introduction

Green hydrogen economy

Hydrogen is emerging at the center of the global energy discourse, as an energy carrier with a great potential to reshape the global energy transition (Capurso et al., 2022; Kovač et al., 2021; McPherson et al., 2018). It is conventionally produced through carbon-intensive methods such as steam methane reforming and coal gasification (IEA 2024a; Younas et al., 2022). However, the focus has recently shifted to green hydrogen, which is produced through the electrolysis process separating water into hydrogen and oxygen with renewable electricity and is anticipated to be a crucial element for the replacement of fossil-based fuels (IEA, 2024a; Kovač et al., 2021). Green hydrogen offers a carbon-neutral alternative to decarbonize hard-to-electrify sectors, including chemical, steel, and aviation sectors, and to contribute to climate change mitigation (Hassan et al., 2024; Lebrouhi, et al., 2022). It also provides flexibility to be stored and transported across regions, at the same time serving as a solution to overcome intermittency issues of the renewable electricity generation (Anderson & Leach, 2004).

Global hydrogen demand reached 97 million tonnes (Mt) in 2023, predominantly produced from natural gas and coal and mainly consumed in the petroleum-refining and chemical industries (IEA, 2024a). While green hydrogen currently plays an insignificant role, an estimation of more than 300 Mt of green hydrogen will be needed to reach global Net-Zero emissions by 2050 (IEA, 2024b). The future expansion in green hydrogen production is foreseen to be shaped by geographical variations in renewable potentials, particularly solar and wind (Franzmann et al., 2023). This potential of renewable resources, coupled with the availability of land and water resource endowments holds the capacity to drive a significant geopolitical transformation in the global energy value chain (IRENA, 2022).

Solar expansion for green hydrogen

IEA (2024b) projects that around 15% of the global renewable electricity is expected to be allocated to electrolytic green hydrogen production to achieve the Net Zero emission target by 2050 with approximately 80% of this capacity derived from solar electricity. This growing demand in solar energy for the production of green hydrogen may also bring about considerable land-use implications for sustainability (Terlouw et al., 2024; Cremonese et al., 2023). Compared to another predominant renewable electricity source - wind energy, solar energy facilities require significantly larger direct land occupation areas, with around a 10 to 12 times difference to produce the same unit of electricity (Lovering, 2022; Maguire et al., 2024). The number can be even larger when considering the land footprint of the infrastructure of the solar systems (Wu, et al., 2021). Tonelli et al. (2023) demonstrated the limited land availability for scaling up green hydrogen production with solar and wind electricity to meet the demand in 2050. Terlouw et al. (2024) employed a geospatial analysis and highlighted an expected large land occupation resulting from green hydrogen in the climate 1.5 °C pathways. Results from both studies highlight the need for future increasing land requirement and expansion of solar energy for the global electrolytic green hydrogen development.

Solar electricity generation has been estimated to be a significant driver of future conversion of cropland by 2050 (van de Ven et al., 2021; Diffendorfer et al., 2024). Cropland has been found to offer the highest potential for solar photovoltaic deployment (Adeh et al., 2019), which could serve as a risk-aversion strategy for farmers to consider land conversion (Moore et al., 2022). Studies have demonstrated that a large proportion of solar photovoltaic installations has been sited on previously cultivated cropland

(Kruitwagen et al., 2021; Hernandez et al., 2015). Curioni et al. (2025) also estimated that around 13% of the global solar capacity is linked with the agricultural land-use change from 2003 to 2020. This competition between agricultural production and solar infrastructures is expected to be a factor limiting the expansion of solar technologies (De Castro et al., 2013), as well as generating economic impacts on the agricultural market. Yet, these potential impacts have not been quantified.

Although it might be considered a relatively simple solution to place solar facilities on non-agricultural unmanaged land area, commercializing unmanaged land for solar energy development, however, could indirectly contribute to the loss of natural land cover (van de Ven et al., 2021). Around 4% of the current solar PV facilities are estimated to be placed on protected or fragile areas (Curioni et al., 2025). In addition, deforestation has also been observed to be one of the consequences resulting from solar energy developments (Zhang et al., 2024). It could further impose large stress of loss to natural areas and biodiversity, increasing the vulnerability of food security and biodiversity conservation (Capellán-Pérez et al., 2017).

Van de Ven et al (2021) have used an Integrated Assessment Model, GCAM, to simulate the future solar expansion and land competition in the European Union, Japan, Korea, and India by incorporating the solar occupied land into the land system module. They found strong indirect land-use change effects driven by solar energy shifting the unmanaged land into economic use (Van de Ven et al., 2021). The research has provided an innovative method to evaluate the impacts of the solar land, while several aspects could further be included and assessed. First, the land-use and economic implications and the interlinkages across the energy sector and agricultural sector have not been addressed. Second, hydrogen as a future key energy carrier for hard-to-abate industrial sectors with an estimated high demand in solar electricity is absent from the energy system.

Green hydrogen and CGE model

Computable General Equilibrium (CGE) models are well suited to illustrate the interplay of multiregional and multisectoral economic activities and are widely applied in assessing economic and policy impacts of energy transitions and challenges, for instance, fossil fuel subsidy reform (Argueyrolles et al., 2025), and biofuel policy (Delzeit et al., 2018). Hydrogen has also been introduced in CGE models in the past with a focus on the economic development of the technology and its effects on emission reduction. Espegren et al. (2021), for example, focused on Norway and employed a regional CGE model to assess the economic implications of hydrogen export and its potential contribution to value creation. Lee (2014) coupled a dynamic CGE model with Life-Cycle Assessment to project the future hydrogen technological development in Japan. Wei & Glomsrød (2023), on the other hand, implemented a global CGE model to simulate how the cost reduction in hydrogen technologies can facilitate carbon emission reduction. Bae & Cho (2010) assessed the impacts of different hydrogen subsidy rates on emission reduction in Korea through a dynamic CGE model.

While the economic and climate implications of the hydrogen economy have been discussed, the land-use implications and the interlinkages across the energy sector and agricultural sector, however, still require to be investigated. *This study aims to address this research gap by evaluating the impact of the expected expansion of renewable sources for the global green hydrogen production on land-use change, as well as the associated economic impacts on the electricity market and agricultural market.*

Data Preparation

Overview of the database and aggregation

The main datasets used in this study are the Global Trade Analysis Project (GTAP) version 11 datasets with a reference year of 2017 (Aguilar et al., 2023). Due to a need for detailed information of the electricity sector to represent the electrolysis production of green hydrogen well, the version 11 of GTAP-Power database (Chepeliev, 2023) is integrated. GTAP-power version 11 contains 76 sectors, 76 products, 141 countries with 19 regions and 4 factors, with high disaggregated information of the electricity and heat generation sectors (Chepeliev, 2023). In this study, we aggregate the global map into 24 regions shown as figure 1. The regional aggregation was chosen based on similar GDP per capital as well as solar power potential according to ESMAP (2020).

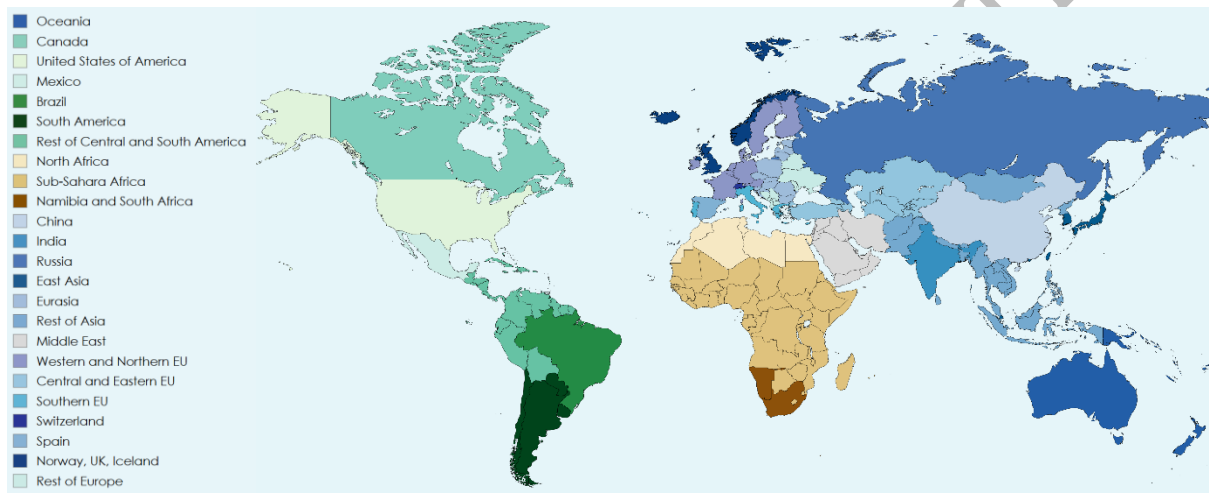


Figure 1: the 24-regional aggregation of the study

Hydrogen sector and product

Since hydrogen is not a separate sector in the GTAP database, the information on hydrogen first needs to be built and introduced. Hydrogen products in this study are categorized into green hydrogen and fossil-based hydrogen according to the primary energy source. Green hydrogen product is assumed to be produced from renewable electricity, which consists of the solar, wind, hydro and other renewable power sectors (see Figure 2). Green hydrogen value is collected through this approach for the following reasons: (1) Green hydrogen is an energy carrier, and its changes in supply and price can be directly driven by the changes in the renewable electricity sector. (2) Green hydrogen is an intermittent solution to renewable electricity. The production decision in resource allocation between electricity and hydrogen can be represented through this multi-output specification. (3) This approach also enables a representation of current additional requirement for green hydrogen generation in the European Union (EU, 2023), which is demanded to be directly connected to additional renewable electricity facilities to avoid a challenge of electricity competition. On the other hand, fossil-based hydrogen values are taken from the chemical sector, disaggregated into coal-based hydrogen sector, and natural gas-based hydrogen sector. These two sectors jointly produce fossil-based hydrogen product. The input share of natural gas and coal into fossil-based hydrogen is derived from IEA (2019).

To integrate the information into the SAM, output shares as split factors are collected to construct the hydrogen economic account for each region from the renewable electricity and chemical sectors. The output shares are derived from the IEA electrolysis plant database (IEA, 2024c) for green hydrogen, and the IEA hydrogen report (IEA, 2019) for fossil-based hydrogen. For the regions which did not produce hydrogen in the base year, a small value is assigned to allow a future hydrogen technology development. Sectoral intermediate demand in hydrogen is derived from IEA (2019) with 33% for the petroleum and coal product sector, 38% for the chemical sector and 3% for the ferrous metal sector. The rest of the hydrogen demand is allocated to household consumption, transport sectors, manufacturing sectors, and food processing sectors.

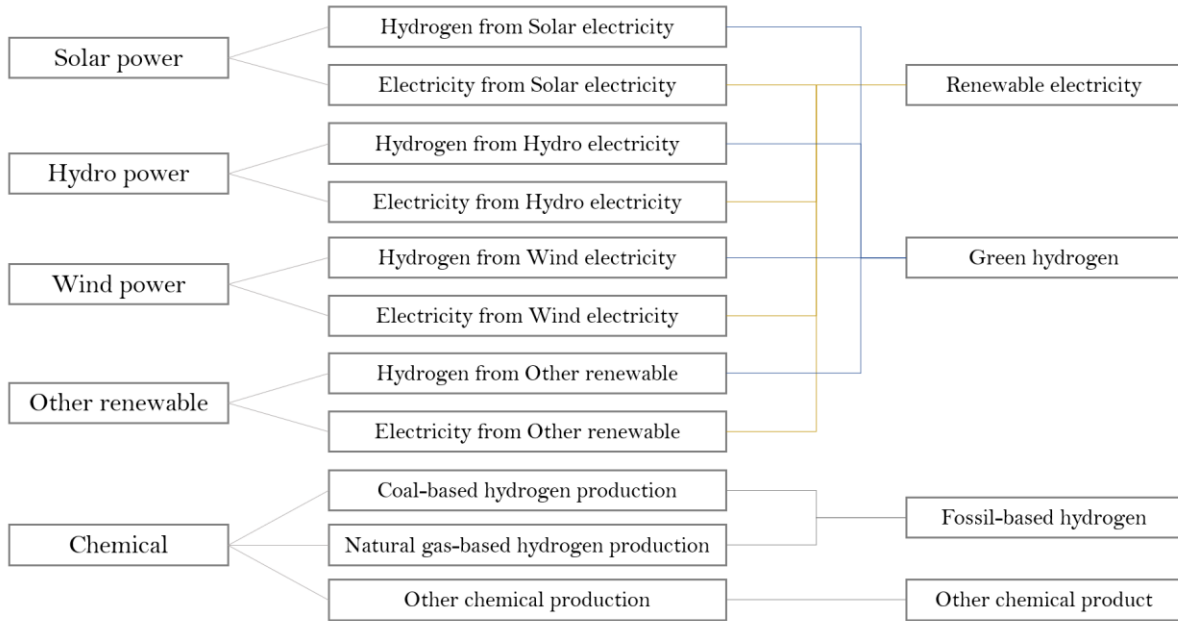


Figure 2: Overview of the aggregation and disaggregation for the hydrogen sectors and products

Solar electricity sector and land data

To capture land-use allocation between solar production and other land-using sectors, we differentiate different types of solar electricity production and add a land rent to one of these production types. Solar electricity is disaggregated into four sectors based on the previous land cover type: Solar Photovoltaics (PV) on managed land (cropland, pastureland, forest), Rooftop-based PV (urban land), Solar Photovoltaics (PV) on unmanaged land (other land cover type), and Concentrated Solar Power (CSP). We assume that the four sectors possess the same cost structure and a homogenous output. Land is only assigned a value in the production of the solar energy in the case of ‘Solar PV on managed land’, as the cost of unmanaged land is assumed to be null.

To identify the previous land cover of solar facilities in the reference year we apply a geospatial overlay analysis via Google Earth Engine. It is also used to collect the information of solar land area and marginal land productivity of electricity in this study. For the identification of the previous land cover of global solar assets and the calculation of the solar occupation area, the spatial datasets of global inventory of solar photovoltaics (Kruitwagen et al., 2021) and the land use/cover change datasets of

Historic Land Dynamics Assessment (HILDA+) (Winkler et al., 2021) are employed. In addition, the land rent is assumed the average land rent of the aggregated land factor value for each region.

With the consideration of land heterogeneity, the marginal electricity productivity of land is introduced exogenously as a land productivity shifter in the production function. Building on the functional form developed for calculating the marginal productivity of solar land by Van de Ven, et al. (2021), we define the marginal productivity of solar land at the pixel level, illustrated as figure 3.

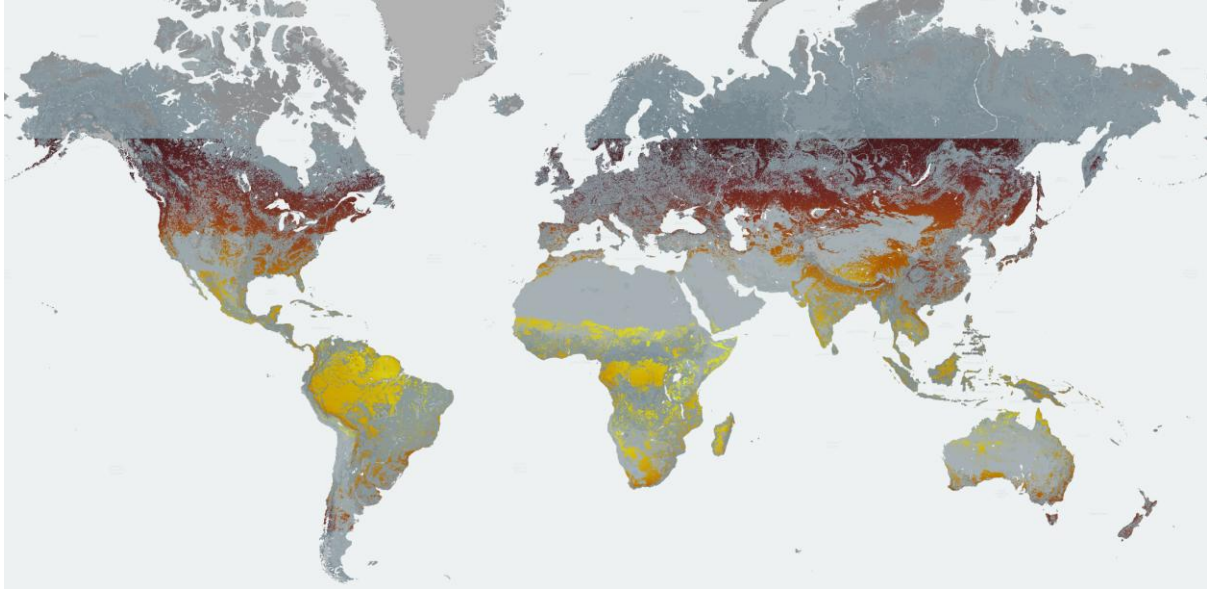


Figure 3: Global marginal solar electricity productivity of cropland, pastureland and forest, which can be observed that the highest potential areas are estimated to be in Sub-Saharan Africa and South America.

Model

CGEBox

CGEBox, a global recursive-dynamic CGE model (Britz & van der Mensbrugghe, 2018) is used to examine the land-use change and impacts of the agricultural market induced by the green hydrogen economy until 2050. CGEBox is a modelling framework based on the GTAP database with flexible regional and sectoral aggregations as well as flexible nesting structure in production and factors (Britz & van der Mensbrugghe, 2018). This flexibility in the structure of production allows an introduction of new technology, for instance, hydrogen in this study. The production structure in the model is built with a series of nested CES (constant elasticity of substitution) functions. The output at the top level is produced by the composites of intermediate inputs and value added. Regarding household consumption, a demand system of A Modified Implicit, Directly Additive Demand System (MAIDADS) is used to capture the non-linear Engel curve with flexible marginal budget shares (Britz & Roson, 2019; Britz, 2022). Moreover, an Armington specification is used to differentiate the domestic demand and import, and constant elasticity of transformation (CET) is used for the export and domestic supply (Britz & van der Mensbrugghe, 2018).

We simulate the long-term economic dynamics and generate a baseline with a two-year resolution to 2050 with the GTAP-based Recursive-Dynamic Economic Model (G-RDEM) within CGEBox (Britz & Roson, 2019). Several features in G-RDEM are incorporated to build the temporal change of the

economic structure: (1) Socio-Economic Pathways (SSPs) can be integrated into the baseline construction to represent the future socioeconomic changes and energy development (2) Saving rates are endogenized and driven by the dependency ratio of the population and real GDP growth. (3) The total productivity shifter is heterogeneous across sectors, distinguishing from manufacturing, agriculture, and services. (4) Input-output coefficients are influenced by variations in GDP per capita across economic sectors. (5) The compositions of the governmental and investment consumption are income dependent.

Hydrogen extension

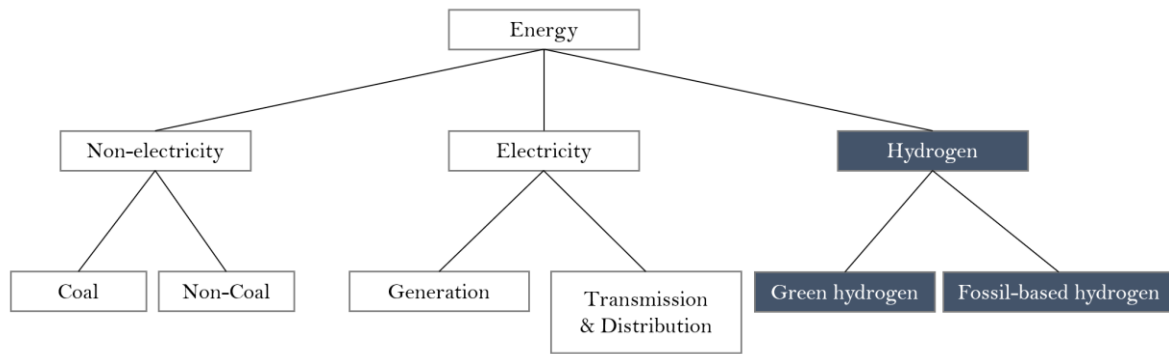


Figure 4: Energy nesting structure with an extended hydrogen nest

Figure 4 illustrates the nesting of the energy systems with the integration of the hydrogen technology. The top nest of the energy nesting is a composite of electricity, non-electricity, and hydrogen in a form of CES function. The non-electricity bundle is a composite of coal and non-coal products, and electricity bundle combines the electricity generation and transmission as well as distribution with Leontief functions. The extended hydrogen bundle is a composite of green hydrogen and fossil-based hydrogen products in a CES function with a relatively large substitution parameter, resulting from a homogenous output of hydrogen and a capacity to support the simulation of an accelerated low-carbon transition.

Solar land extension

The land factor nest is built for different land use types in a three-level additive form of constant elasticity of transformation (ACET), as shown in figure 5. In the bottom level, the total managed land is allocated to forest use and agricultural as well as solar land use. At the second level, pasture land can be substituted with the composite of crop land and solar land. At the third level, cropland directly competes with solar land, since cropland has been identified as the most suitable and extensively utilized land type for solar energy deployment (Kruitwagen et al., 2021; Hernandez et al., 2015; Adeh et al., 2019).

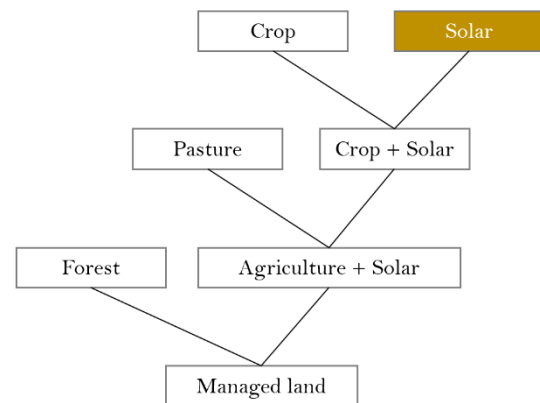


Figure 5: Land nesting structure with an extended solar land nest

Hydrogen analysis and scenarios

In this study, the analysis focuses on the dynamics and interlinkages of the land factor and the corresponding responses from the energy and agricultural sectors, led by the increasing demand for the hydrogen products. The land factor encompasses changes in land cover and land rent, as well as shifts in land allocation. In the agricultural sector, the study examines variations in output levels and commodity prices, while the energy sector is analyzed through the changes in the composites of primary energy sources as well as the changes in output levels and prices, alongside an evaluation of competitive dynamics between green hydrogen and renewable electricity within the electricity market. Exogenous projections for the GDP and population growth are employed in G-RDEM based on OECD and Shared Socioeconomic Pathways 1. SSP1 is selected due to its high level of efforts in climate mitigation, reflecting factors such as high social acceptability for renewable technologies and slow technological improvements in fossil fuels (Bauer et al., 2017). Three scenarios are constructed as followed:

Sustainability: The GDP growth and population growth are calibrated on the basis of OECD data and on the SSP1 as baseline. This scenario is anticipated to have a large growth in renewable electricity production, and the competition among the renewable technologies will be driven by the prices to meet the future energy demand. The global output of green hydrogen is endogenously determined by model.

Sustainability with green hydrogen project development: The pathway of green hydrogen production follows the Net Zero Emission scenario in IEA World Energy Outlook 2024 with an expected amount of 326 Mt in 2050 (IEA, 2024b), coupled with SSP1. This exogenous introduction of green hydrogen is to represent its development within a focused and, at the same time, achievable pathway. This scenario is expected to generate the highest value of green hydrogen product to decarbonize the carbon-intensive manufacturing sector, due to a relatively large growth in renewable electricity adoption and production.

Sustainability with a solar-focused green hydrogen development: The pathway of green hydrogen production also considers the Net Zero Emission scenario and SSP1. This scenario follows the projection from IEA (2024b) that solar power contributes 80% of the renewable capacity for green hydrogen production. It is anticipated to have the largest land-use impacts among the three scenarios.

Expected Results

This study could contribute to the understanding of the land-use impacts under different scenarios induced by the future green hydrogen technology diffusions, as well as highlight the responses of the energy sectors and agricultural sectors. Green hydrogen demand is expected to increase substantially coupled with a large intermediate demand in renewable electricity, driving the resource allocation from electricity production to hydrogen production. This market change could be expected to either increase the electricity price in general indirectly increasing the fossil source for electricity production, or reallocate input resources from other sectors to rapidly expand the renewable electricity to meet the increasing global demand in electricity. On the other hand, direct land-use impacts are expected to be considerably greater in the future as larger land expansions for solar generation could be foreseen to support the green hydrogen production to meet the future demand. Consequently, this is expected to result in indirect land-use changes, such as the conversion of forest into crop land to meet the growing demand in the agricultural market, or an increase in agricultural output prices due to a reduction in land availability for production. From geographical perspectives, the direct land-use change induced by solar photovoltaics is mostly observed to occur in the developed countries in the reference year. However, the direct and indirect land-use impacts could be expected to shift in the future to the Global

South due to higher solar potentials and land availability for expanding electrolysis projects and exporting green hydrogen products.

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