Land-use implications of solar power expansion and agrivoltaics deployment

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Introduction

The growing demand for solar energy resulting from efforts to decarbonize the global economy and to reduce greenhouse gas emissions may bring about considerable land-use implications for sustainability (Capellán-Pérez et al., 2017; van de Ven et al., 2021). In fact, solar electricity generation has been estimated to be a significant driver of future land conversion by 2050 (van de Ven et al., 2021; Diffendorfer et al., 2024). Cropland has been found to offer the highest potential for solar photovoltaic (PV) deployment (Adeh et al., 2019), and its conversion to solar power could help farmers mitigate rising agro-climatic risks associated with climate change and increasing extremes (Moore et al., 2022). Studies have demonstrated that a large proportion of solar PV installations has been sited on previously cultivated cropland (Kruitwagen et al., 2021; Hernandez et al., 2015). This competition between agricultural production and solar infrastructures is thus expected to be a factor limiting the expansion of solar technologies (De Castro et al., 2013), and it might generate economic trade-offs in the agricultural market.

Although it might be considered a relatively simple solution to place solar facilities on non-agricultural unmanaged land areas, commercializing unmanaged land for solar energy development, could contribute to the loss of natural land cover (van de Ven et al., 2021). Currently, around 4% of the existing solar PV facilities are estimated to be located in 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 expansion (Zhang et al., 2024). Renewable energy expansion on unmanaged land could therefore further impose a large loss of natural areas, negatively affecting biodiversity (Capellán-Pérez et al., 2017).

A dual-land use system for a joint agricultural and electricity production, so-called agrivoltaics (AVs), is often framed as a win-win solution to mitigate potential land-use conflicts between solar facilities and agricultural production (Barron-Gafford et al., 2025; Widmer et al., 2024; Trommsdorff et al., 2025). However, AVs have not yet been widely adopted as a technology, meaning that supportive policies and incentive mechanisms will be critical to facilitate their deployment (Trommsdorff et al., 2025; Pandey et al., 2025).

The land-use implications of future solar power growth have been underrepresented, since current studies have only focused on projecting the potential land-use area and emissions of solar expansion for certain regions. Van de Ven et al. (2021) have considered the solar direct land occupation coupled with Agri-Ecological zonings for European Union (EU), India, Japan and Korea in an Integrated Assessment Model (IAM), GCAM. The study found that approximately 0.5% to 5% of the total land area in these regions will be occupied by solar deployment in 2050. Mongird et al. (2025) also employed a multi-modelling framework to simulate the solar land expansion in the United States of America (USA). The results show that compared to a business-as-usual scenario, an additional 30% of land will be required for solar development to realize a high renewable share in the electricity mix. Diffendorfer et al. (2024) simulated scenarios through capacity expansion modeling and projected that around 2% of cropland and 0.5% of natural land in the USA will be displaced by solar infrastructure in 2050. In addition, Capellán-Pérez et al. (2017) simulated a scenario in which all electricity is supplied by solar power for 40 countries, and showed that land requirements will be a significant constraint for most of the countries in the EU and Japan.

These studies show that a growing demand for land to support solar electricity production is expected. However, the competition and trade-offs between solar power and agriculture for limited land resources are not well understood and the potential impacts on agricultural markets remain uncertain (Stid et al., 2025). Moreover, AVs have been a shared limitation in many existing studies, as they are often underexplored or excluded from analysis despite their potential to mitigate land-use conflicts and support both energy and food production goals (Van de Ven et al., 2021; Diffendorfer et al., 2024). To our knowledge, solar land use expansion and AVs including associated crop yield changes have not been addressed in a Computable General Equilibrium (CGE) analysis. The study aims to address this research gap by evaluating the impacts of the expected expansion of global solar deployment on land-use change, the associated economic impacts on the energy and agricultural markets, as well as the potential land pressure mitigation by agrivoltaics.

Method

The study employs a global recursive-dynamic Computable General Equilibrium model, CGEBox (Britz & van der Mensbrugghe, 2018), to simulate the long-term economic dynamics until the year 2040. CGEBox is a modelling framework based on the GTAP database with flexible regional and sectoral aggregations as well as a flexible nesting structure in production and factors (Britz & van der Mensbrugghe, 2018). The production structure in the model is built with a series of nested CES (Constant Elasticity of Substitution) functions. 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 a Constant Elasticity of Transformation (CET) function 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 one-year resolution to 2040 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 (2) Saving rates are endogenized and driven by the dependency ratio of the population and real gross domestic product (GDP) growth. (3) A total productivity shifter is heterogeneous across sectors, distinguishing between 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.

The model is calibrated to the Social Accounting Matrix (SAM) from the GTAP 11 database (Aguiar et al., 2023) for the 2017 reference year with power extension (Chepeliev, 2023). In our study, we aggregate the 141 regions into 21 broader regions and extend the database to have disaggregated solar power sectors. The extended database encompasses 81 sectors, 64 products, and 4 factors (labor, capital, land, and natural resources). The disaggregated solar power sectors are introduced based on the previous land-use type of solar farms and based on the different solar technologies: namely PV on managed land, PV on unmanaged land, PV on urban land/rooftop, concentrated solar power (CSP), AVs on cropland, as well as AVs on pasture land. Land is only assigned a value in production of the solar energy in the case of 'solar PV on managed land', and agrivoltaics sectors, as the cost of unmanaged land is assumed to be null. The information for sectoral disaggregation process is supported by a geospatial overlay analysis, to identify the agricultural suitability of solar occupied land and its previous land use type in the reference year.

The land supply nest is built for different land-use types in a four-level additive form of CET function, as shown in Figure 1. In the bottom level, solar PV on managed land can compete with the total agricultural land, since the PV sector encompasses the previous occupied land-use type of cropland, pastureland, and forest. At the second level, the total agricultural land is allocated to forest use and a combined bundle of crop and pasture land uses. At the third level, pasture land can be substituted with cropland. At the top level, the joint production of agriculture and power is allowed to be substituted with agricultural production for both cropland bundle and pasture bundle.

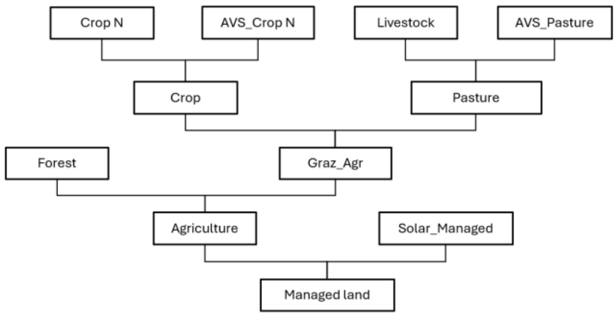

Figure 1: Land supply nesting with an inclusion of solar power land use and agrivoltaics land use (Source: own illustration)

Scenarios

The baseline scenario relies on the SSP 2 (Riahi et al., 2017) to model GDP and population trends, while energy projections are calibrated separately using external assumptions based on a baseline developed by the Joint Research Centre of the European Commission (Garaffa et al., 2024) and on the Current Policies scenario developed by International Energy Agency (IEA, 2025). All existing policies, such as tariffs and subsidies, are assumed to remain in effect at their base-year levels. In addition to the baseline scenario, we implement two scenarios to simulate two policies to mitigate the land-use pressure between power generation and food production, including subsidizing the solar PV deployment on the non-agricultural land, and subsidizing AVs development.

- **Business-As-Usual (BAU) Initialization:** this scenario simulates the model with SSP2 and energy projection **without** considering the constraints of solar land requirement in the model run until 2040. We target the production level of extracting activities and the share of power generation activities using efficiency shifter in order to replicate the external energy projection. In addition, cropland expansion projection and crop yield projection are incorporated based on FAO (2018).
- **Business-As-Usual (BAU) Baseline:** this scenario incorporates the efficiency shifters used in the BAU initialization **with** the consideration of solar land requirement in the model run by constraining the solar yield, building on top of the Business-As-Usual Initialization.
- **Scenario 'TAX-SL':** building on the BAU baseline scenario, this scenario assumes the prioritization of agricultural land use over PV deployment and evaluates how subsidies for PV installations on non-agricultural land could mitigate the land-use pressures driven by rising solar energy demand.
- **Scenario 'AVS-SL':** building on the BAU Baseline scenario, this scenario assesses how the subsidy on AVs technology might mitigate the land pressures induced by the increasing solar power demand.

Preliminary results

- **Solar power output change**

We first evaluate the total solar power output with and without the consideration of solar land between the BAU Initialization and BAU Baseline, aiming to understand the total solar outcome when the external energy projection considers the solar land competition. Figure 2 demonstrates the difference between the initialization and the baseline as percentages. Compared to the external energy projections, we find that solar power output declines in general across all the model regions when the solar power growth is constrained by solar land requirement and solar land yield, which implies a potential overestimation of the solar growth.

Figure 2: difference in total solar output between BAU Initialization and BAU Baseline (Source: own illustration)

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- **Solar land expansion**

This section presents the solar land use (million hectares) in the BAU baseline scenario in the figure 3 and figure 4. In the figure 3, the required land areas of global solar PV for both agricultural land (managed land) and natural land (unmanaged land) have substantial increases. The unmanaged land use for PV deployments has a larger growth rate compared to the managed land use for PV, while the majority of the PV is still sited on agricultural land in 2040. Figure 4 provides a regional disaggregation of the agricultural land conversion for PV siting. China accounts for the largest share of 54.9%, followed by USA (11.5%) and EU (10.6%).

Figure 3: Estimated global solar PV land occupation area over time (million hectares) (Source: own illustration)

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Figure 4: Estimated solar PV occupation land on agricultural area by model region (million hectares) (Source: own illustration)

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- **Solar PV induced land-use change**

Solar PV expansion is expected to convert agricultural land and natural land into power generation land use, which can result in both direct and indirect land-use change. The results compare the difference in land use area in million hectares between the BAU Initialization and BAU Baseline, as presented in Figure 5. We find that when the solar PV is constrained by the land competition with agricultural land, PV development shifts to expand on natural land (unmanaged land).

Figure 5: Estimated land-use change induced by the increasing solar PV land use in million hectares (Source: own illustration)

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- **Agricultural commodity prices**

Due to the agricultural land conversion and increasing land demand for PV production, the overall agricultural land price is estimated to increase. This shift in the land dynamics is interconnected with the agricultural market, further influencing the agriculture commodity prices. Figure 6 demonstrates the difference between BAU Initialization and BAU Baseline, showing the estimated increase in commodity prices of wheat, vegetables and rice. In general, increases in price by around 0.1% to 0.5% across all regions are observed. It implies that the solar PV development could potentially induce trade-offs in food security.

Figure 6: Estimated increase in the agriculture commodity price (Source: own illustration)

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- **Subsidy on PV development on unmanaged land**

- **AVs policy**

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