Land use change implications of Power-to-Liquid Fuels

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1. Introduction

Air transportation plays an important role in the global economy. However, unlike the road transportation, it is hard to decarbonize this sector due to the lack of options for direct electrification. Hence, its decarbonization relies heavily on hydrocarbon "drop-in" fuels, which can be used in the existing fleet. Among a few existing potential options, fuels made from renewable electricity via electrolysis, direct air capture of atmospheric CO_2, and subsequent conversion to hydrocarbons ("Power to Liquid", PtL) are promising pathways (German Environmental Agency (2022)). However, according to the Carbon Offsetting and Reduction Scheme for the International Aviation (CORSIA) of the International Civil Aviation Organization (ICAO), the emission intensity of a Sustainable Aviation Fuel (SAF) should be at least 10% lower than the carbon intensity of the conventional the jet fuel (89 gCO_2e/MJ) to be considered as a CORSIA-eligible fuel (Prussi et al. (2021)). In this scheme, the carbon intensity of a SAF pathway consists of two components. The first component captures the life cycle emissions of the corresponding supply chain, known as "Core LAC". The second component evaluates the associated Induced Land Use Change (ILUC) emissions if the pathway uses land for feedstock production. This paper concentrates on the ILUC emissions for the PtL pathways. For example, the CORSIA-Core-LCA for soybean oil HEFA, corn ATJ, and corn ETJ SAF pathways are estimated to be about 40.4, 55.8, and 65.7 gCO_2e/MJ. The corresponding CORSIA-ILUC values for these SAF pathways are estimated to be about 25, 22, and 25 gCO_2e/MJ, if their feedstocks are produced in the U.S. Hence, among the three pathways mentioned here the U.S. corn ETJ does not pass the CORSIA 10% emission saving, as its LS_f value will be 90.7 gCO_2e/MJ which is higher than the threshold of 89 gCO_2e/MJ.

The existing PtL pathways commonly require relatively high levels of electricity to produce SAFs. To be considered as a CORSIA eligible fuel, the required electricity for these pathways should be produced using low carbon intensive resources such as solar or wind[1]. Land is an essential input to produce electricity from these resources. If the required land for solar and wind electricity is obtained from arable land, then that could intensify demand for these lands and cause induced land use changes, similar to the use of land for biofuel production.

Over the past 15 years, many papers have examined induced land use changes due to biofuel production and policy (e.g., Searchinger et al. (2008), Hertel et al. (2010b), and Taheripour et al. (2017)). Even within the CORSIA approach, ILUC values have been estimated for various pathways that use crops as feedstocks for SAF production (Zhao et al. (2021) and Prussi et al. (2021)). In a recent effort, van de Ven et al. (2021) have evaluated ILUC emissions for producing solar electricity generated in a few regions including European Union, India, Japan, and South Korea. In addition, a few research activities have evaluated land requirements for producing solar

[1] Note that there are other carbon-free generation sources, such as nuclear and hydro power, but since most studies project solar and wind to be dominant technologies in the future, we focus on the solar which is a land dependent source of electricity.

electricity (Ong et al. (2013) and Bolinger and Bolinger (2022)). However, to the best of our knowledge, no major effort has been made to evaluate ILUC emissions for the PtL pathways that use solar and wind electricity for SAF production. This paper aims to fill this knowledge gap by assessing ILUC emission values for a representative PtL technology that produces SAF via solar electricity using a well-known Computable General Equilibrium (CGE) model, GTAP-BIO.

To accomplish this goal, as a first step, this model has been improved and augmented to be able to assess ILUC values for producing electricity using solar energy. To accomplish this task, the GTAP-BIO model reported by Zhao et al. (2021) has been used. This version of GTAP-BIO has been used frequently to assess ILUC values for CORSIA SAF pathways. This paper outlines the implemented changes in the GTAP-BIO model coupled with version 9 of the GTAP data base that has 2011 reference year, introduces the approach used in assessing ILUC values for solar electricity, and provides preliminary ILUC values for solar electricity and its conversion to SAF using a particular PtL technology. This paper paves the way towards more comprehensive assessments in this area of research.

2. Method

2.1. Background of GTAP-BIO model

GTAP-BIO is a static global CGE model which has been developed, frequently improved, and used to assess ILUC values for the first and second generations of biofuels that can be produced from traditional feedstocks such as grains, oilseeds, and sugar crops and lignocellulosic crops such as switchgrass, miscanthus, and poplar (Hertel et al. (2010a), Taheripour et al. (2010), Hertel et al. (2010b), Tyner and Taheripour (2012), Taheripour et al. (2012), Taheripour and Tyner (2013a, b), Taheripour et al. (2017), and Zhao et al. (202)). The model traces induced land use changes due to biofuel production and policy that could impact the world's demand for crops, leading to land use changes globally. Here, we enhance this model to trace global land use changes due to production of solar electricity to be used for PtL SAF pathways.

2.2. Introducing solar electricity for PtL in GTAP-BIO

A new pioneer solar electricity sector is introduced in the model following the approach defined by van de Ven et al. (2021) in adding solar electricity to the GCAM model. To accomplish this task, several steps have been implemented:

- ***Step 1:*** A data set on Direct Normal solar Irradiance (DNI) at the global scale by grid cell is obtained from a data set provided by NASA (2008).
- ***Step 2:*** The global DNI data is aggregated to represent the geographical aggregation of GTAP-BIO by 18 Agro-Ecological Zones (AEZs).
- **Step 3:** Using the results of step 2 and via the following formula a data set is developed to assess potential electricity production (measured in kWh/m^2/day) by region and AEZ:

  $P = I^{rAEZ}.p^{e}.p^{t}.a^{rAEZ}.$

  The variables defined in this formula are: Average solar irradiance of Reg./AEZs (I^{rAEZ}); Estimated average efficiency of solar panels: ($p^e = 0.25$); Performance ratio over the lifetime of the solar panels: ($p^t = 0.65$); and Land-occupation ratio, based on the average latitude of Reg./AEZ. (a^{rAEZ}).

Table 1 shows the results of the above steps for the United States, EU and Brazil by AEZ. As shown in this table, the amount of electricity output per area varies significantly by AEZ. For example, in US AEZ7 the amount of electricity output per area is about 0.4 kWh/m^2/day while the corresponding figure in US AEZ 10 is about 0.23 kWh/m^2/day.

Table 1. Calculated potential solar electricity output by AEZ for the study regions

Row	Region	AEZ	DNI	Panel Efficiency	Performance over time	Land Occupation Ratio	Electricity output (kWh/m2/day)
1	USA	4	5.34	0.25	0.65	0.50	0.43
2	USA	5	4.84	0.25	0.65	0.50	0.39
3	USA	7	6.49	0.25	0.65	0.38	0.40
4	USA	8	5.36	0.25	0.65	0.32	0.28
5	USA	9	4.98	0.25	0.65	0.32	0.26
6	USA	10	4.31	0.25	0.65	0.32	0.23
7	USA	11	4.33	0.25	0.65	0.38	0.27
8	USA	12	4.63	0.25	0.65	0.43	0.32
9	USA	13	3.28	0.25	0.65	-0.01	0.00
10	USA	14	3.37	0.25	0.65	0.03	0.02
11	USA	15	3.01	0.25	0.65	0.06	0.03
12	USA	16	2.35	0.25	0.65	0.13	0.05
13	USA	18	3.19	0.25	0.65	-0.01	-0.01
14	EU27	7	5.04	0.25	0.65	0.53	0.43
15	EU27	8	4.98	0.25	0.65	0.52	0.42
16	EU27	9	3.86	0.25	0.65	0.28	0.17
17	EU27	10	3.38	0.25	0.65	0.23	0.13
18	EU27	11	3.57	0.25	0.65	0.27	0.15
19	EU27	12	3.63	0.25	0.65	0.35	0.21
20	EU27	13	3.52	0.25	0.65	0.39	0.22
21	EU27	14	3.56	0.25	0.65	0.51	0.29
22	EU27	15	3.28	0.25	0.65	0.25	0.14
23	EU27	16	2.85	0.25	0.65	0.23	0.11
24	EU27	18	3.67	0.25	0.65	0.24	0.14
25	BRAZIL	2	5.73	0.25	0.65	0.74	0.69
26	BRAZIL	3	5.68	0.25	0.65	0.74	0.68
27	BRAZIL	4	5.40	0.25	0.65	0.74	0.65
28	BRAZIL	5	4.87	0.25	0.65	0.75	0.59
29	BRAZIL	6	4.08	0.25	0.65	0.73	0.48
30	BRAZIL	10	5.66	0.25	0.65	0.75	0.69
31	BRAZIL	11	4.99	0.25	0.65	0.76	0.62
32	BRAZIL	12	4.60	0.25	0.65	0.76	0.57

Two checks have been made to validate the results of steps 2 and 3 mentioned above. Figure 1 compares the estimated average DNI obtained from step 2 for the U.S. by AEZ with the observed average GHI from the U.S. installed solar power plants obtained from a data set developed by Bolinger and Bolinger (2022). While one expects to observe some differences between DNI and GHI, Figure 1 shows minor differences in general. The noticeable differences in some AEZs could reflect the high average age of the installed capacities in those AEZs. The results of the second test are presented in Figure 2. This figure compares the estimated average electricity outputs obtained from step 3 for the U.S. by AEZ with the corresponding observed values from the U.S. installed solar power plants obtained from the data set developed by Bolinger and Bolinger (2022). This figure shows that, in general, the estimated outputs are in line with the corresponding actual observations. Due to the lack of actual observations we have not been able to check these tests for other regions of the model

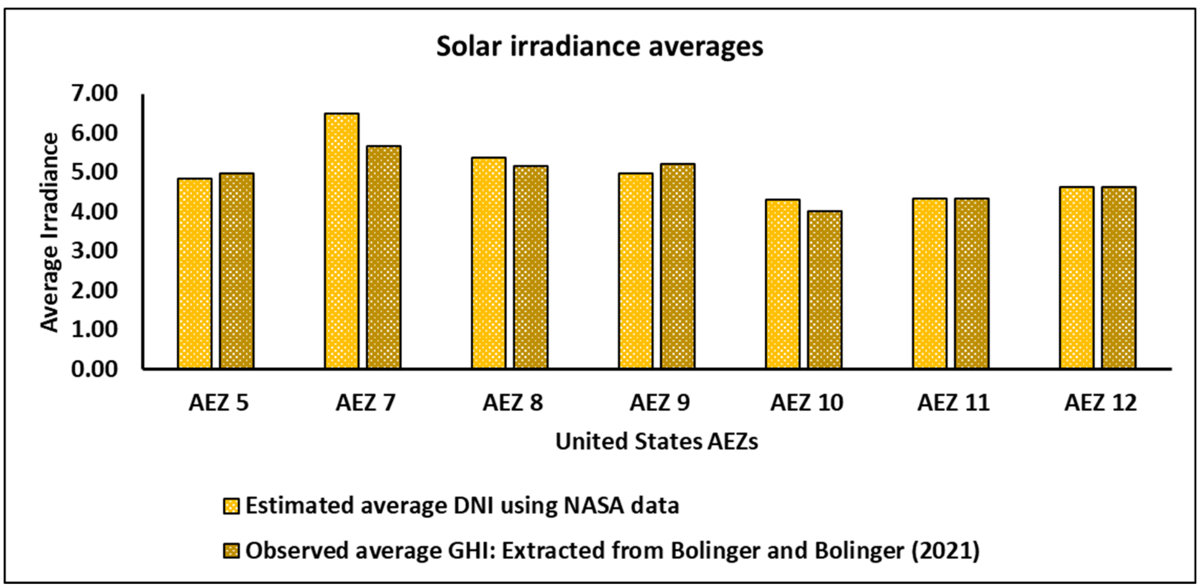


Figure 1. Comparison of the estimated DNI for the US AEZs with the actual GHI observations for the U.S. solar power plants.

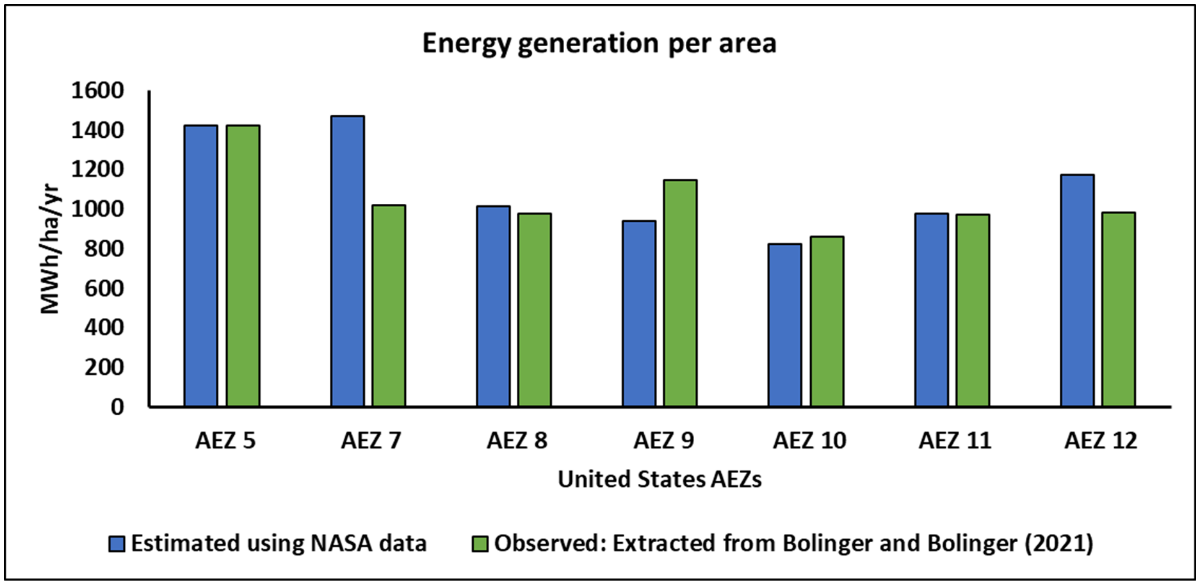


Figure 2. Comparison of the estimated electricity outputs for the US AEZs with the corresponding actual observations for the U.S. solar power plants.

Using the results of step 3 a cost structure is defined for the new industry based on the existing literature that provides data on the costs of producing electricity using solar panels at commercial level (Wiser et al. (2020), Bolinger et al. (2021), Bolinger et al. (2018)). The new sector produces electricity using land and other inputs and converts electricity to SAF. In the current setup, it is assumed that the solar power plant will be installed on marginal land. The new sector is introduced into the model data base by assuming that it has the capacity to produce 155 GWh in the base year.

2.3. Examined scenarios

The study examined the following scenarios for three representative regions: the United States, the European Union, and Brazil.

- ***Scenario I:*** An expansion in solar electricity produced from 155 GWh in the base data to 1705 GWh with no restriction on the location of solar panels by AEZ.

- ***Scenario II:*** An expansion in solar electricity produced from 155 GWh in the base data to 1705 GWh, assuming that the new solar panels will be installed in the most efficient AEZ (i.e., US AEZ7, EU AEZ8 and Brazil AEZ3).
- ***Scenario III:*** An expansion in solar electricity produced from 155 GWh in the base data to 1705 GWh, assuming that the new solar panels will be installed in the least efficient AEZs (i.e., US AEZ10, EU AEZ 10 and Brazil AEZ6).

For each of these scenarios, three emission scenarios have been examined:

- ***Emission scenario E1:*** Land conversion to solar power plants generates the same carbon fluxes as the conversion of land to an annual crop.
- ***Emission scenario E2:*** Conversion of land to solar power plants only generates carbon fluxes due to losses in the above-ground vegetation only.
- ***Emission scenario E3:*** Conversion of land to solar power plants generates no carbon fluxes.

The E1 scenario assumes that the conversion of land to solar power will generate the same carbon fluxes as a conversion of the same land to an annual crop. This could be considered an extreme emission assumption, as converting land to a solar power plant may not affect the soil carbon content. The E2 scenario assumes that converting land to solar power plants only destroys the above-ground vegetation with no losses in soil carbon. The E3 scenario assumes land conversion to a solar power plant does not affect the above and underground carbon stocks. This scenario could be considered an optimistic scenario. The cost structures for the solar electricity sector in different regions have been developed by taking into account the differences in land prices across regions. This was done using data on land rent for each region and AEZ from the GTAP-BIO database. The differences in land area requirements for the initial solar power sector at the fixed specified size are calculated for each region based on the potential solar energy generation values for each region and AEZ. The total capacity for each region is then distributed across different AEZs of the region proportional to their energy generation potential, so more suitable AEZs host a larger share of the initial solar electricity sector.

3. Estimated ILUC values

Table 2 shows the ILUC values for each scenario mentioned above. As shown in this table, the ILUC emissions for producing PtL SAF using solar electricity are generally small and comparable with the lower range of ILUC emissions from producing SAF from food crops, although they are larger than commonly negative ILUC values of cellulosic crops SAF pathways. The results suggest that:

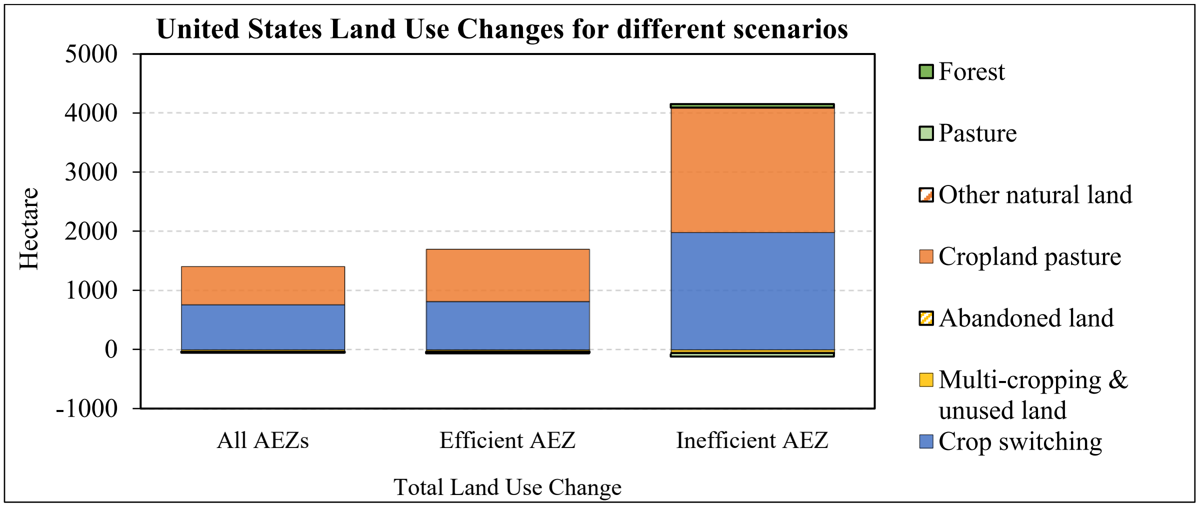
- In each region producing electricity in the most efficient AEZ (scenario II) may note provides the smallest ILUC emissions value, due to various indirect land use change.
- In each region producing electricity in the least efficient AEZ (scenario II) may note provides the largest ILUC emissions value, due to various indirect land use changes.
- ILUC emission values vary by region, as land characteristics are different across regions.
- Across emissions scenarios, the E1 cases generate the highest ILUC values while the E3 cases demonstrate the lowest ILUC values, with a few exceptions.

Table 2. ILUC values for three regions and nine examined scenarios (gCO_2e/MJ SAF)

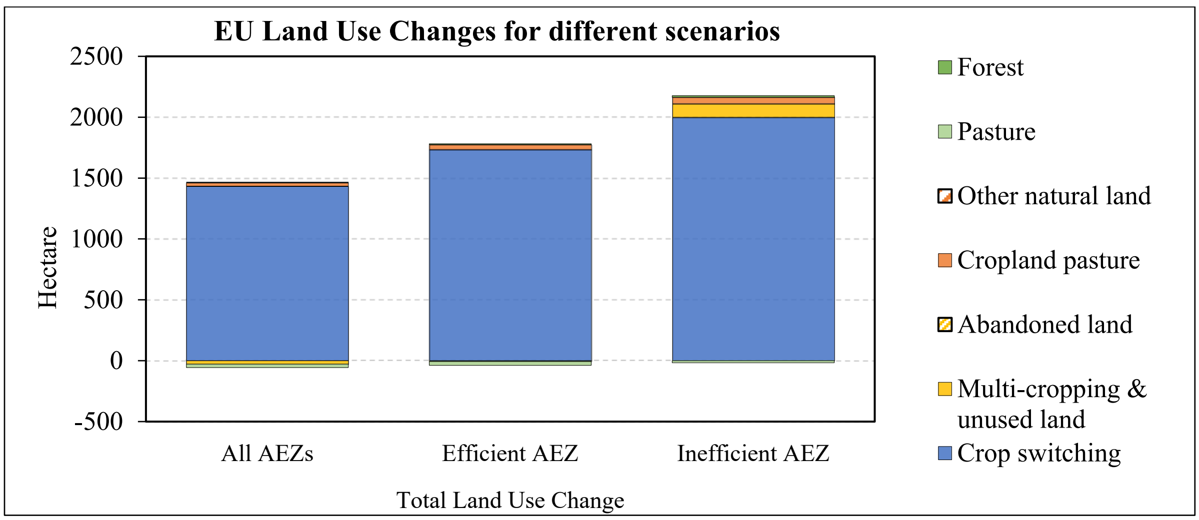
Description		Emission scenario E1	Emission scenario E2	Emission scenario E3
USA	Scenario I	0.88	0.60	0.05
	Scenario II	0.97	0.55	-0.35
	Scenario III	4.42	2.57	-0.70

EU27	Scenario I	0.55	0.54	0.50
	Scenario II	0.12	0.12	0.12
	Scenario III	0.89	0.89	0.89
Brazil	Scenario I	3.74	3.64	3.31
	Scenario II	4.13	4.04	3.52
	Scenario III	7.50	6.98	4.58

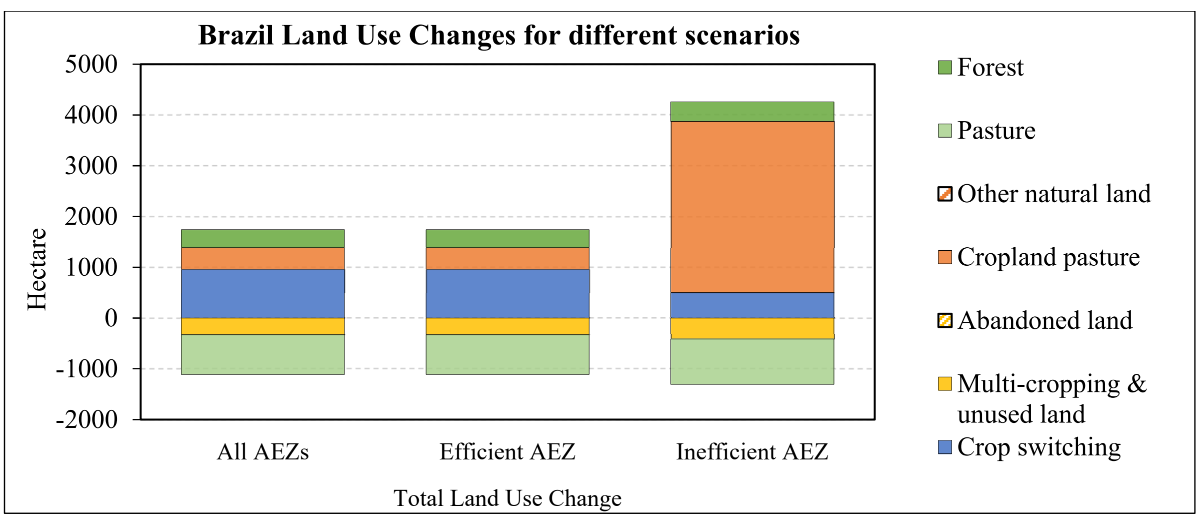
Figure 3 represents the land use changes for each region and scenario. As we can see in Figure 3a, in the US most of the required land for solar electricity production comes from cropland-pasture (a marginal land for crop production) and current croplands. These croplands are not the best lands for crop production. In the EU, due to the absence of cropland pasture, the majority of the required area comes from current less productive croplands which is shown in figure 3.b. For Brazil, figure 3.C. demonstrate that a combination of cropland-pasture, current cropland and some deforestation provides the required land for solar electricity generation. We can also see an increase in Brazil's pasture area to compensate for the decrease in animal feed production due to the reduced area of cropland pasture in this region. Although a similar effect is present in the US and EU land use change profiles, the magnitude of the increase in pastureland is not significant in those regions compared to Brazil's increase in pastureland. Note that cropland pasture is used by the livestock industry.



3.a. United States land use changes for Power-to-Liquid SAF from solar energy



3.b. European Union land use changes for Power-to-Liquid SAF from solar energy



3.a. Brazil land use changes for Power-to-Liquid SAF from solar energy

Figure 3. Land use changes for Power-to-Liquid SAF from solar energy for the examined regions and scenarios

4. Conclusion

In the context of sustainable aviation fuel (SAF), Power-to-Liquid (PtL) technology has been gaining attention as a promising alternative to traditional jet fuels, given its potential to reduce greenhouse gas (GHG) emissions. However, the production of PtL SAF also requires electricity and producing this electricity from renewable sources such as solar can lead to indirect land use change (ILUC) emissions. These emissions result from the displacement of agricultural or forest land caused by the expansion of solar power plants.

Table 2 shows the ILUC values associated with generating solar electricity for SAF via PtL for different scenarios, when solar power plants are installed on the marginal land. The results demonstrate that, in general, producing SAF via PtL generate tiny ILUC values when electricity is generated on marginal land. The ILUC value is smaller, when we assume solar power plants are distributed across all viable AEZs (Scenario1, regardless the emissions assumptions). When we assume the power plants are installed in a single AEZ (either in the most efficient DNI or with the least efficient DNI) ILUC values grow slightly. That suggests that the location of solar power plants cause interactions with agricultural production.

Moreover, the table shows that emission scenario E3, which assumes no emissions from conversion of land to solar power plant, results in the lowest emissions, while emission scenario E1, which assumes the full emission of converting land, produces the highest amount of ILUC emissions, which is consistent with what we would expect. However, the differences between scenarios vary across different regions. The results show that the estimated ILUC emissions are most sensitive to emission scenarios for the United States, followed by Brazil, with very small differences between emission scenarios for the European Union. These observations can be explained by the difference in types of converted land in these regions and the fact that in our version of the model, both the United States and Brazil have cropland-pasture category as a type of marginal land that solar land directly competes with. In contrast, in the European Union, due to the absence of this marginal land type, most of the required land for solar energy generation comes from cropland and the emissions from conversion of cropland to solar land do not vary significantly across our emission scenarios. However, conversion of cropland-pasture or other land covers like forest and pasture to solar land produces significantly different ILUC emissions based on the adopted scenario which is reflected in the United States and Brazil results.

Finally, the energy output of PtL SAF produced using solar electricity from one hectare of land is significantly higher than producing SAF from other biofuel pathways. The comparison between PtL SAF from solar electricity and biofuel SAF from poplar, for instance, reveals that we can produce 17 times more SAF using the former. This finding explains small emission numbers for PtL pathways compared to most of biofuel pathways and suggests that the PtL pathway using solar electricity can potentially maximize the use of available land, making it a promising option for producing sustainable aviation fuel. However, producing SAF with cellulosic materials could generate ILUC values as these feedstocks could generate soil carbon benefits.

References:

- Batteiger et al. (2022) “Power-to-Liquids” A scalable and sustainable fuel supply perspective for aviation,” German Environmental Agency, Wörlitzer Platz 1, 06844 Dessau-Roßlau Germany.
- Bolinger et al. (2019) “Empirical trends in project technology, cost, performance and PPA pricing in the United States,” Lawrence Berkely National Laboratory.
- Bolinger, M., Seel, J., Warner, C., & Robson, D. (2021). Utility-Scale Solar, 2021 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States [Slides]. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).
- Bolinger, M., & Seel, J. (2018). Utility-scale solar: Empirical trends in project technology, cost, performance, and PPA Pricing in the United States–2018 Edition. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).
- Bolinger and Bolinger (2022) “Land requirements for utility-scale P.V.: An empirical update on power and energy density,” *IEEE Journal of Photovoltaics*, Vol 12. No. 2.
- CORSIA (2021) “CORSIA eligible fuels - life cycle assessment methodology,” Version 4, November 2021, ICAO.
- Hertel et al., (2010). “Effects of us maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses,” *Bioscience*, 60.
- Hertel, et al., (2010b), The global impacts of biofuel mandates, *Energy Journal*, *30*(1), 75–100.
- NASA Langley Atmospheric Sciences Data Center. Solar: Average Monthly and Annual Direct Normal Irradiance Data, One-Degree Resolution of the World from NASA/SSE, 1983-2005. [Shapefile]. NASA Langley Atmospheric Sciences Data Center. Retrieved from https://geo.nyu.edu/catalog/stanford-fd535zg0917
- Ong et al. (2013) “Land use requirements for solar power plants in the United States,” Notational Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-6A20-56290.
- Prussi et al. (2021) “CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels,” *Renewable and Sustainable Energy Reviews*, 150, 111398.
- Searchinger et al. (2008) “Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change,” *Science,* 319.
- Taheripour et al. (2010), Biofuels and their by-products: Global economic and environmental implications, *Biomass and Bioenergy*, *34*(3), 278–289.
- Taheripour et al., (2012), Biofuels, cropland expansion, and the extensive margin, *Energy, Sustainability and Society*, *2*, 25.
- Tyner, W. E., and F. Taheripour (2012), Land-use changes and CO2 emissions due to U.S. corn ethanol production, in *Encyclopedia of Biodiversity*, vol. *4*, second ed., edited by S. A. Levin, pp. 539–554, Academic Press, Waltham, MA.
- Taheripour, F., and W. E. Tyner (2013a), Biofuels and land use change: Applying recent evidence to model estimates, *Applied Sciences*, *3*, 14–38.

- Taheripour, F., and W. E. Tyner (2013b), Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors, *Economics Research International*, *315787*, 12 pp.
- Taheripour et al. (2017) "An exploration of agricultural land use change at intensive and extensive margins, *Bioenergy and Land Use Change*. John Wiley &Sons, Inc.
- Taheripour et al. (2022). "Oilseed Cover Crops for Sustainable Aviation Fuels Production and in Greenhouse Gas Emissions Through Land Use Savings," *Frontiers in Energy Research*, 9 (790421), 10.
- Zhao et al. (2021) "Estimating induced land use change emissions for sustainable aviation biofuel pathways," *Science of the Total Environment,* 779, 146238**.**
- van de Ven et al. (2021) "The potential land requirements and related land use change emissions of solar energy, *Scientific Reports*, 11: 2907.
- Wiser, R. H., Bolinger, M., & Seel, J. (2020). Benchmarking utility-scale PV operational expenses and project lifetimes: results from a survey of US solar industry professionals. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).