Land conservation and the renewable energy transition are simultaneously possible in Brazil

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Land conservation and the renewable energy transition are simultaneously possible in Brazil

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1 Abstract

Brazil is crucial to tackling climate change and halting biodiversity loss. Yet given its intention to rely on biofuels for clean energy, there is a growing risk that uncoordinated policy leads these goals to compete with each other. Here we explore their interplay through long-term energy scenarios based on a spatially explicit energy system model. We find that in a baseline scenario where Brazil doubles biofuel use by 2050, substantial dedicated land is needed, converting mostly degraded pastures. More importantly, with appropriate planning, renewable energy combined with biofuels can meet demand in highly electrified systems where emissions decline by 40%-91% without conflicting with conservation-relevant lands and without a noticeable effect on energy system costs. Finally, these conservation-relevant lands can be reforested and thereby contribute up to 15.43 Gton of carbon stored, showing that climate change mitigation and ecosystem recovery can be synergistic.

2 Introduction

Though it is critical for successful climate mitigation, there is a growing risk that the clean energy transition conflicts with other Sustainable Development Goals such as SDG 15 (life on land), SDG 14 (life below water), and SDG 6 (clear water and sanitation) [1]. In particular, large-scale land requirements for bioenergy crops [2] and renewable energy technologies [3, 4] can drive ecosystem loss and degradation. This is particularly acute in Brazil, which is by far the most biodiverse country in the world [5] and therefore critical for stemming biodiversity loss while being critical for successful climate mitigation through its energy and land use. Despite the importance of conservation-relevant lands for supporting ecosystem services, many remain unprotected and vulnerable to human activities that might lead to land conversion and fragmentation [6]. Brazil's long-term commitments include climate neutrality by 2050 [7] and using biofuels as vectors for decarbonization and development, supported by the RenovaBio program launched in 2020. However, these long-term goals fail to provide guidance for spatial planning. By pushing new crops and pastures onto native lands [8], they risk worsening issues related to food security, land conflict, biodiversity [2, 9] and deforestation, particularly in the Cerrado savanna and Amazon rainforest. Likewise, onshore wind farms have been leading to conflicts with local communities [10], while several parks have been deployed in priority areas for biodiversity conservation [11].

From the energy system perspective, a massive expansion and penetration of renewable energy leads to operational questions related to balancing variable generation and demand. Energy systems models with high temporal and spatial resolution can design technically feasible renewable energy supply systems [12], usually by performing cost minimization. However, most such studies use location-specific resource profiles, assuming (implicitly) unlimited land availability [13]. Also, many studies do not consider sector coupling and the interdependencies among different energy carriers, leaving potential synergies and curtailment minimization unaddressed [14, 15].

Here, we explore both the long-term future of the Brazilian energy system and its connection to land use and biodiversity conservation through a spatially explicit multi-model that minimizes costs while meeting the demand for 2050 (Figure 1a). The first model component assesses bioenergy, considering suitable lands for feedstocks and their seasonality, conversion technologies, storage, and transportation costs. The second model component depicts the power sector, including the expansion of mature technologies. Across both models, we focus on scenarios for different degrees of electrification (adding to the current electricity demand [16]) combined with policies of land use (preventing the use of conservation-relevant lands for energy purposes) and fossil fuel phaseout (enforcing 100% renewable energy supply), as well as the combination of both these policies (Figure 1b). Our approach permits us to show how much land is needed for bioenergy crops and energy-related infrastructure in 76 zones (Figure 1c), where this infrastructure should be located, as well as the resulting costs and land use impacts. Comparing scenarios with and without land use restrictions permits us to investigate the potential for negative land-use emissions by shifting energy infrastructure away from conservation-relevant lands (Figure 1d) to preserve and restore them. For that, we calculate the potential contribution of reforestation by using a carbon stock difference approach (Figure 1d).

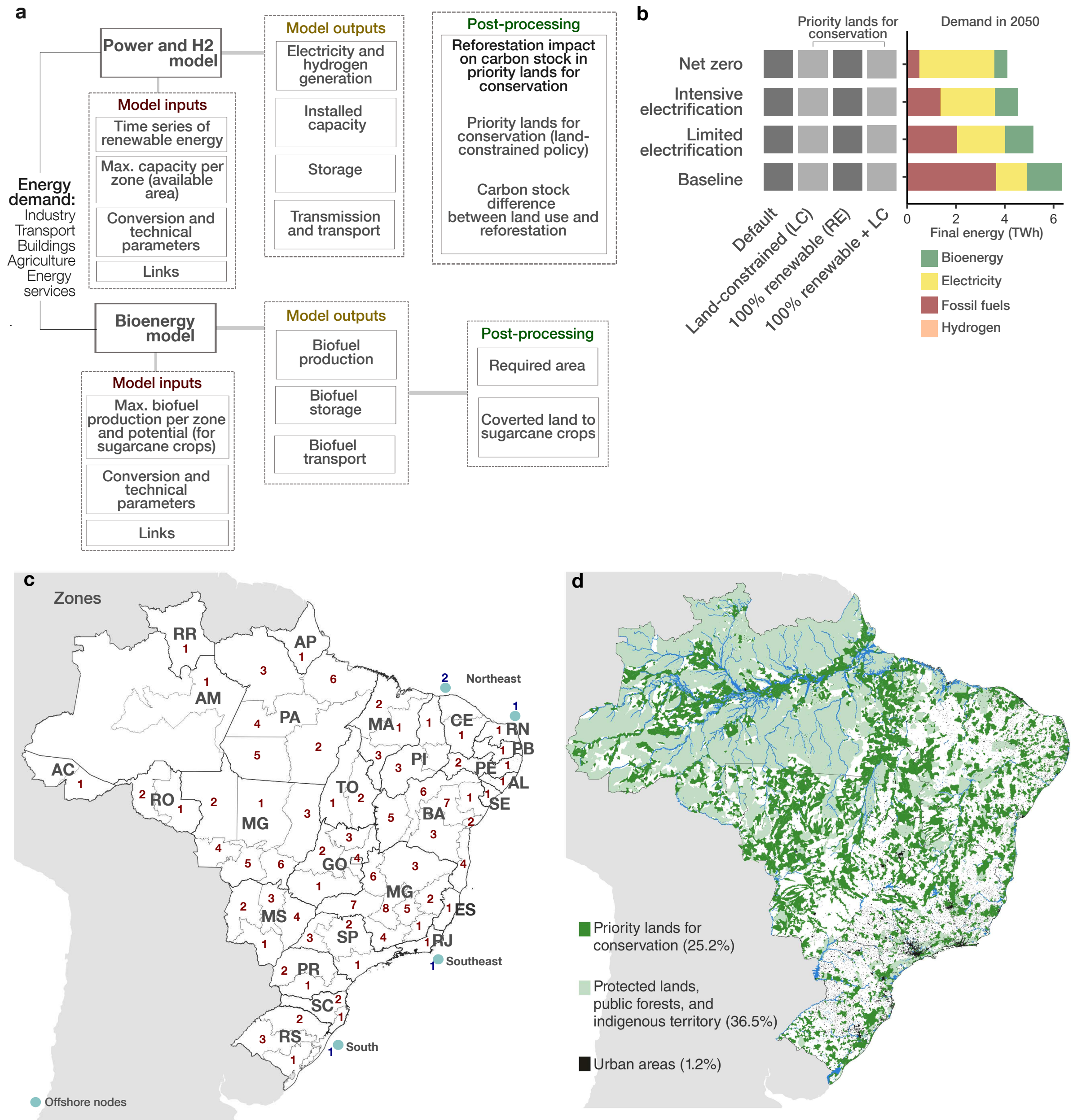

Figure 1 **a,** The workflow indicates the inputs, outputs, and post-processing stages such as the required area calculations, land use conversion analysis, and carbon stock potential of reforestation in priority lands for conservation. **b,** Scenarios for energy demand and energy system transformation (y-axis) and the policies for land-use and renewable energy deployment (x-axis). Each square of the resulting scenario-policy matrix is assessed in our multi-model approach. The plot on the right represents the total final demand for fossil fuels, electricity, bioenergy, and hydrogen. **c**, 76 Zones of the Brazil power system model. The two-letter state (grey) and the numbers (red) refer to the zones belonging to each state. Four of the zones, represented by light blue dots are the regions considered for offshore wind energy. The name (grey) is related to the region and the numbers to the zones of each region. **d,** Overview of existing protected lands (light green) and additional priority lands for conservation, which are removed from consideration for energy infrastructure or bioenergy in the land-constrained (LC) policies.

Our study is the first comprehensive analysis of Brazil's complex interactions between renewable energy, land use, and conservation. As the speed of energy system transformation increases at the same time as the urgency to preserve the biosphere grows, it provides insights for policymakers into sustainably achieving long-term decarbonization simultaneously to other Sustainable Development Goals (SDGs). Our underlying model is made available freely online and fully re-usable for the further study of Brazil or other countries. Our results include multiple years of bias-corrected wind and solar data covering all of Brazil, as well as extensive geo-referenced data, all of which can be freely re-used.

3 Results

3.1 Renewables can meet even highly electrified future demand

We build a cost-minimizing energy system model to design an energy supply system for Brazil that meets all demands for energy across the industry, transport, buildings, and agriculture sectors. We consider the spatio-temporal variability of renewable supply and energy demand resolved to 76 model regions within Brazil with a 3-hourly resolution. The model is run for all combinations of scenarios and policies, resulting in 16 system configurations. In all cases, power generation relies mainly on renewable energy (Figure 2a). In the baseline scenario with default, 100% RE, and land-constrained policies, the system requires 394-398 GW of installed power generation capacity, 92-100% of which are renewable energy technologies. With high levels of electrification in the net zero scenario, Brazil would need more than three times the installed capacity of the baseline, with the cost-optimal configuration consisting of 43% wind energy and 24% solar energy (though other combinations of wind and solar energy are equally possible). To put this into context, in the cost-optimal solution for the net zero scenario, our most ambitious case, Brazil would deploy roughly 633 GW of onshore wind capacity, or 7.5 GW per 100,000 km^2 of land surface. This is less than half the current capacity density of Germany, which has roughly 60 GW of onshore wind capacity as of 2023, that is, 17 GW per 100,000 km^2 of land surface. This suggests that meeting even highly electrified future demand is possible with renewables in Brazil.

We perform two sensitivity analyses: first, running the baseline scenario with both the default and net zero policies with 100% RE + LC across 20 weather years (2000-2019), and second, varying the capital expenditure (capex) and operating expenses (opex) of onshore wind and utility-scale PV technologies based on the conservative, moderate and advanced cases of NREL [17]. The weather year 2017 is the reference, and all results refer to it unless otherwise indicated. The weather sensitivity analysis shows that the standard deviation of installed capacity in the net zero scenario is higher than in the baseline scenario, indicating that large renewable systems are more vulnerable to weather conditions. The cost sensitivity analysis indicates that the moderate case of wind farm costs resulted in larger wind capacity than the advanced case (lower costs), where we observed an increase in solar farm capacity (Figure 2b).

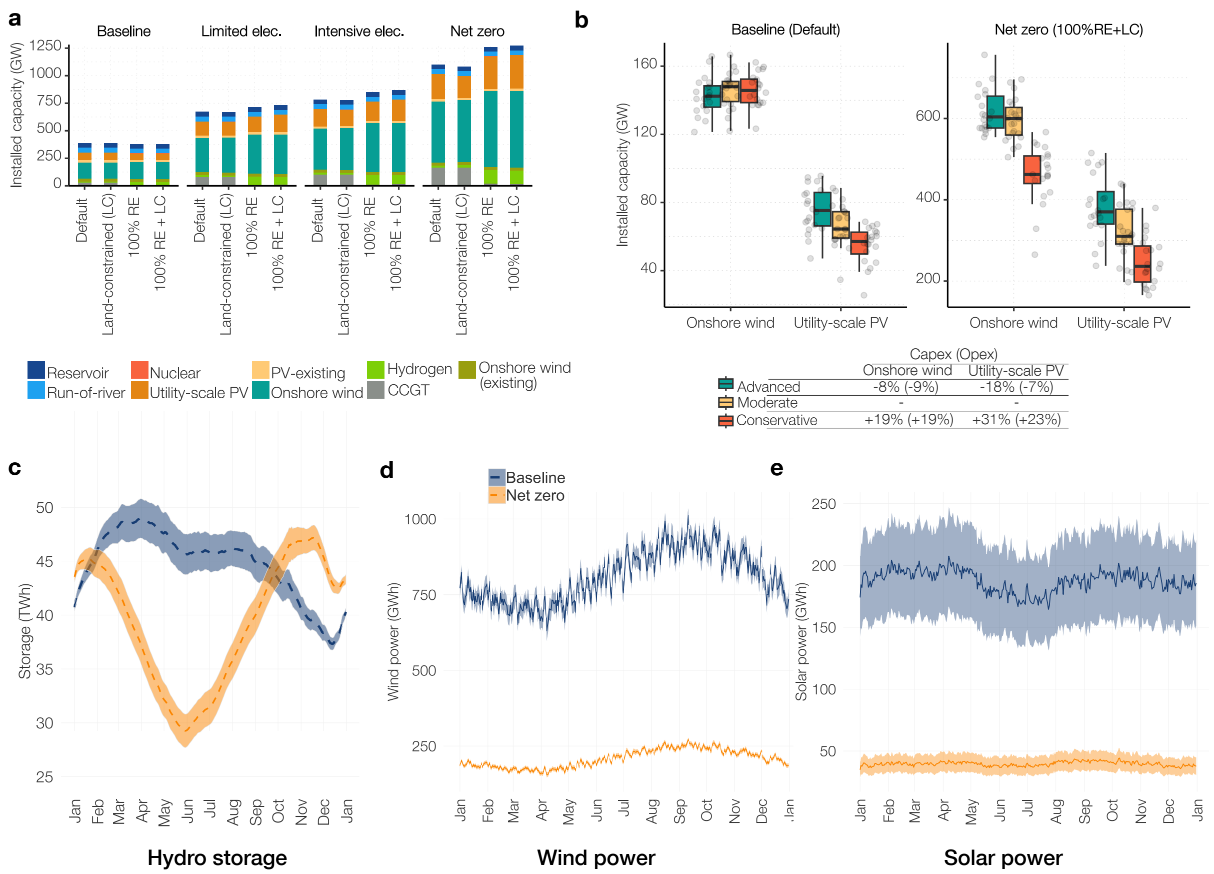

Figure 2 **a,** Installed capacity in the reference weather year of four scenarios and four policies. **b,** Box plots of installed capacity in the baseline (default) and net zero (100%RE+LC) scenarios of three cases of costs: advanced, moderate, and conservative. The light grey markers are the results across the weather years (2000-2019). The capex and opex (in parenthesis) variations compared to the moderate case are indicated below the box plot. **c,** The dashed line indicates the daily hydro storage over the reference year of baseline default (yellow) and net zero 100%RE+LC (blue). All other results of different weather years are in the transparent area. **d,** Wind power production over the reference year (dashed line) in the baseline default (yellow) and net zero 100%RE+LC (blue), and other results of different years (transparent area). **e,** Solar power production over the reference year (dashed line) in the baseline default (yellow) and net zero 100%RE+LC (blue), and other results of different years (transparent area).

We find that hydro reservoirs (145 TWh of maximal storage capacity) remain the main electricity storage system. Their dispatch changes with the addition of large-capacity wind farms in the net zero scenario (Figure 2c). In the dry season (from June to September [18]), wind power output is usually larger than in the rainy season, implying a reduction in hydro dispatch (Figure 2d and Figure 2e). However, the system consumes much of the available hydropower potential during the rainy season, when demand is higher and wind potential is lower, implying less storage of hydropower reserves. Dispatchable natural gas-fired power plants are still part of the solution for peak hours, particularly during the rainy season (summer) in the baseline scenario. However, in 100% RE cases, natural gas is completely replaced with renewable energy, including green hydrogen as storage, which is then converted back to electricity.

3.2 Biofuel production sparks land use conflicts

Although wind and solar farms have a substantial land use footprint, particularly in the net zero scenarios, direct land use is relatively low - for example, wind farms can be placed on farmland, and solar farms can co-exist with grazing animals or certain types of agriculture. However, crops for biofuel production need a significant dedicated land area, in the worst case, leading to land conversion from other uses to agriculture. Given the stated aim of Brazil to let biofuels play a key role in decarbonization, it is important to investigate the resulting land footprint more closely.

The bioenergy model includes 72 zones and five carriers: ethanol from sugarcane (first and second generation), first-generation ethanol from corn, biodiesel and hydrotreated vegetable oil (HVO) from soybean, sustainable aviation fuel (SAF) from ethanol and soybean, and charcoal. In our model we limit land availability for sugarcane crops to the Agroecological Zoning of Sugarcane (revoked decree that established spatial planning for sugarcane crop expansion) [19], that for corn exclusively to existing off-season crops (where corn is grown outside of the typical growing season), that for soybean to existing soybean crop areas. Charcoal's potential is given by existing silviculture activity [20]. We run the bioenergy model for all combinations of scenarios with default and land-constrained policy in a 120-hourly resolution.

Liquid biofuel production reaches 74.7 billion liters in the baseline scenario, almost double the current production, but decreases to 43.3-17.2 billion in the electrification scenarios (Figure 3a). Fossil fuels still represent 57%, 39%, and 30% in baseline, limited, and intensive electrification scenarios. First-generation ethanol is still relevant in the intensive electrification scenario, particularly for the industry sector (food and beverage, ceramic, cement, etc). However, in the net-zero scenario, which assumes near-complete electrification, the demand for ethanol is completely replaced by electricity. We assume instead that the demand for hard-to-electrify transport subsectors (aviation, shipping, and long-distance road freight) is met by 44.6 billion liters of HVO and SAF, eliminating fossil fuels for the transport sector. To see the detailed biofuel demand for each subsector see the Supplementary Material.

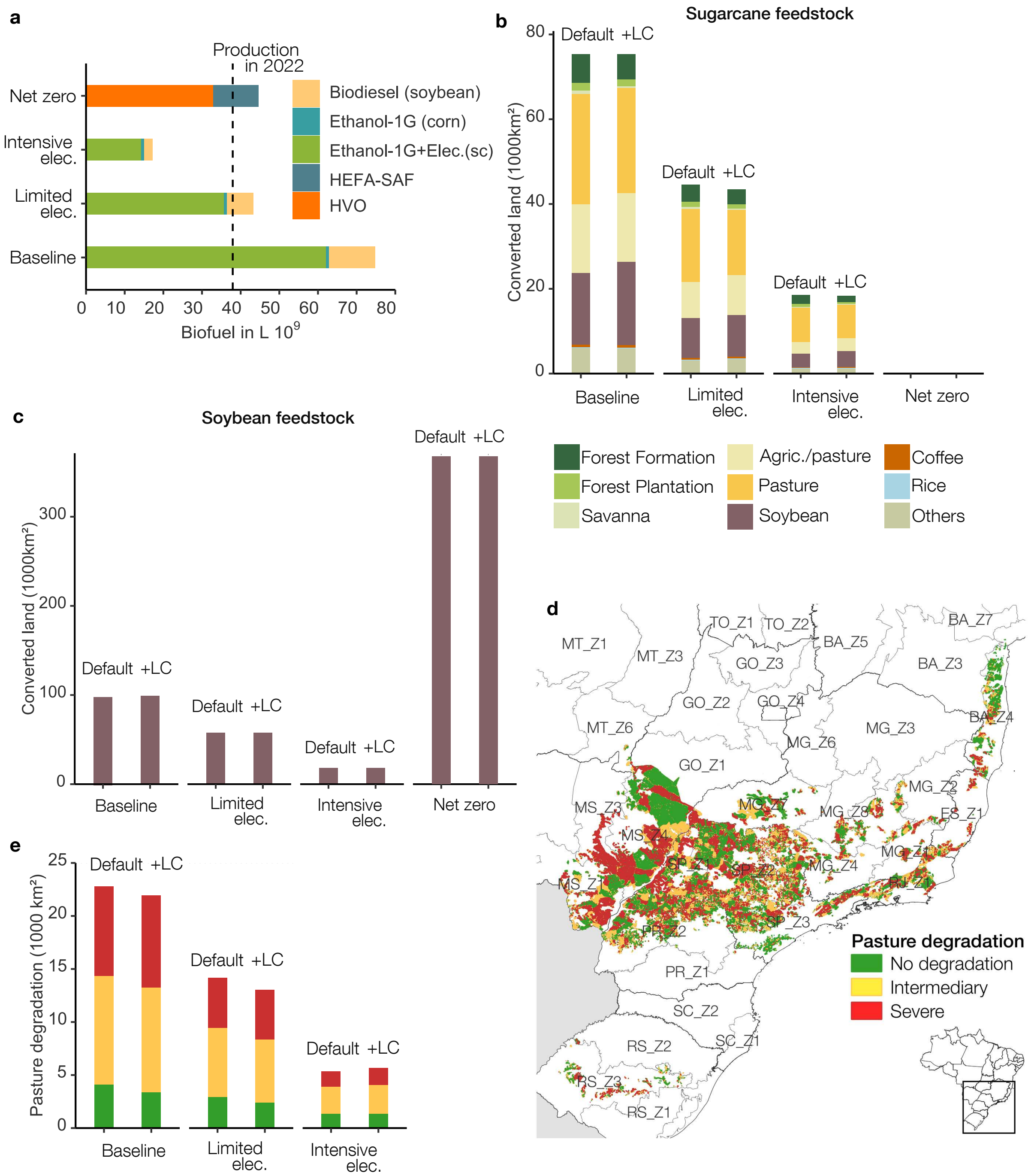

Figure 3 a) Production of liquid biofuels in four scenarios: baseline, gradual electrification, intensive electrification, and net zero. The biofuel production is the same for both default and land-constrained (+LC) policies. The dashed line indicates today's production (37.9 billion liters). (sc.) represents ethanol from sugarcane. b) Total dedicated land area in km² to produce liquid biofuels from soybeans in four scenarios. The total converted land is the same for default and land-constrained policies. c) Land conversion to sugarcane crops to produce ethanol. Default indicates that there is no policy, while +LC represents the land-constrained policy (the use of priority lands for conservation is not allowed for energy purposes. d) Level of pasture degradation (severe, intermediary, and no degradation) in areas with high potential for sugarcane crops. e) Converted area of pasture to sugarcane crops in four scenarios with no policy (default) and +LC (land-constrained).

We consider two technologies for SAF production, however, we assume the least-cost-option (HEFA plants with soybean oil as feedstock) are used for SAF production. For HVO, we consider its production exclusively from soybeans and their existing crops. Due to the lower yield of soy crops compared to sugarcane, the net zero scenario requires more land than other scenarios: 360,000 km^2 compared to around 20,000-200,000 km^2 of dedicated land in the other three scenarios (Figure 3b).

Charcoal rises to 9.8 Mton (baseline) and drops to 8.9 Mton (electrification and net zero) due to the electrification of the building and agriculture sectors. Still, the production of charcoal exceeds current levels by 44% (baseline) and 31% (electrification, net-zero), primarily due to its use in heavy industry (pig iron steel, and cement).

Sugarcane remains the primary feedstock for ethanol production, and utilizing bagasse for electricity combined with storage systems is more viable than second-generation ethanol in our work. To avoid food conflict, we assume that corn-based ethanol expansion beyond the current production is not possible as it requires almost twice the land to produce a liter compared to sugarcane. Corn-based ethanol reached its maximum production in all scenarios (0.67 bln L).

We limit the production of soybean to existing soy crop areas, but allow for expanding sugarcane to produce ethanol on additional potential lands (classified into high, medium, and low potential cultivation areas). This means that the land may currently be used for something other than sugarcane. Resulting from this, we find a large area conversion from pasture, mosaic of agriculture and pasture, and soybean, to sugarcane crops (Figure 3c). Although rice and coffee have a smaller share, their conversion to sugarcane crops may impact food production. Together, the converted area sum up to 848 km^2 in the baseline scenario (default) and would decline to 328 km^2 in extensive electrification (default).

While sugarcane crops compete with other uses, results show that land management can reduce the conflicts. For example, 67-81% of pasture lands converted to sugarcane crops are degraded pastures (Figure 3d,3e), which could have higher livestock productivity through their recovery occupying a smaller area.

3.3 Restricting use of conservation priority land does not lead to higher costs

The land-constrained (LC) and 100% renewable (RE) + land-constrained (RE+LC) policies entirely prevent the use of lands with priority conservation status for energy purposes. This shifts the deployment of wind and PV capacity or bioenergy crops to different locations. The power system configuration remains entirely unchanged when introducing land constraints in the baseline scenario, as sufficient land remains available at the most optimal deployment locations. On the other hand, we observe significant changes in where renewable electricity generation is deployed in the electrification and net zero scenarios. For biofuels, the largest shifts of bioenergy crops occur when imposing land constraints in the baseline scenario, which has the largest ethanol demand. Sugarcane crops for ethanol production move into a new arrangement, with a reduction of crops in the Southeast and an increase of crops in the Midwest (Mato Grosso do Sul), South (Paraná), and Northeast. Figure 4 shows the main changes in wind and solar capacity in the net zero scenario and ethanol production in the baseline scenario.

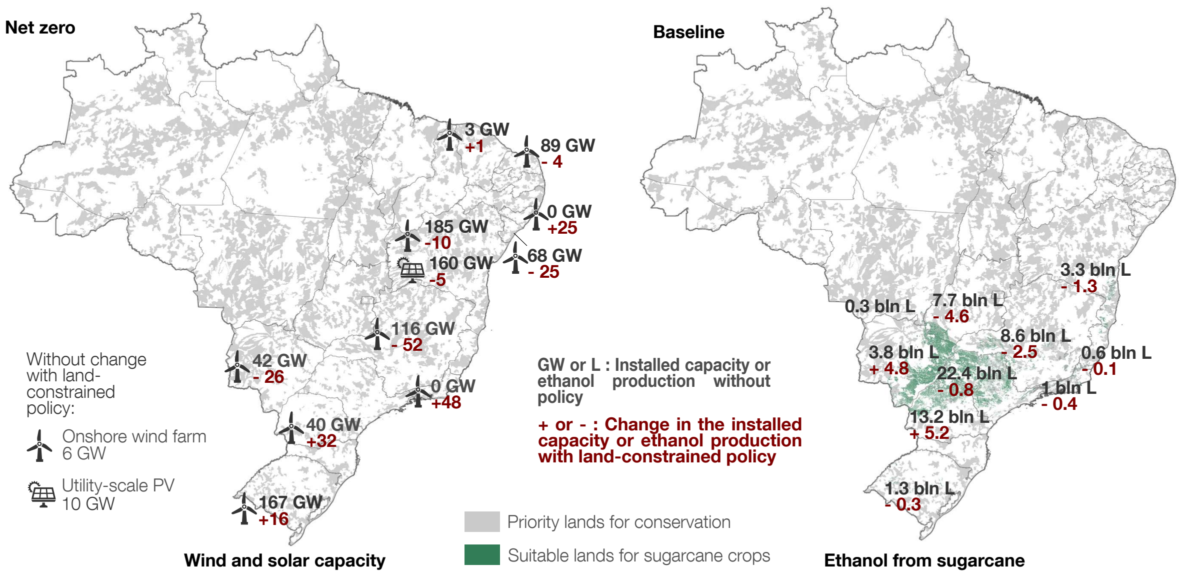

Figure 4 Shifts in the installed capacity of wind and solar farms (left) and in ethanol production (right) when land-constrained policy is considered. The first map represents the changes in the net zero scenario, and the second one indicates the changes in the baseline scenario.

We find that preserving priority land for conservation has no cost effect in the baseline and only a minimal additional cost in more electrified scenarios, ranging from 0.1% to 4% of the total levelized costs without land-constrained policy, even with significant shifts of optimal locations. For sugarcane crops dedicated to ethanol production, we observed that the total costs remain unchanged with the land shifts. This further suggests that many near-optimal alternative solutions exist and shows that a completely renewable energy system can co-exist with a strong land conservation policy.

3.4 Land management and energy transition are essential to reduce emissions effectively

The baseline scenario has substantial emissions, reaching 887 MCO_{2eq} from fossil fuel combustion and an additional 137 MCO_{2eq} from biogenic emissions (Figure 5a). As the scenarios progressively shift towards electrification, the emissions decline. In the net zero scenario, the emissions fall by 91% compared to the baseline (without biogenic emissions), to 79 MCO_{2eq}. The remaining emissions come from cement, chemical, and metallurgical industries, which our model assumes cannot be decarbonized (possible solutions such as CCS are not considered).

The carbon stock balance from land conversion to sugarcane crops is positive, as many converted lands are currently degraded pasture. The CO_2 removal varies according to the demand for ethanol, being larger in the baseline scenarios (174-223 MCO_2) and lower in the electrification scenarios (21-119 MCO_2). Scenarios with the default policy have lower CO_2 absorption than the land-constrained (LC) policy, in which removals increase by 21-48 MCO_2. This is because with the land-constrained policy we avoid land use for energy purposes in areas with larger carbon stock. Emissions due to land conversion for the production of HVO, SAF, corn-based ethanol, and biodiesel are considered inexistent, as we restrict their feedstock production to existing cropland areas and thus assume no changes in the land use class.

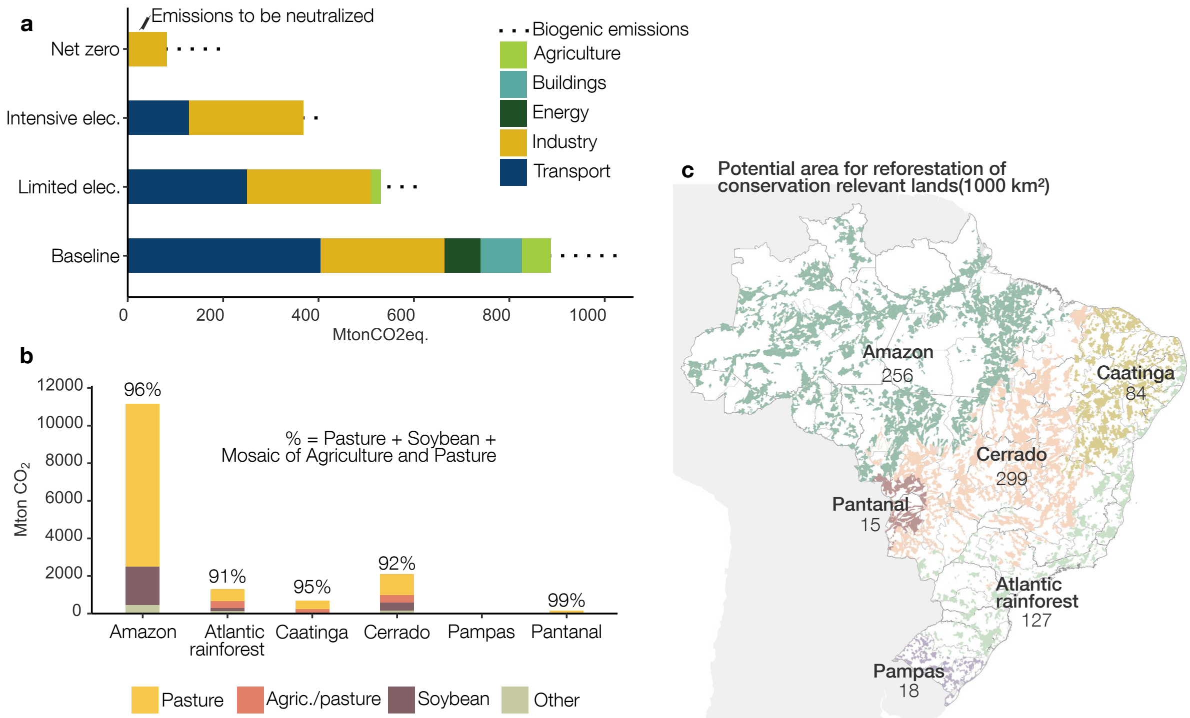

Figure 5 a) Fuel combustion emissions from the agriculture, building, industry, transport sectors, and energy services for hydrogen production in the 100% RE scenarios (except LCA emissions). The plot does not include the power sector. The dots represent the biogenic emissions. b) Carbon stock potential of six biomes by recovering 100% of priority lands for conservation. The percentage above the bars indicates the share of land use that is pasture, soybean, and mosaic of agriculture and pasture. The absorption is for the area highlighted in 5c. c) Potential area for reforestation by biome considering the total area of priority lands for conservation. The number below the biome's name represents the total area of proposed recovery in 1000 km^2.

We find that land management toward land recovery and reforestation in conservation-relevant lands could further help mitigate climate change. When lands are freed up from energy use in scenarios with the land-constrained (LC) policy, the potential CO_2 sequestration due to reforestation is high. A total of 15,43 MCO_{2eq} additional carbon stored is possible (Figure 5b), without considering possible losses due to wildfires. The Amazon Rainforest contributes to 72% of the potential, followed by the Cerrado, which has an additional carbon stock of 2,090 MCO_{2eq} and contains the largest area of priority lands for conservation (Figure 5c). Apart from the carbon stored, the annual CO_2 absorption is slightly higher in the Cerrado (386 $MCO_{2eq}.year^{-1}$) than in the Amazon (314 $MCO_{2eq}.year^{-1}$).

Most of the land proposed for reforestation is currently used for pasture and soybean production in all biomes (91-99%), while food production (excluding beef) represents 0.98%. There is a potential for better land management, particularly of pastures, but the high dependency on soy-based biofuel in the net zero scenario may itself lead to significant land conflicts.

4 Discussion

We find that optimal energy systems rely mainly on renewable energy, even in highly electrified systems. In our scenarios, onshore wind is the predominant source of clean electricity, followed by centralized solar generation, regardless of the policy considered. Offshore wind farms were not assumed to be cost-competitive in our work, but based on work elsewhere in the world [15], it is reasonable to assume that looking for near-optimal alternative energy system configurations, systems with high shares of offshore wind would be equally feasible. The demand for biofuels in 2050 is significant for both the net zero (HVO and SAF) and the baseline scenarios (mainly ethanol), exceeding the current level of biofuel production.

Crops for biofuels need significant direct land use, leading to land conversion, impacting particularly existing pastures and soybean crops in baseline and electrification scenarios. A deeper analysis of converted pasture lands reveals they are primarily degraded pastures, suggesting potential positive outcomes through transitions to sugarcane crops and increased ecosystem services, as also confirmed in another study [21]. Biofuels in the net zero case are fully based on soybean feedstock, requiring a land area equivalent to 49% of Brazil's current soybean land (360,000 km^2) [22]. With a substantial portion of current soybean production being dedicated to animal feed (76% [23]), further land expansion may occur to meet energy and non-energy feedstock demand. Without significant worldwide dietary shifts and land management, Brazil risks facing land conflicts and deforestation. Diversifying feedstocks could help alleviate the land conflict associated with biofuel production, although it may not completely eliminate land stress. We only consider national demand for energy, however, the demand for biofuels may be considerably higher if they are traded internationally.

The required area for the expansion of the energy system, particularly for biofuels, is significant. Restricting the energy-related use of priority lands for conservation impacts the energy system's configuration and feedstock crops' location. Findings show that the land-constrained policy is a strategic way to mitigate biodiversity loss, resulting in no significant difference in energy costs compared to cases without land restriction. Even in the more electrified scenarios, where optimal locations may undergo substantial shifts, the cost increase does not surpass 4% beyond the optimal cost. Given the considerable uncertainties in future technology costs, this can be considered an insignificant increase and essentially the same cost as the cost-optimal configuration. Past work using Modelling to Generate Alternatives (MGA) methods has considered a cost increase of even 10% acceptable [24].

Another point of attention is water use, which we ignore in our model. Although sugarcane crops for ethanol production are shifted to regions with a well-developed agribusiness sector, the water conflict between consumptive uses is a drawback, particularly in the Northeast region, where irrigation is necessary in an area regularly suffering from droughts [25, 26].

Regardless of the land-constrained policy, our findings indicate that emissions can almost double the current levels if no significant changes are made in the energy transition. In the net zero scenario, emissions from fuel combustion decreased by 91% compared to the baseline but still had a remainder associated with heavy industries. Although not included in this work, carbon capture and storage (CCS) has been discussed as an alternative to net zero pathways in industry [27]. However, in Brazil, a commercial scale of CCS can take another 12 years and cost MUSD 58 to store 190 million tons of CO_2 [28].

Bioenergy is essential to reduce emissions in sectors where electrification is difficult (e.g., aviation, maritime, and long-distance road transportation). Its biogenic emissions are absorbed by the plants grown in a carbon-neutral cycle. Still, reforestation in conservation-relevant lands has a huge potential for carbon sequestration (16 times the emissions in the baseline scenario). However, while burning emissions are instantaneous, removals by natural cycle might take a long time [29]. Such lags in re-sequestrating carbon might negatively impact rapid decarbonization.

4.1 Future work and conclusion

Our scenario setup makes some strong assumptions, for example, that Brazil will indeed rely heavily on biofuels for decarbonising hard-to-electrify sectors, and that there will be no major deployment of CCS in Brazil. Further research could investigate the potential of CCS, as well as consider further types of feedstock for biofuels. Moreover, more consideration of electricity and fuel transport alternatives could reveal further trade-offs between different decarbonisation strategies. We considered distance-related loss but left out the existing capacity and costs associated with transmission lines and the adaptation of pipelines for a hydrogen-based infrastructure. Also, we did not consider emissions from wildfires and the industrial processes associated with non-energy-related uses. Finally, we assume the current land use will remain unaltered by 2050. In reality, of course, land use can and likely will change significantly depending on public policy, economic development, and people's behavior.

Nevertheless, our results make a clear case for the possibility of achieving both deep decarbonisation by 2050 while protecting and restoring conservation-relevant land, all while building on Brazil's strengths of natural resources - abundant hydropower, bioenergy potential, and wind and solar resource. Brazil's NDCs and the SDGs are synergistic. For example, restoring ecological lands can reduce emissions and preserve biodiversity (SDG 15). Yet reforestation alone is insufficient since a transition to clean energy is essential to avoid local pollution and support sustainable cities and communities (SDG 11). Careful spatial planning will help minimize environmental impact and conflicts, and should also be conducted for "low land footprint technologies" like wind farms, since their necessary support infrastructure might still affect ecological corridors and natural habitats. Addressing climate change and halting biodiversity loss have become an urgent issue involving all societal levels. Brazil has the potential to become a major player in the fight against climate change and ecological degradation - if policy is designed accordingly.

5 Methods

We develop the Brazilian energy model using Calliope and analyze four scenarios: baseline, limited electrification, intensive electrification, and net zero. Then, we explore these scenarios under land conservation and 100% renewable system policies. Finally, we propose the recovery of conservation-relevant lands to estimate its contribution to carbon storage.

We prepare the model inputs in a pre-processing step that includes the spatial analysis (land availability), time series of renewable resources and demand, and definition of scenarios. As the final results from the model, we obtain the energy system configurations across multiple scenarios and weather years. Besides the energy-related results, we discuss further implications on converted lands and GHG emissions.

The dataset for this paper is deposited at `https://doi.org/10.5281/zenodo.`

10366868, the power model at https://doi.org/10.5281/zenodo.8020907, and the bioenergy model at https://doi.org/10.5281/zenodo.8020971.

Energy model

We build the Brazilian energy model using Calliope, an open-source, linear optimization-based energy modeling tool [30]. Calliope is flexible and appropriate for highly renewable systems since the framework can incorporate resource fluctuations through time series and spatial nodes.

Large energy models usually suffer from high computational costs. Due to our extensive scope, we split the model into two parts (the bioenergy model and the power and hydrogen model) that can be run independently. With that, we keep the computational complexity manageable and increase accessibility to further research without necessarily depending on high-performance computing (HPC).

With the bioenergy model, we investigate liquid and solid biofuels. The power and hydrogen model explores two other carriers: electricity and hydrogen. Electricity in the bioenergy model is an exclusive production from by-products. Part of its production is consumed at the refinery or distillery, and the surplus goes to the grid. The surplus power generation in the bioenergy model is then discounted from the demand of the energy model.

We include time series of demand and renewable energy in the power model available at hourly resolution. We run the scenarios of the energy model at a 3-hourly resolution on DelftBlue High-Performance Computer [31]. The bioenergy model is run at a 120-hourly resolution.

Scenarios

We investigate four scenarios: baseline, limited electrification, extensive electrification, and net zero. The baseline represents the demand estimation for 2050 from the Brazilian Energy Research Office (EPE) [16]. From that demand, we make assumptions on demand varying the carrier for electrification and net zero scenarios. To ensure logical and realistic assumptions, we consider electrification technologies that are already fully developed. However, there may be obstacles related to infrastructure or technical implementation that can potentially hinder the progress of electrification (e.g. absence of charge stations for electric vehicles in remote regions, irrigation in rural areas not connected to the grid, etc). Therefore, limited electrification considers these barriers and has a smaller share of electrification (even with available technology at a commercial scale); extensive electrification and net zero scenarios assume barrier elimination and, consequently, a higher level of electricity demand. The detailed assumptions for every subsector are available in the Supplementary Material.

Besides the exploratory demand scenarios, we analyze them under four policies:

- Default: No new policy is implemented.
- Land-constrained (LC): Priority lands for conservation are preserved.
- 100% renewable power system (100% RE): The power system is transitioned to 100% renewable energy.
- Land-constrained combined with 100% renewable power system (LC+100%RE): Priority lands for conservation are preserved, and the power system is transitioned to 100% renewable energy simultaneously.

We analyze the sensitivity of the power system capacity to weather years and cost variation. For the weather analysis, we investigate 20 years of wind, solar, and hydro resources and demand profiles. For the cost analysis, we consider three levels for wind, solar, and battery costs: conservative (higher costs), moderate, and advanced (lower costs) based on data published by [17] (see supplementary material).

Land availability

Land availability is a key factor in determining the maximum available area for technologies or feedstocks that require large areas and could impact human activities or natural ecosystems.

We exclude lands protected by law, public forests [32], rivers, lakes [33], and indigenous territory [32] in all scenarios and policies. Then, for the land-constrained (LC) policy, we exclude priority lands for conservation [6]. These lands are not protected by law yet but are conservation-relevant areas due to their biodiversity importance. For rooftop PV, we assumed the surface availability in m^2/household given by region of Brazil [34] and multiplied it by the number of households [35] to find the total available area. For offshore technologies, w available area for wind farms and their optimal locations from previous work [36].

The land suitability for sugarcane crops is given by the Agroecological Zoning of Sugarcane (ZAE Cana, in Portuguese) [19]. ZAE indicates the potential (high, medium, and low) of sugarcane crops according to the soil's physical, chemical, and mineralogical characteristics and weather conditions. For corn-based ethanol, we considered its production only from existing off-season crops, where corn is grown outside of the typical growing season. Soybean oil is the most commonly used feedstock for biodiesel [37] and hydrotreated vegetable oil (HVO) [38] production due to its high competitiveness compared to other oilseeds [39]. Charcoal is by existing silviculture activity given by [20].

Zones and links

Although Brazil has interconnected transmission lines covering almost the entire territory, we create zones to include the heterogeneity of different regions. We divide the Brazilian state territories into zones following two steps. The first one is based on concession areas of power distribution companies. With that, we have a more realistic demand per zone, making it possible to distinguish the share of electricity consumption in different economic activities and population levels. In states with many companies, particularly in the South and the Southeast, we merged small concession areas to form a single zone. In some large states (e.g., Pará), where only single companies control distribution, we used mesoregion limits to determine zones and divided the state's demand by the zone's population. We exclude part of the Amazon region where the supply comes from isolated systems.

We establish links between zones to make the carrier exchange possible. For electricity, we identify the nearest existing substations [40] to the centroid of each zone. Using QGIS function *simplify vector*, we simplify the existing and planned transmission lines [40]. We consider estimated losses (5%) per distance between zones.

Today, ethanol transportation relies mainly on road transport for the internal market and shipping for exports. To calculate the road distance between zones, we estimated the shortest path through roads between the zone's centroids using the QGIS function *network analysis - shortest path*. Costs per distance traveled by trucks are from [41]. Similarly, we create pipeline connections using the same road path and assume the costs and parameters of an existing pipeline between Ribeirão Preto and Paulínia [42].

Conversion technologies

For the bioenergy model, we consider five carriers: ethanol, hydrotreated vegetable oil (HVO), biodiesel, and sustainable aviation fuel (SAF), and charcoal. We assumed two types of distilleries for ethanol production that use traditional sugarcane. The first one is the conventional able to produce first-generation ethanol (from the juice) and generate electricity from the residuals (bagasse). The second one produces both first- (juice) and second-generation ethanol (bagasse). For corn-based ethanol, we assume a full distillery capable of processing only corn and producing first-generation ethanol.

The overall efficiency improvement happens through better distillery conversion and agricultural progress [43]. We consider an annual productivity increase of 0.9% for conventional sugarcane [44] since our estimation is based on historical values and many farms do not operate with available cutting-edge technologies. We consider that the efficiency increase for ethanol from corn follows the same overall progress as traditional sugarcane. Still, we assumed that ethanol capex and opex will be reduced by

10% and 25%, respectively, by 2050 [45].

Soybean oil is one of Brazil's most commonly used feedstocks for biodiesel and, consequently, a competitive feedstock option. Here, we conside soy oil as feedstock to produce HVO and biodiesel in the long term. For SAF, we consider two types of refineries: hydrotreatment of soybean oil (HEFA) and dehydration and oligomerization of ethanol (ATJ technology). Estimated costs for SAF are from[46], for HVO from [47], and for biodiesel from [37].

About 80% of the charcoal production in Brazil is through low-tech kilns, which miss the control of gas emissions generated by carbonization [48]. Here, we consider a more technological system called Ondatec (microwave carbonization kiln) and the feedstock from *Eucalyptus Urophylla* with costs from [49].

In the power and hydrogen sector, we assume costs given by EPE (Energy Research Office) [16] for conventional and mature technologies, such as hydropower plants, CCGT, and nuclear. For onshore wind and solar farms, rooftop-PV, and batteries, we consider costs for 2050 reported by [17]. For offshore wind farms, we estimate the costs based on equations compiled by Tavares *et al.* [50] and consider a reduction by 50% by 2050 [51].

Time series of renewable energy and maximal capacity

Renewable energy resources are highly variable over a year and between years. To analyze the weather variability, we consider two decades of data for the baseline and net zero scenarios. For the hydropower potential, we rely on the observed hydro resources from existing hydropower plants, and for wind and solar time series, we use reanalysis data from NASA's MERRA-2 [52].

Hydropower

We use 20 years of observed data of available hydropower from [53], and we aggregate them in basins. The data depend on the hydrological balance and the productivity of a hydropower plant. The cascades of hydropower plants connected through linkages among water bodies allow exchanging flows and increase the control over hydropower dispatch and storage.

In a reservoir, the remaining hydro resource, accumulated over a certain period, works as potential power storage. The maximal storage in a basin in GWh, results from the sum of maximal storage from individual reservoirs. The minimum operation level to maintain the river's ecosystem and its navigability limits the usage of stored hydro resources. Thus, the maximal storage is limited following the average security levels adopted by ONS [54].

Wind power

We simulate 20 years (2000 to 2019) of wind power generation through Renewables.Ninja [55, 56, 57], a platform based on reanalysis data from MERRA-2. Bias correction using data assimilation aims to reduce or remove systematic errors by comparing the data outputs with observed or already corrected data, bringing them closer to the real values. To correct the bias of offshore nodes, we simulate capacity factors of existing onshore wind farms near the sea and compare them to actual capacity factors, as indicated in a previous work [36]. For onshore wind farms, we used data from the Brazilian wind atlas [58] to compare to the simulated reanalysis data due to the absence of existing wind farms in some regions of Brazil.

The maximal installed capacity results from land availability (km^2) multiplied by a capacity density (MW/km^2). We assume an installed capacity of 3.56 MW/km^2 for onshore wind farms and 5.2MW/km^2 for offshore wind, calculated based on [59].

Solar power

Similarly to the wind simulation, we obtained solar data from MERRA-2 and the interface Renewables.Ninja, which provides solar power outputs from interpolated grid cells and estimates irradiance on the plane of the PV. Generally, the largest annual irradiation levels are obtained when the tilt of PV modules is equal to the site latitude and when the module faces to the North, in the Southern hemisphere (azimuth = 0^o) [60]. PV modules have tilts equal to the local latitude for each coordinate point. We correct the solar reanalysis data using the solar atlas provided by INPE [61], which covers 16 years (2000-2015) with monthly resolution. We use solar irradiation on every node's inclined plane (same as the latitude).

For solar utility-scale PV, we apply the density of 79 MWp/km^2 [62], while for rooftop PV, we assume a density of 162.5 MWp/km^2. Here, we assume a PV module with an area of 1.6 m^2 and a capacity of 260 Wp.

Bioenergy

Feedstocks for bioenergy production are variable resources since they depend on seasonal harvesting. In our work, sugarcane-based ethanol production results from suitable lands for sugarcane crops combined with sugarcane yield and distillery efficiency. We calculate overall productivity in terms of liters per hectare using historical data from the National Supply Company (Conab) [63]. We assume data from four recent harvests (from 2018 to 2022) to include possible changes in sugarcane productivity due to weather variability, agricultural and technological improvements, and sugar prices.

Our estimation is based on the Total Recoverable Sugar (TRS), a measure of quality and payment for sugarcane, which indicates the potential to produce ethanol or sugar. However, several variables that affect ethanol production (e.g. yield, sugarcane variety, weather, soil, etc) are available only aggregated and at a state level, making it difficult to access the exact productivity at a farm/distillery level. To avoid having a single theoretical value that can overestimate or underestimate the potential, we assume that low-suitable lands have yield equal to the first quartile of the dataset at the state level. We assign the median and third quartile to medium and high-potential lands, respectively. In our estimated yield, we remove today's level of sugar production to avoid food conflict. We included seasonality by considering the first month of the harvest period of the most common sugarcane variety (See Supplementary Material) in each state given by [64].

Corn cultivation for energy purposes requires larger areas than sugarcane, which can significantly impact food production if consumption increases at a large scale [65]. To avoid this, we limited corn production for biofuels considering its current production. Yet, we define the corn crop for energy purposes to be available in the off-season of other main growing of existing crops, with the harvest period varying by region.

To estimate the charcoal yield, we assume the parameters of *Eucalyptus Urophylla*, which contains an estimated charcoal potential of 42.5 kg per tree [66]. With trees spacing 3x3m, the total potential per area is 358.81 GWh/km^2. Here, we assume that charcoal is invariable over the year.

We assume no temporal variability for soy oil as feedstock, such as biodiesel, HVO, and SAF.

Demand

Energy demand includes five sectors: industry, transport, building, agriculture, and energy services. The baseline's demand (given by EPE [16]) is in terms of final energy (the energy supplied to the equipment). To estimate the final demand in the what-if scenarios of electrification and net zero, we calculate the useful energy (the energy after conversion) and multiply that by the efficiency associated with the new carrier (efficiency is given by [67]). The share by subsectors is available in the Supplementary Material.

The hourly electricity demand is reported according to the four subsystems by ONS [68]. To compute the demand profile per zone, we apply the consumption proportion given by distribution companies [69] to the demand. If one distribution company operates in more zones, we use a proportion based on the zone's population.

Our model considers seven carriers (electricity, hydrogen, ethanol, biodiesel, hydrotreated vegetable oil (HVO), sustainable aviation fuel (SAF), and charcoal. We leave other carriers out of the model, such as fossil fuels that cannot be replaced with other alternatives (i.e., in some industrial subsectors). However, we consider them in the emission balance.

Emissions

We calculate the emissions and removals associated with the energy sector and the land conversion to dedicated sugarcane crops. For other bioenergy crops like soybean and corn, we assume that their production does not change land use, as we restricted their cultivation to existing crops. Therefore, their impact on emissions balance is negligible.

We use the "stock-difference approach" for land conversion emissions. This method calculates greenhouse gas emissions resulting from land-use change, which considers the net change in carbon stocks between the current land use and its conversion to sugarcane crops [70].

We estimate emissions and removals due to land use change using data on carbon stocks in living biomass (above and below ground) and dead organic matter. We leave out the soil's organic carbon due to a lack of data.

We also analyze the potential of carbon removal by restoring 100% of priority lands for conservation that are currently occupied by human activities and are freed up in terms of energy in scenarios with the land constraints (LC) policy. For that, we also used the "stock-difference approach". We exclude the existing forests, cities, and non-vegetated lands from our analysis. To find the area of each land use type, we analyze a land use raster dataset from [20] within priority lands for conservation.

We also consider the native vegetation types in the biomes and regions to calculate the exact carbon storage impact. We extract this information from a shapefile depicting native vegetation types within priority areas. Using this data, we calculate the area covered by each vegetation type. We apply a weighted average approach to estimate the average carbon stock for each biome and region. This involves assigning weights based on the respective areas of different vegetation types, resulting in a more accurate representation of carbon stock variations across biomes and zones.

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