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A land-neutral expansion of Brazilian renewable fuel production

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Biofuels are currently the only available bulk renewable fuel. They have, however, limited expansion potential due to high land requirements and associated risks for biodiversity, food security, and land conflicts. We therefore propose to increase output from ethanol refineries in a land-neutral methanol pathway: surplus CO₂-streams from fermentation are combined with hydrogen from renewably powered electrolysis to synthesize methanol. We illustrate this pathway with the Brazilian sugarcane ethanol industry using a spatio-temporal model. The fuel output of existing ethanol generation facilities can be increased by 42%-49% or ~100TWh without using additional land. This amount is sufficient to cover projected growth in Brazilian biofuel demand in 2030. We identify a trade-off between renewable energy generation technologies: wind power requires the least amount of land whereas a mix of wind and solar costs the least. In the cheapest scenario, green methanol is competitive to fossil methanol at a carbon price of 80€/tCO₂.

Biofuels occupy an integral role in netzero emission scenarios¹, as they are the only bulk re-

newable alternative to liquid fossil fuels currently available^{2,3}. In particular bioethanol production from sugarcane (*Saccharum spp.*) shows high potential for land-based carbon mitigation^{4,5}. Brazil, the largest ethanol producer from sugarcane globally, has put in place a series of policies, such as the National Biofuels Policy (RenovaBio) or the current proposal for a credit subsidized COVID-19 Emergency Program to Support the Brazilian Sugar-Energy Sector (Peasse). These policies aim to safeguard the contribution of sugarcane ethanol toward the renewable energy targets of Nationally Determined Contributions (NDCs) and generate new incentives for biofuel production and technological innovation^{2,6}.

However, the benefit of such a pathway is controversial due to a number of concerns specific to sugarcane expansion: (1) the land-use intensity of sugarcane causes significant environmental impacts including biodiversity loss, soil degradation, pollution and depletion of water resources⁷⁻⁹; (2) the competition for other land uses affects small-scale family agriculture and food security¹⁰⁻¹², and (3) the high land-use intensity of biofuels has caused fundamental criticism regarding their CO₂-savings potential¹³, in particular when taking into account emissions from indirect land-use change⁹.

To tackle these negative impacts of sugarcane ethanol production, several land-efficient production pathways have been proposed. Such pathways increase output by intensifying existing production instead of expanding sugarcane plantations^{14,15} either through converting degraded pastures with agricultural potential into cropland with a concurrent intensification of active pastures¹⁶ or through second-generation (2G) ethanol production technology^{17,18}. Under 2G ethanol production, the ligno-cellulosic part of the sugarcane, i.e. the bagasse, is used for ethanol production in addition to the sucrose. When combined with alternative hybrid sugarcane crops which increase the amount of the fibre at the cost of the sucrose content², the increase in land efficiency can reach more than 50%¹⁹. 2G ethanol, however, comes with the down-side of less surplus electricity production as sugarcane bagasse not used as 2G feedstock is typically combusted for electricity generation¹⁸.

Here, we present a new land-neutral methanol pathway and assess by how much the fuel

output can be increased if the total plantation area is fixed at current levels of ethanol production. This way, the associated negative impacts of sugarcane ethanol expansion are avoided. We propose to synthesize methanol using CO_2 from the fermentation process in ethanol plants and H_2 produced from electrolysis powered entirely by on-site variable renewable energy sources (VRES). The higher land efficiency of VRES in comparison to biomass increases the land efficiency of combined ethanol and methanol output significantly, while the almost clean CO_2 -streams from ethanol fermentation allow to produce methanol from H_2 and CO_2 . This is beneficial, as methanol is much easier to handle and transport than pure H_2 ²⁰. We illustrate the land-neutral methanol pathway for the case of the sugarcane ethanol frontrunner Brazil, which has experienced rising expansion of sugarcane plantations into biodiversity hotspots of Amazon, Pantanal and Cerrado biomes during the last decade^{21,22}.

Understanding costs and magnitudes of the required infrastructure is a key element for the implementation of the land-neutral methanol pathway. Recent estimates of power-to-methanol processes show that costs are more than double compared to their fossil counterparts^{23,24}. However, our proposed pathway includes important elements that can make green methanol more competitive: the size of H_2 and CO_2 storage is optimized to maximize capital utilization²⁵, while the almost pure and low-cost CO_2 -stream from the ethanol production process can further lower the costs. Consequently, we are able to show that under certain plausible techno-economic assumptions, the CO_2 abatement cost from the land-neutral methanol pathway is competitive to other mitigation technologies.

Illustrating the land-neutral methanol pathway

We optimize power-to-methanol processes at all Brazilian sugarcane plants in a spatially and temporally explicit way that accounts for the seasonality of sugarcane production, and the variability of PV and wind power at all plant sites (Fig. 1). CO_2 , H_2 , and electricity storage options are incorporated to handle the temporal asynchrony of the electricity and gas streams. The entire process is studied under a variety of technological assumptions in two scenarios. First, we differentiate

82 between a scenario with mixed PV and wind power generation (solar-wind scenario), and a sce-
 83 nario with wind power generation only (wind scenario). We do not assess a PV only scenario,
 84 as it would not improve on costs or land-use efficiency over the solar-wind scenario. In contrast,
 85 the wind scenario can improve on land-use efficiency – at a higher cost – due to the lower land
 86 footprint of wind power. Second, we assess how varying techno-economic assumptions regarding
 87 annualized electrolyzer costs, efficiency of the electrolysis, and annualized costs of PV generation
 88 affect land-use, methanol cost, and system configurations (see methods and supplementary Table
 89 1 for details). The production of green methanol can be easily combined with other land-efficient
 90 technologies in ethanol production, as the CO_2 -streams from fermentation increase proportionally
 91 to the amount of ethanol produced. We therefore also explore the implications for the feasibility
 92 of the proposed pathway of ethanol production at higher land-use efficiencies.

Fig. 1. The proposed land-neutral methanol pathway.

93 We choose methanol as the final product, as i) the process to derive it from H_2 and CO_2 is

comparatively simple, ii) it is a liquid fuel, easy to transport without additional infrastructure, and iii) it has a variety of applications as feedstock for the chemical industry and transportation fuel. In particular, it can complement ethanol in blends of methanol, ethanol, and gasoline²⁶. Therefore, it can be used in flex-fuel engines optimised for ethanol-gasoline blends without requiring modifications to the engine or vehicle, as well as in heavy-duty long-distance road and maritime transport²⁷.

Combining methanol with ethanol production significantly improves land-use efficiency

The additional output in energetic terms increases by 43%-49% when implementing the land-neutral methanol pathway. The lower value results from the solar-wind scenario, where a significant amount of PV generation capacity is installed. The higher value for the wind scenario is a result of the much smaller direct footprint of wind turbines, as spacing areas between turbines can be used for sugarcane production (Methods). If the same volume of sugarcane ethanol would be produced at the average Brazilian land-use efficiency, between 23,000 km² to 27,000 km² of additional land would instead be required²⁸.

The available amount of methanol, i.e. about 100 TWh, could cover several times the domestic fuel demand for shipping²⁹ or 28% of freight transport in the country³⁰. The average land-use efficiency of today's Brazilian ethanol production is 3.7 GWh/km². The combined land-use efficiency of methanol and ethanol production for the wind scenario is 5.5 GWh/km², and for the solar-wind scenario is 5.2 GWh/km². While the wind scenario outperforms the solar-wind scenario in land-use efficiency, it is more expensive under all techno-economic assumptions.

The high land-use efficiency of the land-neutral methanol pathway is highlighted for all installations and the two scenarios in Fig.2. The figure also illustrates that variability within the scenarios is very high for the wind scenario and very low for the solar-wind scenario. This is a consequence of highly variable wind conditions and comparably low heterogeneity in solar radiation between locations. There are some outliers in terms of land-use efficiency for some facilities in the solar-wind scenario in the North-East and the South-East. These facilities are located close

to the coast where wind resources are much higher than inland, allowing for a mix of wind and PV. At all other locations, the wind share is very low or even 0, highlighting the low wind resources at most sugarcane production sites. Facilities that have higher land-use efficiency in the solar-wind scenario, however, also have low total fuel production potentials due to currently low amounts of ethanol production at those sites. Lowering land-use and costs by incorporating sites with excellent wind conditions is therefore possible only for a small share of overall production, i.e. 1.5% of total methanol production at 14 locations. Ethanol plants, and therefore the potential for combined ethanol & methanol production, are highly concentrated in two regions; the Central-West, and the South-West, both states with low wind resources. In this area, the state of São Paulo is the most important one, producing 45% of total Brazilian sugarcane ethanol volume (Supplementary Fig. 1).

Fig. 2. Land-use efficiency of methanol production vs. total fuel production for all Brazilian facilities.

The relative increase in land-use efficiency - made possible by the land-neutral methanol pathway - decreases if the sugarcane-to-ethanol land-use efficiency increases (Supplementary Fig. 2) for a simple reason: at high sugarcane-to-ethanol efficiency increases, substituting sugarcane by VRES will not save as much land as at a lower efficiency. The sugarcane-to-ethanol efficiency has increased by around 1% every 3 years in the period 2005-2020³¹. If efficiency gains remain

at this order of magnitude, impacts on the overall efficiency of the land-neutral methanol pathway are very low. However, a technological leap such as an upgraded conversion technology (i.e., 2G ethanol), potentially combined with sugarcane breeds of higher yield², could allow for a one-off increase in ethanol output by 50%. At this value, the land-use efficiency gain implied by the land-neutral methanol pathway drops by 3% in the solar-wind scenario (from 43% to 40%), and by 0.6% in the wind scenario (from 48.9% to 48.3%). We also assess how much sugarcane-to-ethanol efficiency would need to increase to make adding methanol from renewable power inefficient in terms of land-use: an increase of ethanol land-use efficiency by 10 times in the solar-wind scenario, and by 70 times in the wind scenario would decrease total output if substituting sugarcane for VRES. This magnitude clearly illustrates that the land-neutral methanol pathway can provide land-use efficiency improvements under any realistic future increase in sugarcane-to-ethanol land-use efficiency.

Cost of methanol determined by electrolysis and solar PV

The methanol cost of the land-neutral methanol pathway strongly depends on uncertain costs of the technological components. We test a range of plausible cost estimates from the highest – where costs stay at today’s level – to the lowest – where costs fall to around two thirds (PV) and one third (electrolyzers) of what they are today (Methods, Supplementary Table 1). We find that the cost of methanol in the proposed pathway is most significantly impacted by the costs and efficiency of the electrolyzer, and the cost of solar PV, whereas assumptions on the costs of storage technologies and wind power and the selected weather year have comparably minor impact on our results (Supplementary Note 1). The spread in methanol costs across the sets of assumptions is significant but is consistently lower under the solar-wind scenarios than the wind scenarios by about 1.5 to 2.5 times under similar techno-economic assumptions (Figure 3). This implies that the wind scenario is by far not cost competitive and we therefore do not discuss it in the following. We emphasize here that these particular results are not generalizable but are specific to the wind resources at most sugarcane plants: at some limited locations where wind speeds are higher, wind power is added to the cost-optimal mix.

In the solar-wind scenario, average production costs of methanol vary due to different techno-economic assumptions between about 0.07€/kWh and about 0.14€/kWh, i.e., the costs double between sets of assumptions. Compared to fossil methanol (0.04 €/kWh), this is an increase in production costs between 67% and 240%. The higher end of our cost estimates matches recently modeled costs of producing methanol in 2030 with alkaline electrolyzers, CO₂ from direct air capture and electricity from PV power³². Our carbon abatement costs are between 80€/tCO₂ and 320€/tCO₂, when compared to fossil production of methanol from steam reforming and synthesis gas conversion of natural gas (See Supplementary Note 2).

The supply curves show that differences in the climate conditions for VRES generation and the load profiles of CO₂ have an impact on methanol costs. I.e., when assessing variation in methanol cost within one set of techno-economic assumptions, the methanol cost of the most expensive location is by 20%-57% higher than that of the cheapest one, depending on which underlying techno-economic assumptions are chosen. To assess in detail the impact of climate conditions and CO₂-profile on methanol cost, we ran a regression model for the solar-wind scenario. We select one set of techno-economic assumptions (see Supplementary Note 3 for details) and regress average capacity factors of PV, a dummy variable which indicates if the wind power capacity factor is higher than 0.3, and the length of the CO₂-supply season on methanol costs. Our regression explains 64% of variation in the data. Average PV capacity factors are strongly significant and inversely related to cost: an increase in the capacity factor of 0.01 would decrease cost by 0.2 €/Cent/kWh on average. Capacity factors vary by at most 0.04 between locations, thus solar radiation can explain up to 0.8€/Cent/kWh or 8% of variation in costs between locations with lowest and highest possible solar radiation. This is caused by lower investment requirements into PV and electrolyzers at those locations. The differences between locations with wind power capacity factors below or above 0.3, respectively, is on average 0.5€/Cent or 5%. Single locations with exceptionally good wind conditions, however, show substantially lower methanol cost. Counter-intuitively, the longer the CO₂-supply period, the higher the final methanol cost. This is a consequence of very low CO₂-storage costs: if the CO₂-supply is concentrated in a short period of time, the CO₂ storage can be filled up quickly and the variation in renewable power supply can be balanced by the CO₂

191 storage at most times. However, if the CO₂ supply is stretched over a long period, the CO₂ stor-
 192 age needs time to fill up and, in some circumstances, renewable power supply will be higher than
 193 the currently stored CO₂. As storing electricity or H₂ is much more expensive than storing CO₂,
 194 instead higher renewable electricity generation facilities and higher methanol synthesis capacities
 195 are installed at those locations to compensate for curtailed power and methanol production at the
 196 start of the season. The effect can become relatively large for extreme cases: a CO₂ supply season
 197 which is 100 days shorter will decrease the methanol costs by 0.4€Cent. The difference between
 198 the shortest and the longest period is 270 days, so in total, ceteris paribus, the factor could explain
 199 about 1.1€Cent or 12% of differences in costs. Multi-annual CO₂ storage is one way of addressing
 200 this challenge, but was not assessed by us.

Fig. 3. Cost-supply curves for all scenarios and costs assumptions. Upper: solar-wind scenario. Lower: wind scenario. From left to right: annualized electrolyzer cost assumptions.

Methanol plants components sizing

Here, we show the size of the different technical components in GW, GWh or Kt used in the land-neutral methanol pathway under different techno-economic assumptions (Fig. 4). In general there is at least one order of magnitude more PV capacity than wind power capacity in the solar-wind scenarios due to low wind resources available at sugarcane plantation sites. In terms of storage, there is about three orders of magnitude more CO₂ storage than H₂ storage - and battery storage is not installed under any of the techno-economic assumptions. This can be explained by the fact that CO₂ storage is the least costly form of storage and therefore balances the system seasonally and hourly. If the process is installed at all locations in Brazil, the required capacities of the components are large: PV capacities of over 100 GW and electrolyzer capacities of between 60 and 80 GW would have to be installed, depending on the scenario. In total, CO₂-storage capacities of up to 10 MtCO₂ are necessary, as a constant CO₂ stream has to be guaranteed throughout the year, while the fermentation process runs only seasonally. The scale of these installations is huge, e.g. for PV it is one order of magnitude higher than currently installed PV generation capacity in the Brazilian electric system²⁹. Both CO₂-storage as well as electrolyzer capacities are not deployed at scale in Brazil, and corresponding deployment challenges will emerge.

The mean size of PV installations at plants is around 300 MW. While this is less than half the size of the currently largest PV installation in Brazil (São Gonalo)³³, the largest installation would be over 1.5GW, which is about the scale of the largest installations globally³⁴. The largest ethanol plants require storage sizes of almost 190 KtCO₂, while the mean size is at 30 KtCO₂.

The pattern of component sizing is robust to changing the underlying techno-economic assumptions: a decrease in electrolysis efficiency increases the size of electricity generation and electrolyzer components due to higher losses in the production of hydrogen, but the methanol synthesis size and the size of CO₂ and H₂ and storages remain almost unaffected. Higher PV costs shift generation slightly to wind power, but the effect is minor, illustrating that PV outperforms wind power by far at the given locations in terms of cost-efficiency. A change in electrolyzer cost drives changes in electrolyzer size, but the effect is relatively small, given that a three times higher

electrolyzer cost reduces the size by only about 15%. While methanol costs are therefore uncertain, the sizing of components is robust to strong parameter variations.

Fig. 4. Sizes of generation, conversion and storage components (sum of all locations) in the solar-wind scenario.

Discussion

The implementation of the land-neutral methanol pathway would substantially decrease Brazilian CO₂ emissions by about 27 MtCO₂ annually, which amounts to 7% and 3% of total Brazilian CO₂ emissions related to energy generation and land-use change, respectively³⁵. Similar to biofuel production, Brazil could become a forerunner in synthetic fuel production. This could in the long-term pave the way to future fully synthetic fuel production using direct air carbon capture instead of carbon captured by biomass, thus increasing output on the same land by at least a factor of 10 compared to today's ethanol pathway¹⁹.

To achieve the full potential of social, environmental and industrial co-benefits of the land-neutral methanol pathway and to make it economically competitive, a supportive land-use policy, which enforces land-neutrality of Brazilian biofuel production, would have to be implemented. Only under such a policy could potential rebound effects from increased demand³⁶ be prevented. At the same moment, such a land-neutral policy would increase biofuel prices, making our pro-

posed land-neutral methanol pathway more competitive. In contrast, current political practice is weakening Brazilian land conservation policies by lifting a ban on sugarcane expansion in the Amazon and the Pantanal²¹: under such conditions and without additional carbon pricing, the new technologies are not competitive, even under optimistic assumptions on technology cost. Policy makers also have to consider that the highly capital and land intensive pathway may lead to increasing the profit share of capital and land owners at the cost of the labour share, compared to ethanol production only.

There are also uncertainties for the land-neutral methanol pathway, which can only partly be addressed by today's policy and decision makers: short-term demand reductions for fuels due to the COVID-19 crisis and long-term demand reductions due to electrification of transport will have a negative impact on the demand for liquid, *fossil* fuels. At the same time, under strict climate change mitigation scenarios, demand for *renewable* fuels will increase as they are fundamental to fully decarbonize industry, heavy-duty transportation and electricity systems. The short and medium-term development of the Brazilian industry is therefore controversially discussed and a future decrease of production cannot be ruled out³⁷. There is also uncertainty about the costs of future PV generation and, to an even greater extent, of electrolyzers, which strongly affect the cost-competitiveness of the land-neutral methanol pathway. The development of technological cost will partly depend on global investments into research and development and deployment of these technologies. Still, the land-neutral methanol pathway alone would increase demand for these technologies to a scale that would allow building up a national industry in the synthetic fuel sector, thus substantially lowering cost. Finally, little is known about the environmental impacts of substituting sugarcane plantations by PV and wind turbines. Presumably, most environmental impacts will decrease³⁸. However, life cycle analysis shows that in some cases, the negative impacts of solar PV on water ecotoxicity exceed those of biomass-based energy³⁸. Also, volant wildlife species are at risk from wind turbines^{39,40}, as are environmentally vulnerable areas⁴¹. The analysis of these uncertainties is crucial for e.g. biodiversity conservation and can best be tackled by future research.

Methods

Producing methanol from surplus CO₂ and renewable hydrogen. Sugarcane to ethanol plants in Brazil use mostly first-generation conversion technology which produces ethanol by distillation of sugarcane juice. Ethanol plants are energy self-sufficient thanks to Combined Heat and Power (CHP) plants, where bagasse is burnt to produce electricity and process heat^{28,42}. Surplus electricity is exported to the electric grid. Bagasse can alternatively be used as feedstock for 2G biofuel production, thus increasing the fuel output, while decreasing the electricity output of the plant. We propose to upgrade existing sugarcane plants by adding a water electrolyzer, driven by VRES generation, and a methanol synthesis unit which combines H₂ from the electrolyzer with CO₂ separated from the ethanol fermentation process. We assume that the electrolyzer is not connected to the electricity grid, but that it relies on electricity generated by VRES locally. This assumption is justified as electricity demand for electrolysis would be substantial at large ethanol facilities. The required transmission infrastructure is not available currently and building it would be very costly. More importantly, the generation of electricity on-site is less costly than paying wholesale market prices plus grid fees.

We developed a linear optimization model (LP) to minimize the costs of VRES-based synthetic methanol production (See supplementary Note 4). The methanol production process is an adaptation of the electrochemical methanol process model proposed by Hannula⁴³, and the sugarcane ethanol refinery model proposed by Gnansounou et al.⁴⁴. The detailed model with streams of sugarcane, electricity, heat, CO₂, ethanol, and methanol in the facility derived from these two sources was simplified to streams of electricity, H₂ and CO₂ as functions of the amount of produced ethanol (see Supplementary Fig. 7).

Based on the premise of energy self-sufficiency of the installation, we assumed that the CHP runs always when heat is required for the ethanol production process, but that surplus electricity is not used in the electrolyzers. Currently, surplus electricity from the CHP is exported to the grid. Assuming internal use would likely indirectly affect CO₂ emissions in the Brazilian electricity system. To make our assessments of carbon abatements independent of those indirect impacts, we do

not take changes in electricity exports from the CHP or VRES into account. The model was solved over one year of operation for each installation individually, as there are no interactions between facilities. We assumed that the sizing of components at the existing sugarcane refinery remains fixed, while we optimized the size of PV and wind power generation facilities, electrolyzers, and methanol synthesis reactors, as well as electricity, H₂ and CO₂ storage sizes. All processes were simulated on an hourly basis. The simulation year does not start on the 1st of January, but at the moment when the cumulative sum of (CO₂-stream - mean(CO₂-stream)) is minimal: this coincides with the moment in the year when, optimally, the CO₂ storage is completely emptied and starts to be filled again. As production profiles for the installations are homogenous for all installations within one state, within each state the simulation year starts at the same point in time.

A synthetic data set of the Brazilian ethanol industry. At the moment, there is no single or consolidated source of data on ethanol generation plants in Brazil. In contrast to previous studies, we therefore have developed our own consolidated database. This includes data from three official sources, i.e. the Energy research company (EPE–Empresa de Pesquisa Energética), the National Agency of Oil, Natural Gas and Biofuels (ANP–Agência Nacional do Petróleo, Gás Natural e Biocombustíveis), and the Ministry of Agriculture (MAPA–Ministério da Agricultura, Pecuária e Abastecimento). Details can be found in Supplementary Note 5.

Little is known about the temporal production profiles in ethanol plants. In all related modeling approaches (e.g.^{17,28}), a certain number of hours of continuous generation is assumed, as the daily or hourly operation profile of the plants is irrelevant in these studies. The seasonality of ethanol production, as well as intra-day operation variability, is however crucial to our approach. We therefore approximated the time profile of ethanol production using the CONAB statistics for sugar cane grinding on a state basis⁴⁵. This source included data on the number of operation months, running days, and hours of operation per day, as well as processing volume shares by month and state. We used the volume shares to define in which months plants are operating, the total number of running days to restrict the length of the season, and accommodated the operation hours in the middle of each operating day to determine the hours of operation (e.g., a plant with

20 hours of operation runs between 02:00 and 22:00). The volume of ethanol generation per hour is equal to the total annual ethanol production divided by the number of operation days per year and the number of operating hours per day. Due to limited data availability, temporal profiles of sugarcane production therefore only differ between states. However, we scaled the level of production to the sizes of the individual plants. Assuming that sugar cane fermentation and therefore CO₂ formation occurs at the same pace as ethanol production, the CO₂ emission time series were calculated for each installation using the hourly ethanol generation profiles (see Supplementary Fig. 8).

Photovoltaic energy generation potential and footprint. Hourly electricity generation of PV installations was calculated for the location of each ethanol plant using PV_LIB⁴⁶ and ERA5-land⁴⁷ data. Time series were generated assuming the use of monocrystalline panels with a fixed-tilt orientation towards north and inclination equal to the latitude. This configuration is a common approximation for installations to maximize the output of electricity per year. The approach has been validated against hourly electricity generation data of PV installations in Chile⁴⁸. Since there are no PV installations close to ethanol plants which are available for validation, we compared the average yearly and monthly generation totals of PV electricity output calculated with our approach to solargis data⁴⁹ for each location. The correlation, relative mean bias error and relative root mean squared error are on average 0.99, 0.08 and 0.09 respectively (For details see the repository). This implies a slight overestimation of the PV production compared to solargis. The average capacity factors of solar PV installations at all ethanol plants locations are presented in Supplementary Fig. 9.

The land footprint of PV was estimated for eight large PV plants in Brazil, the locations of which were derived from a dataset provided by ANEEL³³. Using the measuring tool in Google Earth, the extension of these plants was measured in two different ways. In a first step, the area covered by panels was measured. In a second step, the panels and the surroundings used for roads, in-between panel space, and electrical infrastructure were also determined (detailed results are provided in supplementary tables 8 and 9). The number relevant for our model is the total land

requirement including spacing and infrastructure. As an approximation, 10 m²/kWp was assumed for the panel area, with 25-30m²/kWp needed for the PV plant including infrastructure. These results are comparable to values in the literature. Detailed results are provided in supplementary table 10.

Wind energy generation potential and footprint. Potential wind power generation at the location with the highest wind speed in a perimeter of 40 km around each ethanol plant location was simulated using a power curve based model. As a climate data source, we used hourly ERA5 reanalysis wind speed data with a spatial resolution of 30 km and the Global Wind Atlas Version 2 with a spatial resolution of 250 m for mean bias correction at a higher spatial resolution. The model has been validated against generation data in Brazil, the United States, South Africa and New Zealand and shows satisfactory simulation quality, i.e. the RMSE is below 0.4 for most locations (0.16 on average)⁵⁰. On average, the modelled wind power generation underestimates observed generation by around 4% of the capacity factor in Brazil. Two turbine types in different IEC wind classes were simulated: Nordex N100 3.3 MW (IEC class I) and Vestas V90 2.0 MW (IEC class II)⁵¹. Losses due to wake were not considered, assuming that the spacing between turbines is sufficiently large. Time series of average weekly capacity factors at all locations for the two turbine types are presented in Supplementary Fig. 10. We estimated land requirements for wind turbines by measuring the area of the existing turbine pads and roads that connect them via Google Earth. Rio Grande do Norte was used as a benchmark for estimating land requirements as it has the largest number of installed wind parks among all federal states in Brazil⁵². We measured four wind parks i.e., two wind parks with a turbine capacity of 2 MW and two parks with a turbine capacity of 3 MW. Based on these parks, we estimated the average turbine pad area per MW with and without a road for the different turbine capacities. Hence, the area of sugarcane plantations that needs to be replaced by wind turbines was estimated using the respective pad and road requirements per MW. Our estimates for 2 MW and 3 MW turbine capacity, 0.33 and 0.48 ha/MW respectively, are in-line with values reported by Denholm et al.⁵³ i.e., an average of 0.3 ha/MW with a standard deviation of 0.3 ha/MW for US wind parks.

Cost assumptions and scenarios. The annualized costs of the individual systems were calculated assuming an interest rate of 8%, as well as lifetime, CAPEX and OPEX, which vary depending on the technology. The PV and wind power installation lifetime was set to 20 years. PV investment costs in the low cost scenario were derived from Vartiainen et al.⁵⁴ and the Danish Energy Agency⁵⁵ at around 290€/kW for 2030. The high costs represent investment costs in 2020. For wind power, a similar approach was taken. Battery lifetime was set to 15 years, and CAPEX and OPEX were taken from the 2020 and 2030 scenario in Vartiainen et al.⁵⁴. Other technological assumptions were collected from a thorough literature review. H₂ storage costs were assumed based on the numbers in Kruck et al.⁵⁶ and counterchecked with other publications, which presented values in a similar range^{51,57}. For the estimation of CO₂ storage costs, we consulted a range of studies^{58,59}. For the widest possible range, the CO₂ storage costs of the lowest low-cost scenario and the highest high-cost scenario were assumed for the model. The costs of capturing the CO₂ from the fermentation process were assumed to be 10€/tCO₂ in all scenarios, which is the highest cost reported in our selection of publications (see Supplementary Table 3). We assumed that alkaline electrolyzers are used. These have lower ramping capabilities than polymer electrolyte membranes (PEM). They should, however, be able to fully ramp production in less than one hour, which is compatible with ramps in renewable generation, in particular if small buffering batteries are included in the system. Likewise, limited curtailment can help in stabilizing ramping rates. The costs for electrolyzers are highly variable in literature and we therefore covered a wide range of cost assumptions, as outlined in Supplementary Table 1. We tested the impact of different cost assumptions in 24 different scenarios presented in the main text. Additional variations, i.e. a total of 96 scenarios, are presented in Supplementary Note 1. The 24 main scenarios consist of two different VRES configuration alternatives (only wind and mixed solar and wind), three different assumptions on electrolyzer costs, two different assumptions on electrolyzer efficiency, and two different assumptions on the costs of solar PV installations (see Supplementary Table 1). For storage costs, we assumed the upper bound on the cost range shown in Supplementary Table 1, while for wind turbines we assumed the lower bound. An additional sensitivity analysis in Supplementary Note 1 also varied these cost assumptions in 96 scenarios, but the impacts were minor. Also, we tested the impact of using three

different weather years on results in 24 scenarios (Supplementary Fig. 3).

Limitations and areas for future research. The proposed spatio-temporal energy model is a perfect foresight model, as annual supply of CO₂, and generation of PV and wind power are assumed to be known in advance. This makes the sizing of components fit the particular parameters perfectly. However, the sensitivity analysis of climate input shows that the differences in necessary VRES and storage capacities between different weather years are below 10%. We, therefore, are confident that the sizing of components would, in principle, work and that during operation, limited foresight would not affect production costs much. We did not implement site-specific restrictions for storing CO₂ or H₂, which relies on natural formations such as saline aquifers or depleted oil and gas fields. As quantities are quite significant in particular for CO₂, restrictions may arise on feasible storage amounts, although on overall significant CO₂ storage is expected to be available in Brazil⁶⁰. Such restrictions should be assessed in future work, with a particular focus on assessing alternatives in underground pipe storage of CO₂. At the moment, however, pipe storage seems to be economically infeasible for seasonal CO₂ storage purposes, based on assessments of costs of natural gas storage in pipes⁵⁶. The related land-use of CO₂, H₂, and electrical storage was also disregarded, as it is expected to be insignificant, in particular for CO₂ and H₂ underground storage. Furthermore, the model does not allow sugarcane storage which could contribute to balance the strong seasonality of sugarcane availability as an alternative to CO₂ storage. However, storage may cause degradation of the stored sugarcane unless energy-intensive cooling is used⁶¹. We also neglected local water requirements for the electrolyser, as the input was estimated minor⁶², especially compared to water needs of sugarcane plantations. There are also significant uncertainties associated with the approach we used to derive production profiles for ethanol plants. However, these have minor impacts on results, as significant CO₂-storage is deployed at all installations anyhow.

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Supplementary information See Supplementary Information document

Data availability All input and output data for the optimization model will be made available after acceptance under zenodo.

Supplementary information All GAMS, Python and R code necessary to calculate the VRES potential, run the optimization model and create the figures of the paper is available under https://github.com/inwe-boku/sugar_cane_ethanol_brazil/tree/simulation_vsc.

Author Contributions L.R.C.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision. G.C.: Conceptualization, Methodology, Validation, Investigation, Writing - Original Draft, Writing

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Figures

Figure 1

The proposed land-neutral methanol pathway.

Figure 2

Land-use efficiency of methanol production vs. total fuel production for all Brazilian facilities.

Figure 3

Cost-supply curves for all scenarios and costs assumptions. Upper: solar-wind scenario. Lower: wind scenario. From left to right: annualized electrolyzer cost assumptions.

Supplementary Files

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