Modeling and Analysis

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Pathways for a Brazilian biobased economy: towards optimal utilization of biomass

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Abstract. Biomass is responsible for 25% of the primary energy supply in Brazil. However, future biomass demand will be influenced by many factors. This study evaluates potential pathways for the utilization of biomass in Brazil until 2050, while considering novel biobased sectors (renewable jet fuel and biochemicals), resource competition, and greenhouse gas (GHG) emissions. Whereas other least-cost optimization models assess biobased options to meet energy and chemicals demand in Brazil to a limited extent, this study provides a detailed breakdown of biomass feedstock, including an extensive portfolio of biomass conversion technologies. A least-cost optimization model is used to assess the demand for energy and chemicals, and the competition between biomass and other climate-mitigation measures such as renewable power generation technologies, carbon capture and storage (CCS), and energy efficiency. Varied over the three scenarios, 86–96% of the sustainable biomass supply potential is used. Under more stringent mitigation targets, novel biomass conversion technologies start to play an important role: Biobased electricity production with CCS, jet fuel production from lignocellulosic biomass, and chemicals are partly produced from ethanol and bio-naphtha. The modeling framework provides a transparent view of which type of biomass can be used for which specific purpose. It is therefore an interesting tool for future research, for example to examine the dynamic interaction with

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Introduction

Greenhouse gas (GHG) emissions will increase in the coming decades if no action is taken. Biomass is expected to play a critical role in preventing global warming from exceeding the 2 °C limit as it has significant GHG mitigation potential,[1,2] especially in the transport sector, by replacing fossil fuels.[3] Cost-efficient trajectories show that large-scale deployment of modern bioenergy, carbon capture and storage (CCS), and their combination (BECCS) are key mitigation strategies to supply energy, mitigate GHG emissions, and to reach this target.[1,4,5] Brazil has a large biomass potential,[6,7] a long history of producing bioethanol from sugarcane,[8–10] and is currently the second largest producer worldwide.[11] Furthermore, Brazil´s long-term energy-system evolution may rely increasingly on biomass because of its large potential at a relatively low-cost, compared to other renewable resources.[12,13]

The future use of biomass for the production of renewable energy and chemicals depends on the conversion efficiency from primary feedstock to end-use product, and economic competitiveness in comparison to other renewable energy options.[14] To assess the conversion efficiency and the economic competitiveness of biomass, different biomass feedstock types and conversion technologies should be merged into the framework of least-cost energy system models (ESMs) to assess their ability to serve demand for different end-use purposes. The integration of biomass into ESMs is often simplistic or incomplete.[14–16] This is shown by studies focusing especially on the integration of biomass in ESMs. Current approaches have limitations in either the portfolio of conversion technologies or in accounting, fully or partly, for limited land resource availability.[17–22] Studies focusing on the use of least-cost ESMs in the future energy system of Brazil also do not explicitly address the integration of biomass availability, or a full range of biomass conversion technologies, as they focus on other aspects of the energy system.[23–26] As a result, they ignore possible competition for biomass between the different end-use products.

The inclusion of bio-chemicals is also important because biomass is currently the most mature technology to produce large-scale renewable chemicals. Other alternatives are only in the research and prototype phases of development.[27,28] From an energy analysis point of view, it is relevant to include chemicals because a relevant share of the petroleum is used in the petrochemical industry for the bulk production of chemicals.[29–31] With a full portfolio of renewable alternatives for petrochemical products, this study is able to analyze the transition of the petrochemical industry under stringent GHG mitigation measures. This is also highlighted by Brown and Brown,[32] who foresee a large potential for biobased chemicals as renewable alternatives to plastics because the electrification of the transport sector reduces the production not only of petrol but also other refinery products, including naphtha, the base feedstock for the production of plastics. Naphtha is a co-product of oil refineries. Oil refineries are designed in such a way to produce oil products with a fixed ratio. Gasoline is one of the products. As the demand for gasoline decreases due to electrification of passenger transport the production of the other oil products (including naphtha) may decrease as well as they are produced with fixed ratios. As electrification is seen as a very important measure for reducing GHG emissions from the transport sector,[33] the analysis of substituting naphtha should be part of integrated assessment studies.

The production of bio-chemicals is considered in the energy-system modeling literature. Hoefnagels *et al.*[20] show that fossil chemicals can be replaced by biobased chemicals. However, they do not consider the development of other fossil and renewable technologies. Tsiropoulos *et al.*[14] assess a full range of biotechnologies, as well as other fossil and renewable technologies to be integrated into the energy system of the Netherlands. However, the modeling of oil refineries is simplified due to data complexity, and the dynamic interaction between fixed outputs of oil refineries and substituting biofuels is therefore not optimally addressed.[14] Moreover, due to limited domestic biomass resources, the majority of the demand for bioenergy is met by imported biomass,[14] which leaves the competition for land partly out of the assessment.

The aim of this study is to explore the role that biomass can play in meeting the demand for energy and chemicals along with the mitigation of GHG emissions in Brazil up to 2050. The assessment is carried out in a least-cost optimization energy system model built with the TIMES (The Integrated Market allocation EFOM (Energy Flow

Optimization Model) System) platform. The modeling structure of TIMES makes it possible to examine the development of a biobased economy, in relation to the development of fossil and other renewable conversion technologies for the production of energy and chemicals. This assessment connects the issue of resource competition to a full-range portfolio of biomass conversion technologies. Three scenarios are used to explore the potential pathways for a biobased economy (BBE) in Brazil, considering GHG mitigation policies, biomass supply potential, and techno-economic uncertainty (rate of progress and maturity of novel conversion technologies).

Methods

TIMES is a linear optimization model that is used to calculate the least-cost energy system expansion under a set of user-defined restrictions.[34] The objective is to meet the demand for energy in specific sectors (power, transportation, industry, residential and commercial, and agriculture). The demand can be fulfilled by different conversion routes and / or primary energy carriers. Figure 1 shows a simplified structure of TIMES together with the prime parameters. More information on TIMES can be found in Appendix I in the supplementary material. The characteristics of (1) the supply of primary energy feedstock, (2) the conversion technologies, and (3) the policy constraints determine the extent to which biomass will be used in the future energy system of Brazil as modeled in this study.

This research builds on the TIMBRA (TIMES-Brazil) model developed by Nogueira.[36] TIMBRA is especially designed for the Brazilian energy system. Details about TIMBRA can be found in Appendix I and in Nogueira.[36] The operating timeframe runs from 2010 until 2050.

Extension of TIMBRA with a biobased module

To explore the role that biomass can play in meeting the demand for energy and chemicals until 2050 in Brazil, the original TIMBRA model[36] has been updated with information on the biomass supply chain for energy and chemicals. A biobased module has been created within the existing modeling framework to deal with biomass supply information, biomass conversion technologies, and demand for biobased products. In general, the share of biomass to meet final energy and chemical demand in 2050 is influenced by three factors:

- supply of biomass feedstock: supply potential and feedstock costs;
- biomass conversion technologies: available technologies and technological learning curves;
- environmental policy: GHG budget (the GHG budget in this study refers to the total accumulated GHG emissions over the period 2010 to 2050) and biofuel blending mandates.

The biobased feedstock- and conversion types and their links to the end-use of energy are shown in Fig. 2. Techno-

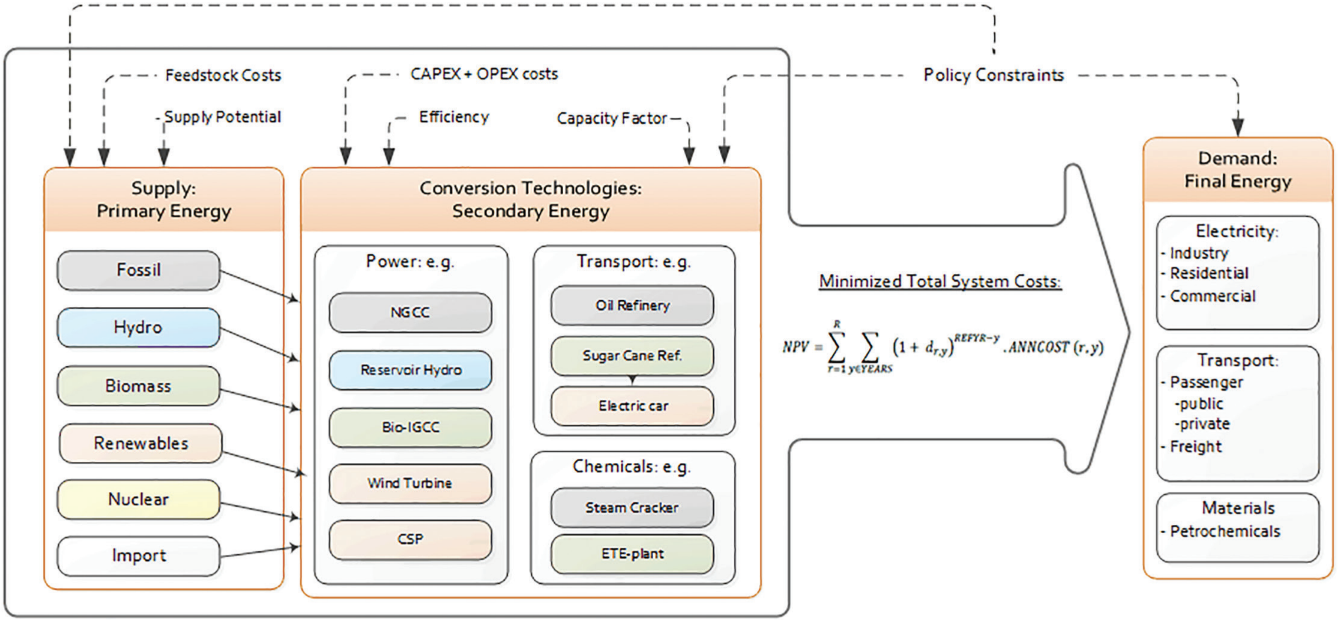

Figure 1. Simplified structure of TIMES (based on figures in references 34,35)

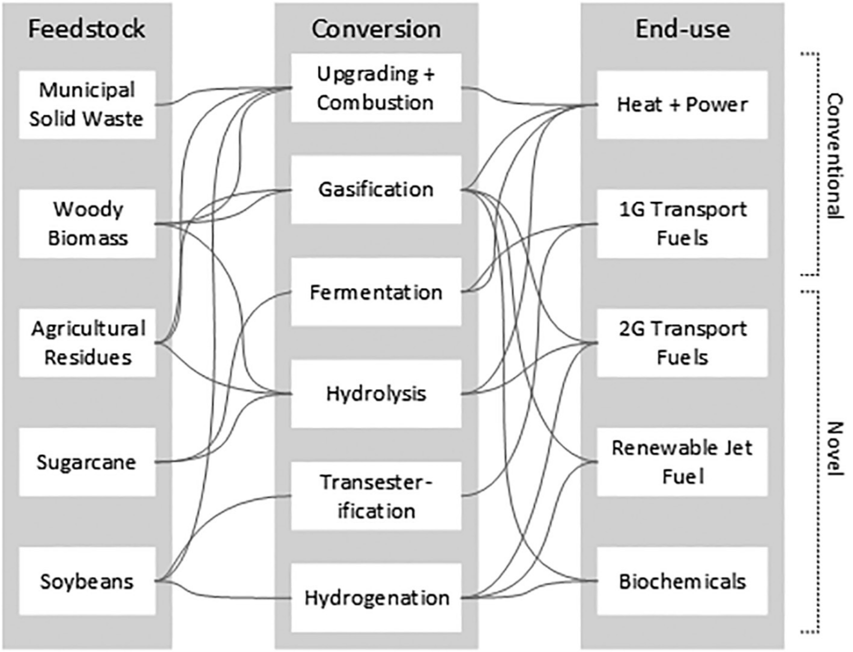

Figure 2. Simplified flow sheet of the flows of biomass feedstock towards the type of conversion and end-use demand used in this study.

economic details about biomass conversion technologies are found in Appendix II, including the costs and supply potential of biomass feedstock types. A list of all non-biobased technologies used in this study can be found in Appendix III. The updated version of TIMBRA is called TIMBRA-BBE from here on.

TIMBRA-BBE components

Supply

Next to biomass feedstock (see Fig. 2), fossil, nuclear, hydro, and renewable resources are included in this study. The supply potential is obtained from the literature on fossil,[37] nuclear,[38] hydropower,[39] wind,[40] and solar[41,42] resources. The supply potential for sugarcane,[6,39] soybeans,[43,44] and woody biomass [6,45] is obtained from international sources and governmental literature. The potential for agricultural residues is estimated by extrapolating the share of rice and maize used for domestic consumption. This is the main driver for rice and maize production. It is assumed that the consumption per capita will not change over time. The method of Portugal-Pereira *et al.*[46] is used to translate the production quantity of sugarcane, soy, rice, and maize into the sustainable potential of the related agricultural residues, husks, straw, and stover. The supply potential for agricultural residues (including the residues from sugarcane and soybeans) is the sustainable potential.[46] The sustainable biomass potential is defined as the part of the technical biomass supply potential that can be harvested without negatively influencing soil functions (e.g. maintain soil organic carbon levels, protection from soil erosion and maintain soil moisture levels) and biodiversity and is sometimes also defined as the ecological potential.[46,47] The supply potential of municipal solid waste (MSW) is estimated by extrapolating the current production of MSW,[48] assuming that per capita production remains the same. The prices of fossil fuels are based on the domestic production costs.[36,49] For the prices of imported fossil fuels, the New Policies scenario of the International Energy Agency (IEA) is used.[50] ('The New Policies scenario is designed to show where existing policies as well as announced policy intentions might lead the energy sector.'[50]) Prices for biomass resources are the 6-year average prices based on data from governmental institutions in Brazil (see Appendix II for more information).

Conversion technologies

The technologies present in TIMBRA-BBE encompass the entire energy sector including fossil, nuclear, renewable, and biobased technologies. The technologies are characterized by their conversion efficiency, capital and operational expenditures, load factors, and size. The efficiency of the technologies is based on lower heating values obtained from the literature. The location factor used in this study for Brazil is 1.3.[51] The location factor is a factor that adds the costs of equipment and machinery that needs to be imported for the construction of (energy) projects.[51] A location factor of 1.3 means 30% extra costs. Hydropower plants built in Brazil require no imports of goods and therefore they have a location factor of 1.[51] Carbon dioxide emissions are attached to the conversion of energy carriers to secondary or final energy, and include process-related emissions. Some conversion technologies can capture CO_2 from the production process. The techno-economic details of the technologies, including CO_2 capture rates, are found in Appendices II and III.

For the selection of biomaterial producing technologies, including biomaterials in other sectors such as the paper and pulp industry, and charcoal production for the iron and steel industry,[36] the focus is on the production of bio-chemicals because they have the ability to mitigate GHG emissions and replace fossil petrochemicals.[52,53] The production of polyethylene, polypropylene, ammonia, and methanol represents 60% of the total volume of chemicals produced in Brazil in 2014.[54] Other chemicals are produced in negligible quantities and are often derivatives of these platform chemicals.[54] They are therefore excluded from this research.

Demand

Demand for energy per sector is determined exogenously based on demand projections for Brazil.[36,49] The demand in the transport sector is given per person/freight kilometer. Other than the demand in the industrial, agricultural, and residential and commercial sector, the demand in the transport sector is for useful energy. There are different transport modes with specific efficiencies present in the model, allowing for energy efficiency measures. Demand for the four bulk chemicals used in TIMBRA-BBE is based on extrapolation of demand per capita data for Brazil from the Organisation for Economic Cooperation and Development (OECD) and the IEA.[30] The demand for polylactic acid (PLA) and poly ethylene furanoate (PEF) is modeled as the demand for ethylene because they have the characteristics to replace ethylene.[55] In total, the demand for PLA and PEF can be no more than 50% of ethylene because this is assumed to be the maximum substitution rate.[56] The demand data are found in Appendix II.

Scenarios

It remains uncertain how the BBE may develop in Brazil. The state of the BBE depends on the development of the economy, technology, and environmental policy. To address the uncertainty in TIMBRA-BBE, the development of these elements is addressed by three scenarios. The scenarios are based on the shared socioeconomic pathways (SSPs), which are designed to structure uncertainty in climate change mitigation and adaptation.[57] Table 1 shows how the general SSP elements can be translated to the scenarios of this study. The technological development is introduced in the scenarios based on the technology readiness level (TRL) of biobased technologies as define in the literature.[27,59,60] A matrix is used to show the relation between the introduction year in relation to the TRL (see Appendix II). The actual data considering the biobased technologies per scenario are found in Appendix II. The supply potential of biomass is discussed in detail in Appendix II.

SSP1: Rapid development towards a sustainable future

Technological development follows a progressive trend. The environmental policy for SSP1 is based on the national determined contributions (NDC) agreements of Brazil until 2030 (as in SSP2). However, to meet the global 2°C warming target more stringent mitigation measures need to be taken by Brazil. Rochedo *et al.*[58] estimated that the total carbon budget for the energy system of Brazil should be 16 Gt CO_2 equivalent to fulfill the global 2°C warming target up to 2050. This is also the target in SSP1. Biofuel blending targets are set at B10 and E30. The supply potential of biomass assumes a high productivity increase. Additional land will be available for short-rotation eucalyptus plantations for energy production following trends from Tolmasquim.[6]

SSP2: Middle of the road / business as usual (BAU)

Technological development follows an intermediate trend. The SSP2 scenario is the business-as-usual scenario. It includes the climate policy actions in the NDC for the Paris Agreement,[61] where the maximum level of annual GHG emission is set at 1.2 Gt CO_2-equivalent in 2030 and the share of renewables at 45%. The share of the GHG emissions for the total energy sector (including industrial process emissions) is estimated at 575 Mt CO_2 equivalent; the rest comes from agriculture, forestry, and other land use (AFOLU).[36] In TIMBRA-BBE this policy is translated to a carbon budget for the energy system, where the CO_2 cap from the NDC is frozen from 2030 until 2050. The carbon budget in SSP2 is 22 Gt CO_2

Table 1. Technical and environmental characteristics of the scenarios as used in TIMBRA-BBE for this study.

Scenario	SSP1	SSP2	SSP3
	Technological development:		
Introduction time of technologies[a]	Progressive	Slightly progressive Medium change	Conservative
Efficiency improvements chemicals over time[b]	0.5%/y (bio), 0.25%/y (fossil)	0.5%/y (bio), 0.25%/y (fossil)	0.25%/y (bio), 0.5%/y (fossil)
Maturity of technologies[c]	Rapid change (fast maturation)	Rapid change (less fast than SSP1)	Slow change (low maturation)
CCS technologies included, and their development	BECCS, ethanol distilleries (early development)	BECCS (late development), ethanol distilleries (early)	Only for conventional ethanol distilleries (late development)
	Environmental policy:		
GHG policy[d]	CO_2 budget of 16 Gt of CO_2 eq. in 2050	CO_2 budget of 22 Gt of CO_2 eq. in 2050	No GHG emission policy
Biofuel blending mandates[g]	B10 + E30	B07 + E27	B05 + E25
	Energy prices and biomass supply potential		
Biomass supply potential[e]	17.3 EJ	14.1 EJ	12.3 EJ
Biomass costs[e] ($\$_{2010}/GJ_{LHV}$)	3.2 (BM), 5.3 (SC), 1.1 (AR), 6.1 (SO), –2.4 (MSW)		
Fossil energy costs[f] ($\$_{2010}/GJ_{LHV}$)	Domestic: 10.1 (O), 1.8 (C), 7.6 (NG). Import: 16.8 (O), 3.3 (C), 9.5 (NG).		

[a] The time when a biobased technology becomes available in the model is based on commercialization matrices. See Appendix II for the actual introduction years for the different scenarios.
[b] Adapted from Tsiroupoulos *et al.*[14] The maximum yield is based on the stoichiometric formula of the conversion route. See Appendix II and III for the data per technology and scenario.
[c] The improvement in costs and efficiency of biobased technologies over time. See Appendix II for the data.
[d] Based on the carbon budgets as discussed in Rochedo *et al.*[58]
[e] The biomass supply potential includes woody biomass (BM), sugarcane (SC), agricultural residues (AR), soybean oil (SO) and municipal waste (MSW). The methods used for the quantification of the supply potential are described in Appendix II, where also the details regarding costs are found.
[f] Oil (O), coal (C) and natural gas (NG). Based on domestic production costs (see Section 2.2.1) and on the new energy policy scenario from IEA.[50]
[g] Biofuel can be blended with fossil fuels. The acronym B05 stands for a fuel blend of 5 vol.% biodiesel (B) and 95 vol.% fossil diesel. E25 stands for a fuel blend of 25 vol.% ethanol (E) and 75 vol.% gasoline.

equivalent. The supply potential is based on a medium productivity increase. No additional land is assumed to be available for short-rotation eucalyptus plantations.

SSP3: No climate mitigation measures

Technological development is more oriented towards fossil fuels because the short-term trends and long-term forecasts (without environmental policy) in Brazil veer slightly towards more use of fossil energy.[12,23,39] There is no development of CCS in this scenario, except for CCS from conventional ethanol distilleries, which is already in a pilot-scale phase in Brazil.[62] Apart from the current biofuel blending targets, no environmental policies are considered. The supply potential is based on a low productivity increase. No additional land is assumed to be available for short-rotation eucalyptus plantations.

Results

Primary energy and final energy consumption

The use of biomass will continue to play an important role in the total primary energy supply (TPES) in the coming decades (Fig. 3(a)). In 2010, nearly 35% (5 EJ) of the primary energy supply was met by biomass. In 2050 the total supply of biomass ranges from 11.4 (SSP3) to 16.6 EJ (SSP1). The supply of hydropower, solar, and wind will grow from 1.5 EJ in 2010 to 3.7–4.1 EJ in 2050, depending on the scenario. The presence of fossil fuels remains important in the total energy mix of Brazil, mainly for the SSP3 scenario and to a lesser extent, for the SSP2 and SSP1. The total amount of energy available for final consumption (total final consumption, TFC) approximately doubles from 2010 until 2050 for all scenarios (Fig. 3(b)).

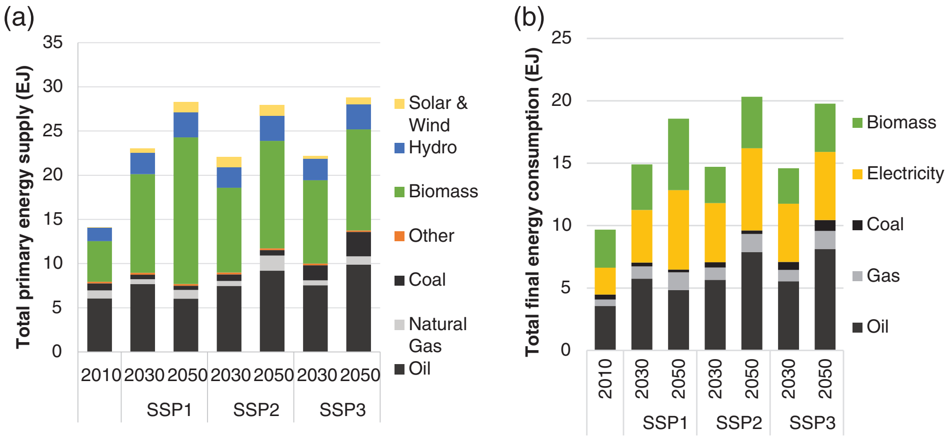

Figure 3 (a) Total primary energy supply (EJ) for the three scenarios for 2010, 2030, and 2050. Other sources exist of nuclear energy and imports of electricity. (b) Total final energy consumption (EJ) for the three scenarios for 2010, 2030, and 2050.

(Final consumption relates to energy use for final consumption per sector as described by the International Energy Agency,[50] e.g. to heat homes, to fuel cars, to produce industrial goods, etc.) However, the TFC of SSP1 is lower, which is mainly caused by more efficient transport modes. The relative share of the energy carriers differs per scenario. In SSP3 the shares remain similar for 2050 in comparison to 2010 but, when the carbon budget is lower, a switch away from oil to biomass (mainly in 2050 for SSP1) and to electricity is noticeable.

The driving force for a larger share of renewables in SSP1 and 2 is climate policy. The differences become visible in 2050, when fossil fuels supply over 47% of the primary energy when no additional climate policy is considered whereas for SSP1 the share of biomass grows to 62%, compared to 22% for fossil energy. Apart from the growing share of biomass it can also be observed that the supply of fossil energy decreases when the climate mitigation targets become more stringent: 13.6 EJ for SSP3 compared to 5.9 EJ in SSP1. In the SSP1 scenario, the amount of primary energy supply decreases in comparison to SSP3 from 28.8 to 26.7 EJ, which shows that energy is converted in a more efficient way because final demands are equal.

Pathways for biomass per scenario

SSP1

In total, 16.6 EJ of the sustainable biomass supply potential is used (Fig. 4). The first result that stands out is the use of lignocellulosic biomass (9 EJ) from different sources for final use. The lignocellulosic material is mainly consumed by gasification conversion technologies producing 2G transport fuels but another relevant share is used for electricity and heat production for the residential and industrial sector. The reason for the large production of 2G transport fuels is that gasification conversion technologies produce renewable fuels for freight transportation and also renewable jet fuel (see Appendix V for more detail). While the cap on CO_2 emissions is the most stringent in this scenario, biomass as primary source for renewable fuels for freight and aviation is selected as the most feasible option. The surplus bagasse from the milling of the sugarcane is used for the production of heat in the industrial sector rather than being used to produce 2G ethanol. (Surplus bagasse is defined as bagasse that is not consumed in the sugarcane refineries to produced on-site electricity and process heat but can be used in other sectors, with industrial heat as optimal application.) The captured CO_2 emissions shown in Fig. 4 are captured by biomass integrated gasification combined cycle power plants (BIGCC) and Fischer–Tropsch synthesis (FT synthesis) plants producing biofuels.

The climate mitigation targets also play a role in the selection of technologies that have the ability to capture CO_2 e.g., BIGCC-CCS and FT-synthesis. Municipal solid waste is the only biomass feedstock that is not used in the energy mix. The climate mitigation targets are likely to be the reason why MSW is not used, because not all carbon in MSW is biogenic and so there will be carbon emissions when MSW is converted to final energy.

SSP2

In comparison with SSP1, the sustainable supply potential of biomass in SSP2 is not fully utilized (86%, 12.2 EJ). This is mainly because there is less demand for renewable bio-

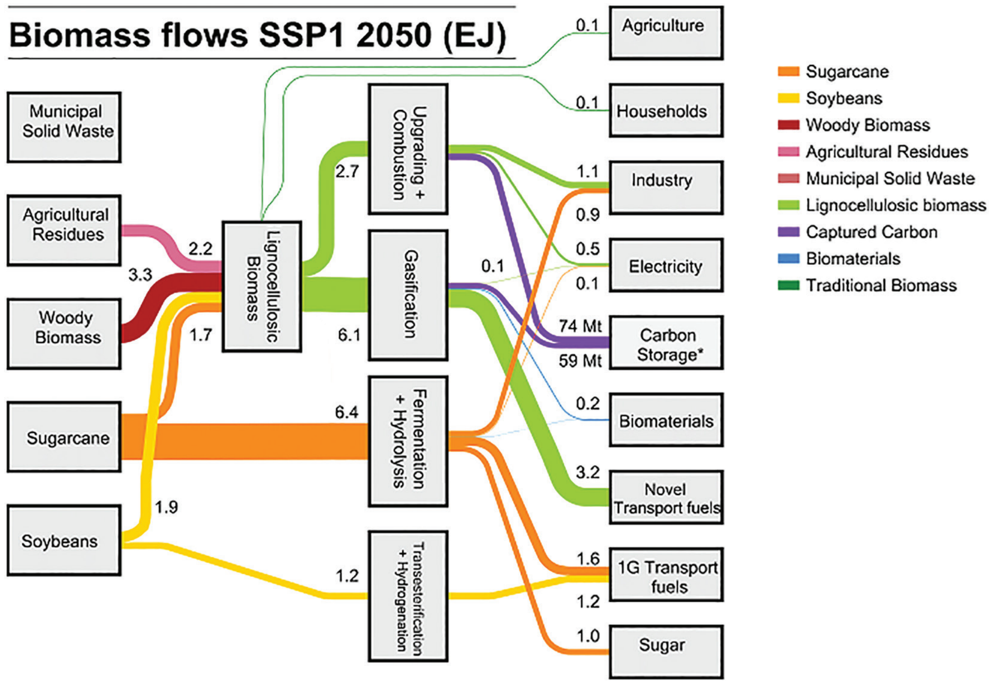

Figure 4. Sankey diagram of biomass flows as modeled in TIMBRA-BBE for scenario SSP1.

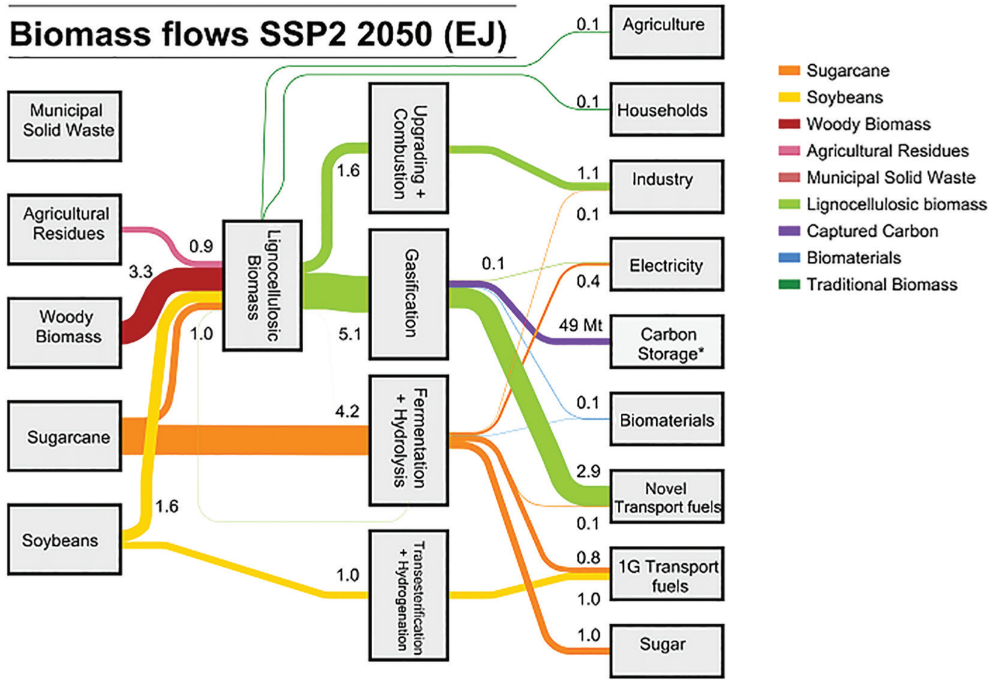

Figure 5. Sankey diagram of biomass flows as modeled in TIMBRA-BBE for scenario SSP2.

mass because of the less stringent climate-mitigation target. In terms of supply this translates into less supply from agricultural residues. Furthermore, the trends in the conversion of biomass are comparable to SSP1; lignocellulosic biomass for 2G transport fuels including CCS (FT synthesis) and also for the industry. In the sugarcane refineries, there are small differences in comparison to SSP1, because the focus switched from bagasse for the industry (0.9 EJ in SSP1 versus 0.1 EJ in SSP2) to the production of ethanol, including a small production volume of 2G ethanol (0.1 EJ).

SSP3

In SSP3, 93% (11.4 EJ) of the sustainable biomass supply potential is used. Municipal solid waste is not being utilized because the production of electricity from MSW is economically unattractive due to high capital investment costs in comparison to other power plants. What is interesting is that 4.6 EJ of biomass is used for the production of novel transport fuels (see Fig. 6), even though there is no climate mitigation target. This can be explained by investment costs for large-scale oil refineries, which are relatively expensive, as mentioned in Köberle *et al.*[51] and Silverio.[63] The model decides whether investments are necessary for oil refineries to fulfill demand for passenger- and freight transportation or if other alternatives are more attractive.

There are two mechanisms incorporated in the modeling structure of TIMES that influence these decisions. First, oil refineries are designed to produce oil-products with fixed ratios. Second, the equations in TIMES to calculate the least-cost optimal solution are demand driven: they incorporate all costs (capital expenditures (CAPEX), operational expenditures (OPEX), fuel, imports) and revenues (exports). There is specific end-use demand for plastics (naphtha), aviation (kerosene), freight (diesel), and passenger transport (gasoline), so the demand can be fulfilled by oil-products from refineries. However, due to the fixed ratio of the oil refineries one particular demand (for instance, gasoline) can be fulfilled while another demand is not. The other demand can be met by other alternatives or by increased production from expanding the oil refineries, eventually leading to overproduction of one particular demand, which can be 'solved' by exporting that commodity (e.g. export of gasoline).

This result shows that investing in biofuels and electric cars, in combination with the export of crude oil, is economically more attractive. The relatively large share of biomass for novel transport fuels comes from the fact that passenger transport will partly be met by electric cars, whereas for freight transportation biomass is the most feasible alternative.

Competition between biomass and other sources for end-use demand

The production of power doubles from 2010 to 2050, in all scenarios, to approximately 5 EJ. In all scenarios hydropower supplies 2.9 EJ. In SSP2 and SSP3 sugarcane refineries supply 0.4 EJ, whereas in SSP1 power from biomass is delivered in combination with the capture of CO_2 from BIGCC power plants (0.5 EJ). The additional demand is met mainly by solar and wind energy for SSP1 and SSP2 (SSP3 to a lesser extent), whereas in SSP3 coal-fired power plants deliver 0.7 EJ. The demand for transport fuels in 2050 reaches approximately 7.5 EJ for all three scenarios. Two trends can be observed when analyzing the scenarios. First, fossil fuels

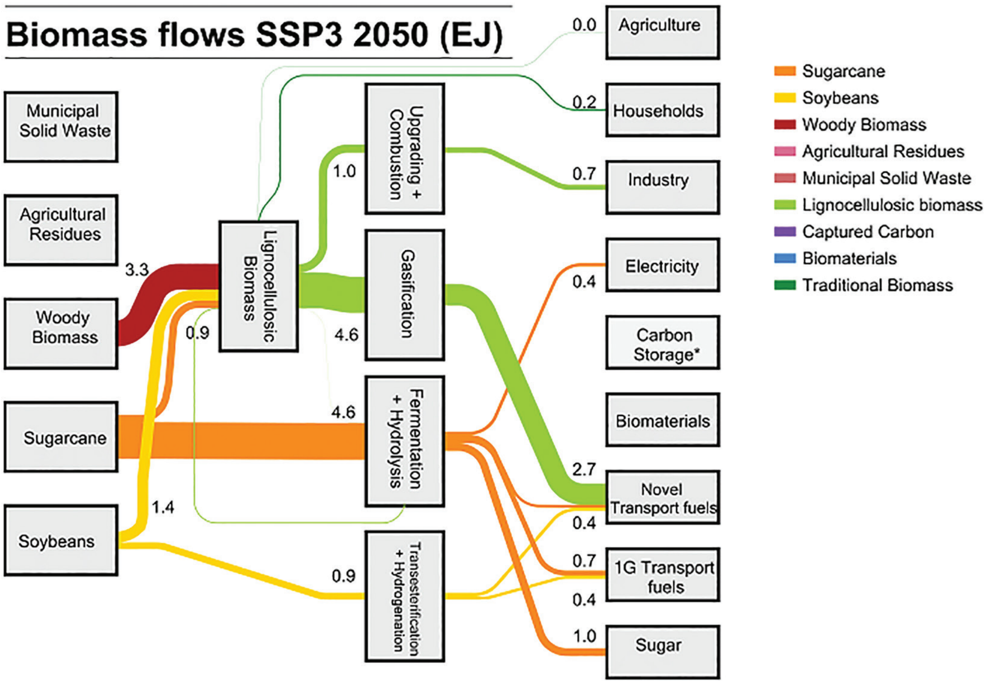

Figure 6. Sankey diagram of biomass flows as modeled in TIMBRA-BBE for scenario SSP3.

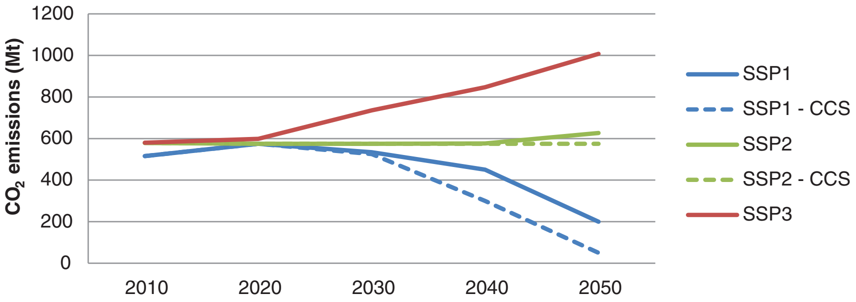

Figure 7. Annual GHG emissions (in CO_2 equivalent) from the energy system per scenario as modeled in TIMBRA-BBE. The difference between the dotted line and the normal line represents the CO_2 emissions that are captured and stored in the subsurface.

become less important when climate targets become more stringent. In SSP3, 40% of the transport fuel demand is met by fossil sources, in comparison with 10% in SSP1. Second, in SSP1 more efficient (but also more expensive) technologies are needed to fulfill demand, like freight transport on biobased hydrogen and passenger transport with electric vehicles. The demand for energy in the industry in 2050 is approximately 4.1 EJ for all scenarios. Biomass (1.6 EJ) and natural gas (1.1 EJ) become more important in SSP1 as they meet 65% of the energy demand, against 35% for SSP3. The demand for petrochemicals (750 PJ) remains dominated by fossil sources in all scenarios. However, in SSP1 the majority (110 PJ, embodied energy) of the ammonia is produced from syngas, while 120 PJ of olefins is produced from ethanol and biobased naphtha. More details regarding final energy consumption can be found in Appendix V.

GHG emissions

The annual GHG emissions in SSP3 will reach 1000 Mt in 2050. The CO_2 emissions from SSP1 and 2 are lower than SSP3 because of the climate policy. In SSP1 the net annual emissions in 2050 will reach 50 Mt, including CCS (150 Mt captured CO_2). The majority of the captured CO_2 in SSP1 is from BECCS (BIGCC: 74 Mt, FT-synthesis: 49 Mt, biobased hydrogen: 11 Mt) and 17 Mt is captured from fossil sources. In SSP2 the net annual emissions are 575 Mt, including 49 Mt of CCS from FT synthesis. If we compare the annual emissions of SSP1 to SSP3 for 2050, in total 800 Mt of CO_2 is mitigated by switching to renewable alternatives, and another 150 Mt of CO_2 is mitigated by CCS.

Annual cost of supply of energy

The annual costs for the supply of energy (see Fig. 8) are highest for SSP2 (275 bn \$/y), followed by SSP1 (245 bn \$/y) and SSP3 (238 bn \$/y). (The costs of supply of energy encompass the costs for primary energy carriers and the costs of converting the primary energy into energy carriers for final energy consumption in the selected sectors. Costs for the conversion of final energy to useful energy – for instance, the conversion of gasoline to kinetic energy in a car – are therefore excluded. More details can be found in Appendix I.) The main reason why SSP1 is lower than SSP2 is that the import-export balance of oil and oil-products changes. In SSP1, the supply potential of biomass is greater than in the other scenarios, and hence imports of oil products are lower than in the other scenarios, as biofuels replace fossil transport fuels. The current shortage of naphtha and diesel production capacity in Brazil is assumed to persist, requiring imports to fulfil the demand. This effect is noticed in SSP2 and SSP3 in this study but not in SSP1 where this demand is met by biomass derived diesel and naphtha. The costs of importing oil products are therefore significant in SSP1, as shown in Fig. 8. The production of biofuels outcompetes the import of fossil fuels in SSP1 to supply energy to the transport sector. More crude oil is therefore available (in comparison to the other scenarios), which is exported. The production costs of power, fuels, and energy for the industry increase under more stringent emission targets.

Discussion

The aim of this study was to explore the extent to which biomass could be used in the future energy and chemical system in Brazil. The results should not be interpreted as final outcomes with absolute values but rather as trends for the future energy system and how much biomass will be needed. The results are influenced by the methods selected and the assumptions regarding the input data.

The total primary energy supply in 2050, as found in this study, is comparable to other studies that assess the future energy mix in Brazil, e.g. IEA,[64] Empresa de Pesquisa

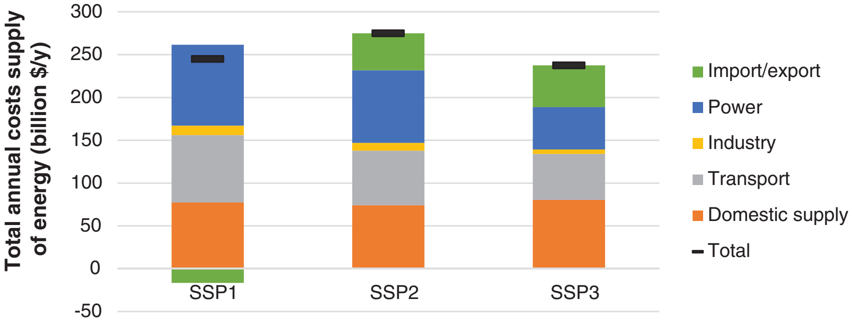

Figure 8. Relative costs of supply of energy for the scenarios as modeled in this study. In this figure SSP2 is considered as the reference situation. Costs for power, industry, and transport represent CAPEX and OPEX for conversion technologies (costs for transportation only represents the costs for the conversion of primary energy to fuels, thus exclude the purchase costs for vehicles, as well as the primary energy carriers). The costs for the category industry represent CAPEX and OPEX for further pretreatment of torrefaction and/or pyrolysis of biomass, and production of chemicals. The costs for domestic supply represent indigenous production of biomass and fossil fuels. The category import/export represent purchases or sales of fossil fuels (mainly oil and oil products).

Energética (EPE),[39] Nogueira *et al.*[24] and Rochedo.[49] The research differs in terms of approach or methodology but the primary energy supply of biomass is comparable (see Appendix IV). However, the level of detail that is given in this study provides us with details on the consumption of biomass per sector, as well as which technology is used. This is important because dynamic competition can therefore be explored within end-sectors, between biomass feedstocks, between other renewable and fossil energy carriers, and between competing technologies. A clear example of this dynamic competition is observed in the use of bagasse. Research shows that, nowadays, only a small fraction of the total potential of bagasse is used for electricity production in sugarcane refineries, highlighting the potential for biobased electricity production.[65] However, this study shows that under a stringent climate mitigation policy, bagasse for industrial use is favored above bagasse for electricity production.

It is noteworthy that the supply potential of biomass plays an important role in the magnitude of the production of biobased energy and chemicals in all three scenarios. In TIMBRA-BBE there is a constraint on the supply of lignocellulosic biomass but, over time, the supply potential increases significantly. Land availability and land-use related issues (competition with food, land use change (LUC)-related GHG emissions, impacts on biodiversity and soil quality) may influence the supply of biomass (either positively or negatively) for energy and chemical production. However, the sensitivity analysis also shows that the need to reduce GHG emissions by using biomass is lower in comparison to the SSP scenarios, as less than 80% is used under high biomass availability (Appendix VI). Moreover, the transportation of biomass is only partially addressed. The price of biomass includes transportation to the processing plant. However, the differences between harvest location and location of demand can be large in Brazil, and it is therefore either economically or environmentally unfeasible to transport biomass over large distances.[66] To assess the influence of biomass on the energy system in more detail, spatially explicit modeling of the supply potential of biomass is necessary.

Furthermore, only direct CO_2 emissions are taken into account in TIMBRA-BBE. In general, the upstream CO_2 emissions are relatively small in comparison to the direct emissions.[67] It is difficult to insert the full lifecycle emissions into the modeling framework,[16] and the upstream emissions are relatively small, so they have been excluded from this research. It should be noted that the full lifecycle emissions of bioenergy can have a substantial effect on the emission factors (CO_2 equivalent/MJ of bioenergy) of bioenergy, if (indirect) land use change emissions are considered.[68–70] In van der Hilst *et al.*,[71] LUC emissions (both direct and indirect) are assessed given an increasing demand for bioethanol in Brazil. The relevance of agricultural management becomes clear as land-use change mitigation measures (high agricultural productivity, switch to

2G ethanol, and strict conservation of protected areas) can result in lowering the LUC emissions from 26 (reference) to 12 gr. CO_2 eq./MJ_{etoh} (all mitigation measures). Until recently, the Brazilian government tried hard to reduce deforestation. Most of the legal mechanisms meant to reduce deforestation are part of the Brazilian Forest Code. However, the latest revisions of the Forest Code (2012) are not yet (fully) implemented due to lobbying from, e.g., agribusiness.[72] On the contrary, new laws outside the Forest Code were put into force in 2017 that enabled private land owners to legalize their land holdings,[73] allowing for land grabbing and subsequently leading to deforestation.[58,74] When the government decides not to live up with the Forest Code it will be impossible to reach targets that are necessary for limiting global warming to 2°C.[58] On the other hand, biomass can also be produced by good agricultural management and spatial planning, which can result in better GHG performance because iLUC is prevented and more carbon is stored in agricultural soils.[5] However, this requires an integrated approach to assess land use change and related emissions, which is not incorporated in TIMBRA-BBE yet. Due to the considerable demand for bioenergy in some of the scenarios of this study, it will be worthwhile investigating this issue in future research.

The impact of the assumptions related to investment costs, fuel prices and biomass supply potential, on the modeling results, are shown in the sensitivity analysis (Appendix VI). The availability of biomass is the major parameter that influences the results: when biomass is limited available renewable energy will be delivered by alternative sources. Fuel prices (both biomass and fossil) and investment costs have less impact on the results. This is because the effect of the carbon budget (strict limit on carbon emissions) is larger than the effect of price differences.

The results show a large increase in intermittent renewables in the power sector. This may affect the stability of the grid in Brazil.[75] The operation of the power sector was not the focus of this study and the assessment of the reliability of the power grid requires a different method because the production patterns of solar and wind energy and the demand for electricity are aggregated to periods of approximately 5 h,[36] while hourly patterns are required to assess the reliability of power systems.[76]

Technological development of conversion technologies can influence modeling results as the costs of solar and wind energy showed large reductions in past years[77] but investments in advanced biomass technologies also slowed down[60] during those years. These developments are assessed in the sensitivity analysis (see Appendix VI for more detail), showing that cost reductions of intermittent power supply only slightly influences the modeling results for 2050, as they are already present due to the restrictions in GHG emissions of the carbon budget. When advanced biomass technologies are introduced less quickly, a switch in technologies is observed. Less efficient biomass conversion technologies (e.g. dimethyl ether (DME) plants instead of FT plants) are present in the technology mix, resulting in lower production of energy available for final consumption. More renewable electricity (mainly produced from solar and wind energy) is therefore required to meet energy demands (see Appendix VI for more detail).

he least-cost optimization method used in this study did not incorporate social dimensions as it was not designed to do so. So-called computable general equilibrium (CGE) models can assess the socio-economics of biomass production. In the case of Brazil, the results of CGE models show that the socio-economic situation can improve when the biobased economy is growing. Brinkman *et al.*[78] show a significant increase, towards 2030, in newly created jobs and GDP growth with growing demand for sugarcane. The effect of growing demand for sugarcane is not only positive for the economic situation but also for the social situation. Walter *et al.*[79] and Gerber *et al.*[80] show a higher human development index (HDI) in municipalities with sugarcane cultivation, in comparison to municipalities without sugarcane cultivation. On the other hand, there are also social issues in the Brazilian agricultural business. Working conditions in sugarcane plantations are described as bad due to the hard physical labor. The International Labour Organization (ILO) noticed that 'forced labor' is still an issue, and the burning of cane can cause health problems,[81] although the recent mechanization of sugarcane cultivation ensured a decrease of the number of employees working under tough conditions.[82] Land ownership is also a problem as Brazil is sensitive to land grabbing by (international) agro-industrials, which threatens small-scale farmers and indigenous communities.[58,83,84] Recently, however, international organizations have expended great effort to include all of these social issues in certification schemes for biobased products, ensuring improvements in social conditions with a growing demand for biobased products.[82]

The results highlight the importance of BECCS in reducing atmospheric carbon emissions. However, the technology related to the capture and storage of CO_2 is still in the development stage.[2] Issues like transportation costs, seasonality, and reservoir capacity will all play an important role in the economic and physical feasibility of CCS.[85]

Energy efficiency measures are present in the transport sector only. For a fair comparison this should be expanded to the whole model. Especially in the residential sector, the inclusion of energy efficiency measures can ensure lower demand for primary energy.[86]

Conclusion

The aim of this study was to explore the role that biomass can play in meeting the demand for energy and chemicals, and the mitigation of GHG emissions in Brazil up to 2050. In comparison with similar studies adopting the least-cost optimization method for analyzing the energy and chemicals demand for Brazil, this study makes methodological improvements in three ways: (1) detailed breakdown of biomass feedstock, (2) conversion technologies are added for the production of advanced biofuels, biojet fuel, and biochemicals, and (3) a demand sector for bulk-chemicals is added.

The primary energy supply from biomass resources increases from 6 EJ (2010) to 11–14 EJ (2050) in the different scenarios. The major drivers for the growth of biomass are supply potential and climate policy. Throughout the SSP scenarios, 86–96% of the biomass sustainable supply potential is used, which highlights the fact that biomass is economically attractive in Brazil. However, the sensitivity analysis (which includes a model run with increased biomass supply potential) shows that biomass use reaches a point of saturation as a climate mitigation measure, because less than 80% of this technical biomass supply potential is used in that case. Biomass is mostly used in the transport sector. Under more stringent mitigation strategies, a switch is observed from fossil fuels towards transportation using electricity (private transportation) and hydrogen (freight transportation). Even without climate policy, 2G transport fuels become economically attractive in comparison to fossil fuels, which are hindered because of the large investments needed in oil refineries. Furthermore, serious growth of the use of biomass in the power sector is observed (BIGCC with CCS), and in the industrial sector, including biobased olefins from ethanol and bio-naphtha. While fossil-based chemicals remain the most produced chemicals, SSP1 and 2 show a growing production of biobased chemicals. This highlights the fact that a wide range of novel biomass technologies will be required to meet stringent emission targets, especially those with the option to capture CO_2. The annual costs for the supply of energy are the highest in SSP2, showing that more stringent climate targets do not necessarily lead to higher costs. The total annual costs in SSP1 are lower ($30 billion) because of the higher biomass potential. Lower fuel costs are the main reason for the decline in annual supply costs, as investment costs for conversion technologies are 17% higher.

Upstream GHG emissions can have either a negative (LUC emissions and large transport distance) or a positive (net increase of the carbon sink) impact on the GHG performance of biomass produced for energy and chemicals. The modeling framework of this study is an interesting tool to link supply-related issues of biomass production to biomass demand for energy and chemicals. It can therefore serve as a platform to inform the debate on the sustainability of biomass resources in Brazil, especially by being transparent about the methods and data chosen.

Recommendations for future research are:

- The linking of TIMBRA-BBE to a land-allocation model. With interlinked models, the dynamic interaction between demand for biomass and (indirect) land use change can be quantified.
- Increasing the shares of intermittent renewables may affect grid stability in Brazil. To model the reliability of low-carbon power systems an improved model is needed that includes hourly demand patterns, and hourly production patterns of intermittent renewable energy.
- Transportation of captured CO_2, and its geological storage potential, need to be assessed to investigate the feasibility of BECCS as a climate-change mitigation measure.

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