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System analysis of the bio-based economy in Colombia: A bottom-up energy system model and scenario analysis

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Abstract: The transition to a sustainable bio-based economy is perceived as a valid path towards low-carbon development for emerging economies that have rich biomass resources. In the case of Colombia, the role of biomass has been tackled through qualitative roadmaps and regional climate policy assessments. However, neither of these approaches has addressed the complexity of the bio-based economy systematically in the wider context of emission mitigation and energy and chemicals supply. In response to this limitation, we extended a bottom-up energy system optimization model by adding a comprehensive database of novel bio-based value chains. We included advanced road and aviation biofuels, (bio)chemicals, bioenergy with carbon capture and storage (BECCS), and integrated biorefinery configurations. A scenario analysis was conducted for the period 2015–2050, which reflected uncertainties in the capacity for technological learning, climate policy ambitions, and land availability for energy crops. Our results indicate that biomass can play an important, even if variable, role in supplying 315–760 PJ/y of modern bio-based products. In pursuit of a deep decarbonization trajectory, the large-scale mobilization

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of biomass resources can reduce the cost of the energy system by up to 11 billion \$/year, the marginal abatement cost by 62%, and the potential reliance on imports of oil and chemicals in the future. The mitigation potential of BECCS can reach 24–29% of the cumulative avoided emissions between 2015 and 2050. The proposed system analysis framework can provide detailed quantitative information on the role of biomass in low carbon development of emerging economies. © 2020 The Authors. *Biofuels, Bioproducts, and Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Key words: bio-based economy; biomass value chains; energy system modeling; TIMES; Colombia

Introduction

The stabilization of atmospheric greenhouse gases (GHG) requires a profound transformation of the global energy supply towards renewable sources.^{1,2} Bioenergy (BE), carbon capture and storage (CCS), and their combination (BECCS), could play an important role in this transformation, especially the latter technology, owing to its net negative emission balance.^{1,3–7} Moreover, biomass can be used in diverse applications, including sectors with limited renewable substitutes for fossil fuels, such as aviation fuels and chemicals.^{8–10}

The terms ‘bio-based economy’ (BBE) and ‘bioeconomy’ have been used increasingly within different narratives.¹¹ We refer to the transition from a fossil-based economy towards a bio-based economy, or the development of bioeconomy sectors,^{12,13} which, as defined by the European Commission, ‘integrates the full range of natural and renewable biological resources – land and sea resources, biodiversity and biological materials (plant, animal and microbial), through to the processing and the consumption of these bio-resources.’¹⁴

For emerging economies with high potential for producing primary biomass resources, the transition to a sustainable bio-based economy (BBE) could be instrumental in achieving sustainable development goals (SDGs) and commitments under the Paris Climate Agreement.¹⁵ Such a path may be viable for Latin American countries,^{16–18} and particularly Colombia,¹⁹ given the country’s potential for supplying biomass resources.²⁰ Globally, it is in a strong position as a producer of first-generation (1G) biomass feedstock,²¹ and it also has a well-established biofuel industry.²²

Several roadmaps have recently been released to stimulate the development of novel bio-based value chains in Colombia.^{19,23–25} However, their qualitative nature may be insufficient to understand the complexity of the transition towards a BBE. Such a transition depends on the dynamic competition between biomass sources, conversion technologies, and sectors.⁹ Other alternatives for the supply of energy and

chemicals, and the imperative for GHG mitigation^{26–29} also need to be factored into the transition process.

The role of biomass in Colombia has been addressed in regional GHG mitigation studies. These have drawn on integrated assessment models (IAMs), computational general equilibrium (CGE) models, and global energy optimization models.^{30–34} These methods have enabled understanding of systemic feedback between different alternatives. However, their aggregate resolution may fall short of addressing the complexity of the BBE at country scale.³⁵ Moreover, their respective scopes may have overlooked the emerging roles of biomass in aviation fuels and biochemicals.^{10,26–28,36,37}

The transition towards a BBE can be addressed using energy system models (ESMs).³⁵ Nevertheless, most of the published Colombian ESM studies have not focused on biomass;^{38–42} they have furthermore given only limited / no account of novel bio-based applications or the role of BECCS.^{43,44} Biomass-oriented ESMs have been applied to other case studies,^{45–51} as in the work of Tsiropoulos *et al.*,^{8,27} who integrated a detailed representation of the (bio) chemical industry and aviation biofuels into an ESM for the Netherlands. In another example, Lap *et al.*²⁶ amended an ESM of Brazil with a thorough depiction of biorefineries and BECCS technologies in the sugarcane sector. Significantly for other countries including Colombia,⁵² these studies excluded the palm oil sector. Focus on the latter sector has primarily been at a process level involving studies on the potential valorization of palm oil residues through biorefinery concepts.^{53–60} However, an understanding of their system-level competitiveness with other options is still lacking.

The aim of this paper is to explore the potential contribution of BBE options, including BECCS, to the low carbon supply of energy and chemicals in emerging economies that have significant potential for production and use of primary biomass resources. An optimization modeling system analysis framework is demonstrated for the case of Colombia.

Methods and data

Modeling framework

This system analysis was executed with TIMES (The Integrated MARKAL (MARKet ALlocation) EFOM-System) model generator. TIMES is a bottom-up demand-driven techno-economic optimization tool, based on partial equilibrium economic rationale and linear mathematical programming. The objective of the optimization solver is to minimize the total discounted cost, or net present value (NPV), of the entire system throughout the time horizon of the analysis, within defined system boundaries.⁶¹

The main components of the objective function could be simplified as follows:

$$\min(NPV) = \sum_t \left(\begin{array}{l} \sum CRF \times CC \times IC + \sum FC \times IC \\ + \sum_{p,c} VC \times E_{out} + \sum_c (P_{imp} \times E_{imp}) \\ - (P_{exp} \times E_{exp}) \end{array} \right) \quad (1)$$

where the subscripts t , p , c , imp , and exp represent periods within the time horizon, the processes (or technologies), the commodity flows, and the import and export flows, respectively. The first term corresponds to the capital investment, through a capital recovery (annuity) factor (CRF), the capital cost per unit capacity (CC, also referred to as CAPEX), and the total installed capacity per process type (IC). The second term depicts fixed operational costs (FC), for example overheads, administration, and patents. The third term describes variable operational cost (VC), for example process maintenance and labor, as a function of activity or commodity flow (E). The fourth term expresses the international trade of commodities, based on import and export prices (P). Note that the output of one process is an input to another.

The minimization problem is subject to several constraints, which include physical boundaries (e.g. resource availability), technical limitations (e.g. operational flexibility), policy decisions (e.g. bounds on GHG emissions), and market penetration constraints (e.g. technology adoption rates). Accordingly, this tool computes the optimal least-cost mix of capacity investment per technology and energy / material flows to meet the final service demand, within the defined system boundaries. A detailed description of the method is presented elsewhere.^{62–64}

The model generated for this analysis builds upon TIMES-CO-9 – a representation of the Colombian energy system and a successor of the MARKAL-Colombia model.^{38–42} To address our research aim, we upgraded and

extended TIMES-CO-9 with a detailed representation of biomass value chains, including its supply and conversion to electricity, heat, fuels, and chemicals. Factors contributing to future uncertainty, including cost-supply potential, technological development, and climate policy targets, were addressed *via* scenario analysis.

The extended and upgraded version is referred to as TIMES-CO-BBE. The differences between both versions are explained in Appendix 1 (For all appendices see the supplementary material). Unless stated otherwise, references to the modeling framework hereafter mean the extended version. TIMES-CO-BBE covers a time horizon between 2015 and 2050, in steps of 5 years. For electricity demand and supply patterns of variable renewable sources, the time resolution per year is divided into 40 time slices. These slices include five representative daily patterns (early morning, morning ramp, afternoon, evening peak, night), for two representative days (weekday, weekend day), in four (hydrological) seasons.

Model structure

Figure 1 shows the structure of the TIMES-CO-BBE model. The system is represented by a network of value chains extending across three main modules: primary supply, conversion, and demand; and a complementary international trade module. The supply module represented the availability of primary resources, for example through upstream extraction. The conversion module included the sectors that transform primary resources into intermediate or final fuels and / or other products. Intermediates, whether produced within the module or imported, referred to commodities that feed other transformation processes. Final commodities were the ones consumed within the demand module to provide the represented service demand. The international trade module included imports and exports at different stages of the value chains. The modules are described in the following sub-sections.

Primary supply

The supply module included fossil resources (coal, crude oil, and natural gas), other renewables (hydro, solar and wind), and biomass. For details on fossil fuels (reserves) and other renewables (potentials and patterns), see Appendices 2.1 and 2.3, respectively.

Primary biomass supply was defined to include both first- (1G) and second-generation (2G) feedstock, as well as traditional firewood. The 1G crops incorporated sugarcane and palm oil fruits as feedstock for edible products and modern applications, while primary 2G feedstock included lignocellulosic biomass from agricultural and forestry residues. It also comprised biogas from animal manure, and

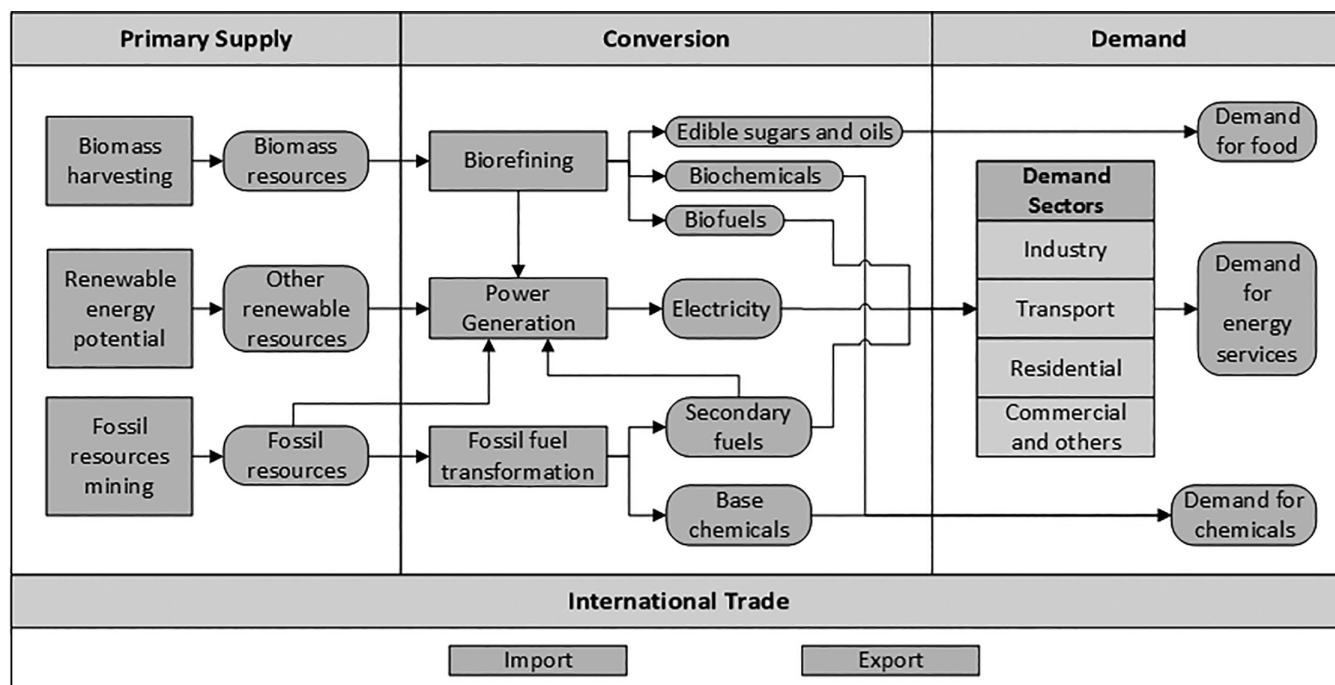


Figure 1. Schematic diagram of the model structure.

dedicated woody energy crops grown on surplus land. The milling of 1G feedstock generates secondary lignocellulosic biomass, which was also incorporated into the study. We have addressed in detail the valorization potential of secondary biomass and its contribution to final demand. However, on the primary supply side, this secondary biomass was already embedded in, and accounted for within, the 1G feedstock.

The potentials of primary residues were based on exogenous data (Appendix 2.2.1), whereas those for energy crops were parametrized by land availability, production yields and costs (Table 1).

The supply potential of bioenergy crops depends on variable factors that could affect the development of land use sectors.^{74–77} However, thorough analysis of future land use was not within the scope of this research. Jimenez⁶⁵ previously studied land use, comparing a reference scenario to a high efficiency scenario in Colombia, in terms of agricultural yields and livestock intensification. Their study concluded that on a high-efficiency path, land use by 2030 could be 19 Mha less than the reference pathway. We extrapolated the Jimenez figure to 2050 and formulated two scenarios representing a wide range of uncertainty. The *BioLo* scenario represented continuation of historical land use patterns, leading to limited availability of land. In contrast, the *BioHi* scenario reflected a transition towards intensive livestock and agricultural production. Thus, a ‘surplus’ of land would be available for biomass without competition with food production.

Conversion technologies

The conversion module included a large database of fossil fuels as well as biomass and other renewable technologies (see Appendix 3.1). Figure 2 provides an overview of the BBE options, including palm oil and sugarcane biorefineries, standalone 2G biorefineries, and bioelectricity.

Technologies were represented by techno-economic parameters, including CAPEX and OPEX, conversion efficiencies, load factors and economic lifetime (see the databases in Appendices 3.2 and 3.3). Cost structures were standardized via a factorial approach⁷⁸ and represented in constant US\$₂₀₁₅, while the impact of the investment climate on CAPEX was represented by a location factor. (Investments in Colombia were assumed to be 30% higher than in industrialized countries and similar to investments in Latin America, e.g. Brazil.²⁶) The database of existing technologies was based on the TIMES-CO-9 model, and was calibrated to the national energy balance year 2015.⁷⁹ The bio-based data were drawn from various sources.^{8,26,59,80,81} Data on non-bio power^{82,83} oil refineries and hydrogen^{84,85} were also used.

Technological learning was represented by improvement in efficiency, economy of scale, and years taken for introduction of new technologies. These factors were determined exogenously from bottom-up process engineering assessments, scaling factors, and technological readiness level

Table 1. The main parameters used to estimate the supply potential of biomass from energy crops, and the corresponding units and values.

Scenario	Present	BioLo (2050)	BioHi (2050)
Land availability* (kha)	550	1000	19400
Energy crops yields (GJ/ha)			
Palm oil**	216		335
Sugarcane***	573		573
Eucalyptus****	260		416
Supply potential: Other biomass (PJ)			
Agricultural and forestry residues*****	165		274
Biogas from animal manure	35		47
Supply costs***** (\$/GJ)			
Palm oil	10.5		9.3
Sugarcane	5.7		5.7
Eucalyptus	3.2		3.2
Agricultural and forestry residues	1.7		1.7
Biogas from animal manure	3.9		3.9

* Current land use corresponded to existing sugarcane and palm oil plantations.²¹ *BioLo* and *BioHi* estimates were based on future projection of historical trends and Jimenez,⁶⁵ respectively.

** Current and future palm oil yields were based on Ramirez-Contreras *et al.*⁶⁶ and the energy yield calculated from Garcia-Nunez *et al.*⁵⁹

*** Current sugarcane yield was taken as an average figure for the last decade,⁶⁷ and it was assumed to remain constant because current figures are relatively high and future expansion could occur into regions of poorer land quality. Energy yield was based on Lap *et al.*²⁶ and included up to 128 GJ/ha of available field residues, considering that at least half of the residues stay in the field for ecological reasons.

**** Current and future projections of eucalyptus were based on the consortium for commercial potential of reforestation (PROFOR).⁶⁸ and the energy yield from Lap *et al.*²⁶ and van den Broek *et al.*⁶⁹

***** Agricultural and forestry residues in estimates excluded sugarcane and palm oil residues, which depend on the harvest of these crops.

***** Palm oil costs were based on Ramirez-Contreras *et al.*,⁶⁶ while sugarcane was based on average reported 7-year costs.⁷⁰ Eucalyptus costs were taken as an average figure from different land qualities in Brazil, including the cost of attaining sustainability criteria as defined by Smeets and Faaij.⁷¹ The average cost of primary agricultural residues was based on field processing and transport costs of 1.2–1.8 \$/GJ and 0.2 \$/GJ, respectively,⁷² assuming similar cost for forestry residues. For secondary process residues not valorized in the same facility, only the transport cost applied. Biogas from anaerobic digestion of manure was an average figure for swine and dairy systems⁷³.

matrices.^{8,26} We then addressed them using scenario analysis (see the data in Appendix 5.1).

The scope of (base) chemicals in our analysis was restricted to olefins and ammonia. The production of olefins in

Colombia is mainly based on steam cracking of ethane feedstock. This process was implicitly represented by linking the refinery non-energy products reported by the energy balance⁷⁹ to the production of olefins (see below). New routes identified for olefins, included fossil- and bio-based (thermochemical and biochemical) production from methanol, naphtha, or ethanol. Ammonia routes included reforming of natural gas, as well as biomass gasification. Moreover, intermediate input to downstream chemicals and fuels included methanol (from natural gas synthesis and biomass gasification) and hydrogen (from methane reforming, electrolysis, and biomass gasification); hydrogen was also identified as a fuel for the transport sector.

Regarding palm oil mills (POMs), the extraction of crude palm oil (CPO) generates residues, which can be valorized through alternative biorefinery options. The common ground is the capture and utilization of biogas from POM effluent for own-process energy. Accordingly, the demand for residues is (partially) substituted, releasing them for alternative uses.

Concerning the power sector, electricity production was represented by a single demand pattern for the whole economy, retrieved at an hourly resolution⁸⁶ and aggregated to 40 time slices (see Appendix 3.4.1). The assumptions on renewable energy potential constraints, grid penetration limits of intermittent renewables, capacity expansion limits of power production, and investment in transmission infrastructure are listed in Appendix 3.4.2.

Demand

The energy services in TIMES-CO-9 were grouped into industrial, residential, transport, and commercial sectors. The commercial sector comprised an aggregation of other demand sectors in the national energy balance, including energy consumption for 'non-identified' purposes. We represented these purposes by a hypothetical technology which meets a non-identified demand by consuming a fuel mix calibrated to the energy balance in 2015. We assumed that the fuel mix of this technology remains structurally constant over time. We complemented these energy services with the demand for base chemicals and edible sugars and oils. Accordingly, the total number of service demands in TIMES-CO-BBE was (Appendix 4.1). The future demand projections were represented by exogenous socio-economic drivers (Appendix 4.2), where the price elasticity of demand is not part of the cost optimization.

Without any constraints on optimization models, the optimal solution requires sudden full market uptake by value chains with the least marginal cost. To avoid these unrealistic technological transitions, we introduced systematic market constraints on demand technologies. For example, new investment in each demand technology to fulfill a given

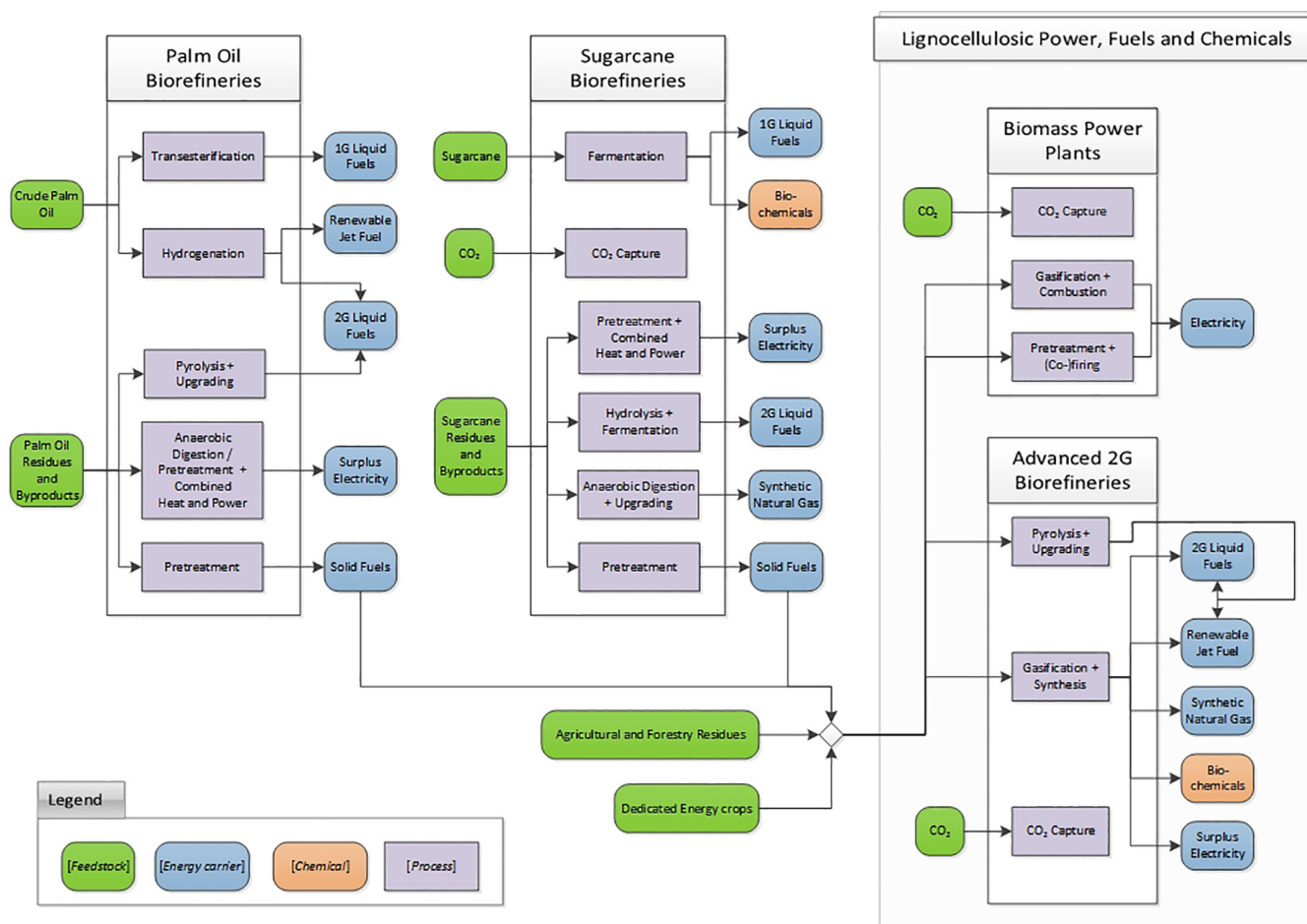


Figure 2. Overview of the conversion technologies that represent the bio-based economy (BBE) in the model. The captured CO₂ is generated in the conversion process.

service demand was roughly limited to 20% by 2020 and linearly increased to 99% by 2050 (see Appendix 4.3.3).

The main techno-economic data for demand technologies is provided in Appendix 4.3. For transport mobility, a modal switch was excluded, while for chemicals, the demand for olefins was estimated by the olefin content of the main polymers produced in Colombia,^{87–89} and that of ammonia by the demand for nitrogen-based fertilizers^{89,90} (see Appendix 4.4).

For low carbon value chains, the integration of advanced biofuels into internal combustion engine (ICE) vehicles in the road transport sector could compete with battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEVs). In the aviation sector, renewable jet fuel (RJF) was projected to be the main substitute to fossil kerosene. The potential for blending of fossil and biofuels depends on technical, market, and policy factors. Market penetration limits were assumed for individual advanced BBE value chains, growing up to 5% in 2020 and 10% in 2030,^{8,91}

extrapolated to 100% by 2050. For the industrial sector, lignocellulosic biomass and biogas can be converted into useful energy for heat and machine drive. Moreover, synthetic natural gas (SNG) can be injected into the gas distribution grid for the demand sectors.

Scenario analysis

The role of biomass depends on feedstock availability, capacity for technological learning, and climate mitigation targets, among other things. We addressed these factors, which cause uncertainty, using scenario analysis,⁹² based on the shared socio-economic pathways (SSP) framework.⁹³ To cover a wide range of uncertainty, we considered three scenarios in line with the SSP storylines (SPPs1–3) (see Table 2).

SSP1 depicts a 'sustainable development'-oriented future where worldwide stringent measures would be taken to mitigate climate change. This scenario is characterized by low

Table 2. Quantitative description of the SSP scenarios used in this analysis.

Scenario variables	SSP1	SSP2	SSP3
Population (millions)/gross domestic product (billion \$) by 2050*	56/1996	62/1837	69/1504
Low carbon technology development**	Progressive	Intermediate	Modest
Energy markets*** (oil price by 2050, \$/GJ)	Low (12.8)	Intermediate (22.2)	High (26.3)
GHG net emission target (Mt) by 2050 and reduction with respect to baseline (%)****	17 Mt (85%)	32 Mt (70%)	52 Mt (50%)
Blending of 1G biofuels***** (% _{vol.}) by 2050	B18–E12	B13–E09	B10–E08
Carbon storage potential***** (Mt CO ₂)	Cumulative: 4303–annual: 150 by 2050		
Biomass supply per scenario	<i>BioLo</i> : 650–1000 PJ– <i>BioHi</i> : 6800–13900 PJ		

*The projections of population and gross domestic product in purchasing power parity are based on the SSP scenarios database.^{94,95}

**The introductory years of technologies and their corresponding CAPEX and efficiency improvement are reported in Appendix 5.1. The average reductions of CAPEX for wind and solar power were $-2\%/y$, $-1\%/y$ and $-0.4\%/y$ in SSP1, SSP2, and SSP3, respectively. The corresponding CAPEX reduction of bio-based technologies was $-2.2\%/y$, $-1.2\%/y$, and $-0.3\%/y$.

***Adapted from the World Energy Outlook scenarios.^{96,97} See Appendix 5.2 for details and breakdown per secondary product.

****The emission targets are expressed in absolute Mt by 2050 and in percentage reduction with respect to the baseline scenarios (without emission constraints). Milestone targets (2030) were based on the intended Nationally Determined Contribution (iNDC) endorsed by Colombia for the Paris Agreement.⁹⁸ Longer-term targets (2050) were loosely inspired by the trends of Latin America in some SSP Representative Concentration Pathway (RCP) scenarios.^{7,94} See Appendix 5.3.

*****Blending mandates for Biodiesel (B) and Ethanol (E) with fossil diesel and gasoline by 2050, respectively, based on Gonzalez-Salazar et al.⁴³

*****The cumulative storage potential represents the capacity of geological formations, taken as the average of reported figures by Godec et al.⁹⁹ and Postic.¹⁰⁰ This includes Enhanced Oil Recovery (EOR), depleted fields, coal bed methane (CBM) and saline aquifers. The annual potential represents the capacity for developing CCS infrastructure, which is assumed to double every decade, up to an upper limit of 150 Mt by 2050 based on²⁶.

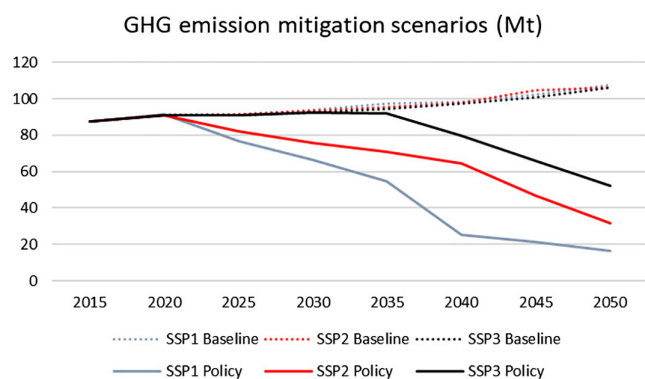


Figure 3. Greenhouse gas emission trajectories for the SSP mitigation policy scenarios and their respective baseline scenarios.

population growth, high urbanization, and high economic growth. Moreover, 'low carbon' technologies would experience rapid learning (early adoption, maturity, and upscaling); this would involve several BECCS technologies becoming available within 15–20 years. Simultaneously, international oil prices would decrease. In this scenario, by 2050 the emissions from the energy system would be 85% lower than the reference baseline case (Fig. 3). Note that (the emissions accounted for in this study were the net CO₂ emissions associated with the direct conversion of primary resources to final energy. The indirect lifecycle emissions were not considered.

At the other extreme, SSP3 represented a regionalized world with high growth of (rural) population, low economic growth, slow technological change (virtual absence of BECCS technologies), reduced trade flows, and high fossil-fuel prices. Under such conditions, a modest emission reduction of 50% by 2050, compared to the baseline, was assumed.

As an intermediate case, future trends in SSP2 would not shift markedly from historical patterns, with slow progress towards attaining SDGs. Some BECCS technologies would be available within three decades and, by 2050, emissions would be reduced by 70%.

For each scenario, we considered two biomass supply cases: *BioLo* and *BioHi*, thereby analyzing six scenarios in all. Accordingly, the influence of biomass supply could be evaluated for different socio-economic drivers, technology development, and GHG mitigation targets.

Results

The contribution of biomass to total energy supply and demand

Biomass could play an important, even if variable, role in decarbonizing the Colombian energy system. The total primary energy supply (TPES) is expected to grow from 2 EJ in 2015 to 2.6–3.1 EJ by 2050 (Fig. 4(a)). Fossil fuels are projected to decrease from 76% in 2015 to 35–36% for SSP1, and to

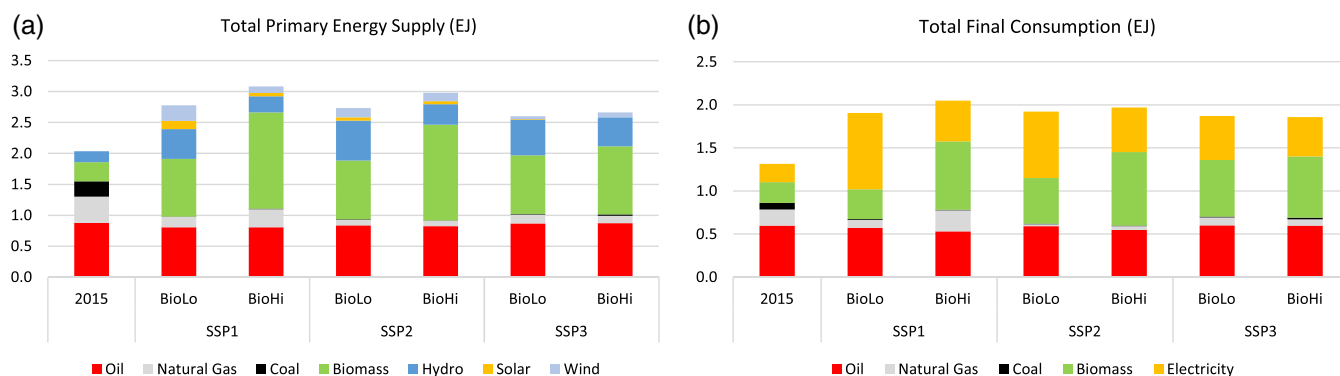


Figure 4. (a) Total primary energy supply (TPES) (EJ) in 2015 and 2050 scenarios for energy and non-energy purposes, where hydro, wind, and solar represent power generation and biomass includes traditional firewood and edible sugars and oils; and (b) Total final consumption (TFC) (EJ) in 2015 and 2050 scenarios represents the consumption of energy carriers to produce useful energy in the demand sectors, the energy content embodied in (petro)chemicals, sugar, and edible oils. Hydrogen use is allocated by source to natural gas, electricity, and biomass.

38–39% for SSP3 by 2050. The supply of oil is nevertheless anticipated to remain at 0.8–0.9 EJ, owing mainly to existing refining capacity. Based on expert consultation, official energy scenarios,¹⁰¹ and recent and upcoming investment and modernization plans of the national oil company,¹⁰² we concluded that large-scale retirement of existing refineries is unlikely within the time horizon of this analysis. An economic justification is to avoid stranding of assets, which could cost Latin America billions of dollars.³⁴ Moreover, the role of the oil sector is governed by energy security for the domestic market. Furthermore, the engagement of the oil sector in research and planning for decarbonization shows its potential role as a stakeholder in low-carbon futures.¹⁰³ Whereas the oil refineries are bounded by a minimum level of operational utilization, no (or limited) additional capacity is expected to be required beyond the recent expansion of the Cartagena refinery. It is noteworthy that the domestic oil reserves will likely be exhausted by 2030, after which the refineries could rely on crude imports. In 2015, crude oil exports were 1.75 EJ (76% of the oil production). For the scenarios, exports were flexibly bounded between current levels as an upper ceiling and zero. Thus, the compromise between export in the short-term and import in the long-term was based on the minimization of total system cost throughout the time horizon.

The decline in fossil resources in the scenarios was counterbalanced by the increasing deployment of renewables, especially biomass. In SSP3, biomass is anticipated to contribute 37–41% of the TPES (1.0–1.1 EJ) while other could renewables supply 21–24% (0.5–0.6 EJ). Note the small difference between *BioHi* and *BioLo*, despite the large difference in biomass availability. With a stringent GHG mitigation target and high biomass potential (SSP1-*BioHi*), the demand for biomass is anticipated to increase sharply to

1.6 EJ (50%), as opposed to 0.4 EJ (14%) of other renewables. Conversely, with restricted feedstock (SSP1-*BioLo*), the demand for biomass could be limited to 0.9 EJ (34%) and that of other renewables could reach 0.9 EJ (31%).

On the demand side, the total final consumption (TFC) is projected to grow from 1.3 EJ in 2015 to 1.9–2.1 EJ by 2050 (Fig. 4(b)). Note that the demand was structurally different per scenario, owing to the difference in underlying socio-economic drivers. The projected population growth in SSP3 scenario is higher than for SSP1, and *vice versa* for gross domestic product *per capita*. This led to higher residential energy demand in SSP3 and lower industrial and transport demand than SSP1. For instance, the transport and residential sectors represented 39% and 13% of the energy demand in SSP1, respectively, as opposed to 36% and 19% in SSP3. The net effect could be an overall higher energy demand in SSP1 than SSP3.

Fossil fuel consumption is expected to decline from 66% in 2015 to 35–38% in SSP1 and 37–38% in SSP3. In SSP3, biomass is likely to be the main substitute for oil in the transport sector, and for coal in the industrial sector, respectively. On the other hand, electricity could be the main low-carbon substitute in the built environment, followed by bioSNG injection into the gas grid. The built environment refers to the residential and commercial sectors, although the role of electricity in the latter was constrained by the rigid structure of the non-identified energy purposes.

In SSP1, electrification could be likewise the main alternative for residential services. In the industrial and transport sectors, the competition between biomass and electricity could depend on biomass resource availability. With a limited biomass supply (SSP1-*BioLo*), the main substitute for coal and gas in the industrial sector and for oil in the transport sector will likely be electricity.

In contrast, with an ample feedstock potential (SSP1-*BioHi*), biomass is projected to be the main low carbon substitute for transport fuels and a competitive alternative to electricity in the industry. Moreover, some industrial and residential services could remain reliant on natural gas. This can be explained by the greater role of negative emissions from BECCS technologies in this scenario, which could compensate for positive emissions elsewhere in the system. The final consumption and electricity demands per sector are presented in Appendices 6.1 and 6.2, respectively.

Sources and end uses of biomass

Lignocellulosic biomass can potentially form the main feedstock of the bio-based economy, yet particular value chains depend on the capacity for technological learning, resource availability, and the mitigation target.

The total biomass supply, starting at 310 PJ, is projected to increase to a range of 930–1550 PJ in SSP1, and a range of 950–1100 PJ in SSP3 scenario (Fig. 5(a)). By 2050, lignocellulosic biomass is expected to be the main feedstock, ranging from 430–1100 PJ (46–70%) in SSP1 and from 470–670 PJ (49–61%) in SSP3. Residues will likely be used to their maximum available potential, whereas the supply of lignocellulosic crops could depend on land availability. In SSP3-*BioLo*, where land was assumed to be constrained to 1000 kha, 70% of the lignocellulosic biomass is estimated to be from residues. With higher land availability (SSP3-*BioHi*), half of the lignocellulosics could be provided by 2G crops, which would raise the total land requirement to 1465 kha. In SSP1-*BioLo*, the composition is not expected to markedly differ from that in SSP3-*BioLo*, owing to the high demand for, and limited supply of biomass. By contrast, with a high

availability of land (SSP1-*BioHi*), the supply of 2G crops could sharply increase to 760 PJ, and the total land requirement could reach as high as 2620 kha; this comprises about 14% of the surplus land considered to be available in this analysis.

The demand for biomass is projected to grow from 38 PJ in 2015 to 315–760 PJ for SSP1 and 435–525 PJ for SSP3 (Fig. 5(b)). In relative terms, its use for manufacturing transport fuels could decrease from 93% in 2015, to 16–50% in SSP1 and 36–37% in SSP3, as new demand emerge in other sectors. The main application in SSP3 will likely be industrial heat, which could represent up to 36–38% of the biomass use (165–190 PJ); this could meet 50–57% of the anticipated industrial demand. Moreover, about 7–10% of the biomass use is expected to manifest in bioSNG injection into the gas grid for the built environment. Furthermore, 14–16% of the bio-based products are anticipated to be in the form of biochemicals, supplying up to 70% of the demand for chemicals.

Despite the comparable supply of biomass in SSP1-*BioLo* and SSP3-*BioLo*, their emerging applications will likely be different. Remarkably, up to 59% of the biomass use in SSP1-*BioLo* is projected to be for bioelectricity, mainly from BECCS power. However, under similar conditions even with high biomass availability (SSP1-*BioHi*), transport fuels will likely dominate the biomass portfolio at 380 PJ. This could supply about 51% of the demand for road and aviation fuels combined. Moreover, industrial heat, power, and chemicals account for 21%, 20%, and 9% of the biomass use, respectively; these in turn could contribute 40% of the industrial demand, 27% of the electricity demand, and 64% of the chemical demand, respectively.

Although SSP2 is an intermediate case, the use of biomass in SSP2-*BioHi* is projected to be comparable to that of SSP1-*BioHi*. This is largely driven by the co-production of road and aviation

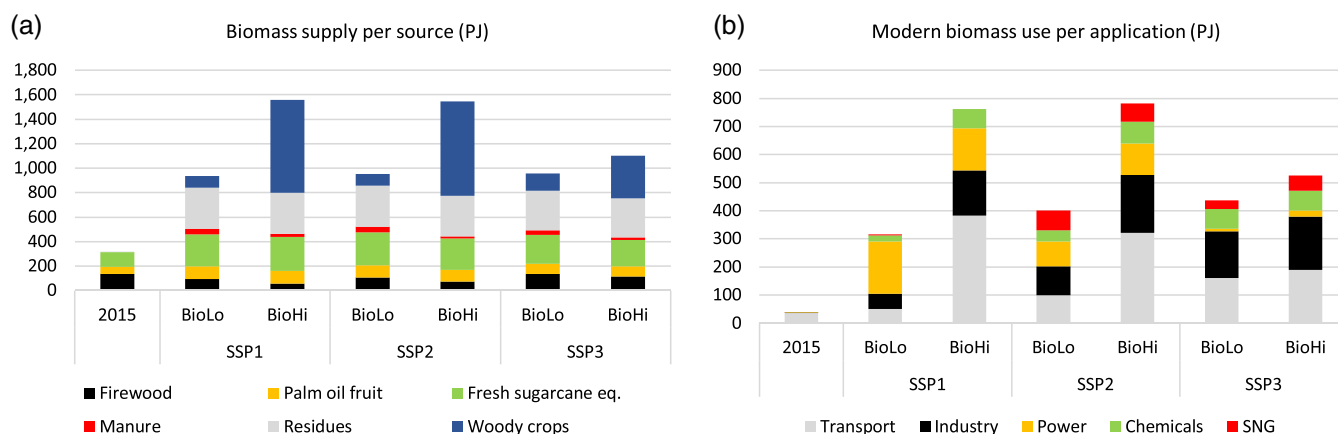


Figure 5. (a) Biomass supply per source (PJ) in 2015 and 2050 scenarios, including 1G crops for (co-)production of edible sugars and oils, 2G crops and residue streams and traditional fuelwood. Fresh sugarcane equivalent comprises the energy content of sugar and bagasse of harvested fresh cane; and (b) modern bio-based product per application (PJ).

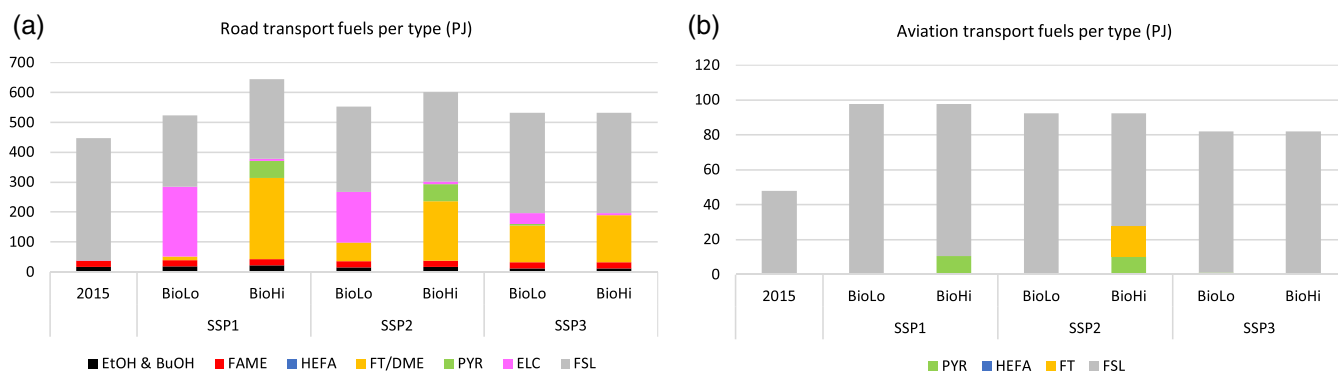


Figure 6. Transport fuels for (a) road and (b) aviation in 2015 and 2050 scenarios (PJ); where EtOH: Ethanol from 1G (and 1.5G) fermentation of sugarcane (and lignocellulosic residues); BuOH: Butanol from sugarcane fermentation; FAME: Fatty acid methyl ether (biodiesel) from palm oil transesterification; HEFA: Hydroprocessed ether and fatty acid (renewable diesel/RJF) from palm oil; FT: Fischer–Tropsch diesel alternative (and RJF) from biomass gasification; DME: DiMethyl ether from biomass gasification; PYR: Diesel and gasoline alternatives (and RJF) from pyrolysis and upgrading of biomass; ELC: Electricity; FSL: Fossil fuels.

transport biofuels (see below). By contrast, an alternative pathway is expected to be adopted in SSP1, characterized by decarbonizing road transport and higher use of negative emissions (see below). Thus, higher mitigation could be attainable in SSP1, based on an equivalent use of renewable energy.

Key bio-based value chains

Transport fuels

The demand for road transport fuels, as per Fig. 6(a), is expected to increase from 450 PJ in 2015 to 525–650 PJ in SSP1 and 530 PJ in SSP3 by 2050. As for SSP3, the use of conventional fossil fuels in ICE vehicles will likely decrease from 92% to 63%, whereas biofuels are anticipated to grow from 8% to 30–35% (160–190 PJ). Moreover, part of the freight and urban public transport fleet could shift to BEV, where electricity would contribute 1–7% of the fuel mix. Turning to SSP1, the difference between *BioHi* and *BioLo* is striking. In the former, biofuels could steeply increase to 58% (370 PJ), feeding a fleet predominantly made up of ICE powertrains. In contrast, in SSP1-*BioLo*, electricity is projected to represent 45% (235 PJ) of the demand because of the large-scale rollout of BEV private cars, freight trucks, as well as some public transport vehicles. Moreover, biofuels could contribute 10% (50 PJ) to the private ICE fleet.

Relating to Fig. 6(b)) the role of RJF will likely be limited to the SSP1 and SSP2 scenarios with high biomass availability (*BioHi*), whereas fossil kerosene from refineries and imports is expected to be the principal jet fuel. Note that RJFs are co-produced and influenced by road transport biofuels.

In SSP3, the main biofuel conversion route is anticipated to be biomass gasification and synthesis to dimethyl ether (DME), which is a diesel alternative. Regarding SSP1, the primary route

for road biofuels could be FT-synthesis (with CCS). In the case of *BioHi*, DME and upgraded pyrolysis fuels could make additional contributions, where the latter would include co-production of RJF. Note that the investments in co-production of RJF or BECCS were considered mutually exclusive. Whereas BECCS is likely of higher priority in SSP1, the opposite could be true in SSP2-*BioHi*, where FT-RJF could contribute 19% of the aviation fuels. In this scenario, BECCS could still be relevant, yet mainly in the power sector (see below).

Electricity and chemicals

The total power generation, as per Fig. 7(a)), is expected to increase from 250 PJ in 2015 to 550–1000 PJ in SSP1 and 535–600 PJ in SSP3. The installed capacity in SSP3 is projected to moderately grow from 17 GW in 2015 to 42–48 GW. In contrast, it could steeply rise to 88 GW in SSP1-*BioLo* because of the higher demand for electrification. Hydropower reservoirs will likely remain the main source of electricity supply, utilizing up to 55% of the technical potential in SSP1-*BioLo*. Moreover, wind power is anticipated to play an increasing role across all scenarios. In SSP1-*BioLo*, the penetration of solar and wind is likely to approach the grid constraints for intermittent renewables, owing to their low CAPEX, and the constrained supply of biomass. As for biomass, its role in SSP3 will likely be modest and limited to the cogeneration surplus of biorefineries. By contrast, biomass could account for 18% (190 PJ) and 27% (150 PJ) of electricity production in SSP1-*BioLo* and SSP1-*BioHi*, respectively. The main source of the bioelectricity is likely to be a form of BECCS technology, namely integrated gasification combined cycle (BIGCC) (see below).

For biochemicals, new markets are projected to be emerged, resulting in an increase of 20–64% for

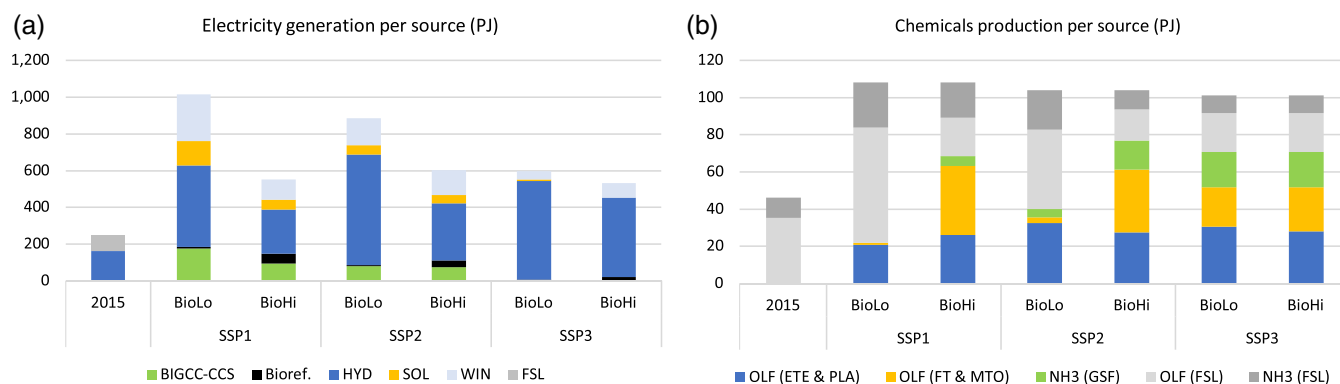


Figure 7. (a) Electricity generation per source (PJ) and (b) chemicals production per source (PJ) in 2015 and 2050 scenarios; where BIGCC-CCS: Biomass integrated gasification combined cycle with carbon capture and storage; bioref.: Cogeneration from biorefineries; HYD: Hydro; WIN: Wind onshore; SOL: Solar photovoltaic; OLF: Olefins (ethylene and propylene); ETE: Ethanol-to-ethylene; PLA: Polylactic acid; FT: Olefins from steam cracking of FT-naphtha; MTO: Methanol-to-olefins from biomass gasification and synthesis; OLF (FSL): Fossil olefins from ethane cracking, naphtha cracking, and MTO from fossil methanol; NH₃ (GSF): Ammonia from biomass gasification and synthesis; NH₃ (FSL): Ammonia from natural gas methane reforming.

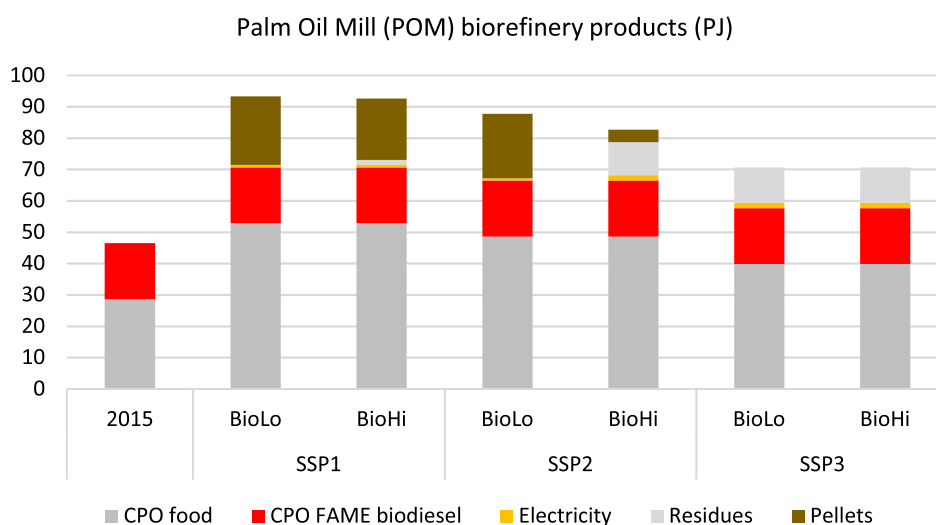


Figure 8. Palm oil mill (POM) biorefinery products in 2015 and 2050 scenarios (PJ); where CPO: Crude palm oil, FAME: Fatty acid methyl ether.

selected chemicals in SSP1 and 70% in SSP3 (Fig. 7(b)). As for olefins, the most robust route is likely to be sugarcane fermentation through ethanol-to-ethylene (ETE) conversion. For SSP3, next to the production of existing ethane crackers, imports could be replaced with investment in methanol-to-olefin (MTO) conversion, based on bio-based feedstock. Turning to SSP1, the trend in *BioHi* could be similar to SSP3, although with additional investment in steam cracking of FT-naphtha, which is a byproduct of transport biofuels. With limited biomass (SSP1-*BioHi*), biochemicals will likely be limited to fermentation routes only. Imports could only be partially

reduced, as fossil-MTO would provide a major part of the olefin supply.

Besides the existing ammonia production capacity from steam reforming of natural gas, the investment in biomass gasification in SSP3, is likely to eliminate the need for imports. In the case of SSP1, imports in *BioHi* could be avoided by investment in fossil-derived and bio-ammonia. However, with limited biomass supply (SSP1-*BioLo*), imports could remain a major source of ammonia supply. These results indicate that the competition for limited land could deem the use of biomass for mean power and transport fuels production more favorable than dedicated biochemicals.

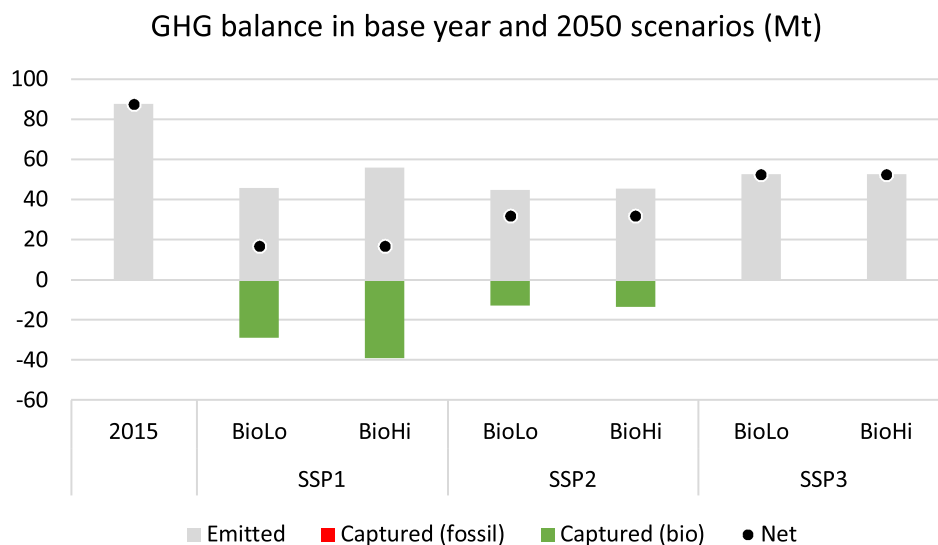


Figure 9. Greenhouse gas balance of the energy system in CO₂ equivalent as modeled in the analysis in 2015 and 2050 scenarios (Mt).

Palm oil mill (POM) biorefineries

Figure 8 shows the total output of POM biorefineries. The supply of CPO, is shown to mainly be driven by the demand for oleochemicals and existing fatty acid methyl ether (FAME) biodiesel capacity. Palm oil hydrogenation, producing hydroprocessed esters and fatty acids (HEFA) renewable diesel value chains, is likely to be outcompeted by the biomass gasification routes (see above). Regarding POM residues, the prevalent valorization option in SSP3 will likely be their release for use elsewhere in the system. In SSP1, and SSP2(-BioLo), pelletization could be the main route, driven by the demand for (torrefied) pellets in the BIGCC-CCS power plants.

The role of (BE)CCS

Figure 9 shows the annual GHG balance of the energy system by 2050. The role of (BE)CCS is found to be higher with a more stringent mitigation target (SSP1). The deployment of CCS could mainly be observed in combination with bioenergy (i.e. BECCS), providing negative emissions. In SSP1, the role of BECCS will likely be higher if more land could be available for biomass (SSP1-BioHi); this could allow positive emissions elsewhere in the system (such as the continued use of natural gas in the industrial and built environments).

In SSP1-BioHi, FT-synthesis and BIGCC power are anticipated to contribute 61% and 38% of the annual CO₂ capture by BECCS technologies, respectively. In SSP1-BioLo, BIGCC could account for 96%, owing to the limited role provided by advanced transport biofuels. Likewise, BIGCC could be the main BECCS technology in SSP2, where

the investment in FT biorefineries is likely to be focused on aviation fuels rather than CCS. Moreover, sugarcane biorefineries could contribute up to 1% and 2–3% of the CO₂ capture by BECCS in SSP1 and SSP2, respectively.

In cumulative terms, the CO₂ capture could reach 393–475 Mt in SSP1 and 68–71 Mt in SSP2. These figures correspond to a mitigation potential of BECCS up to 24–29% in SSP1 and 6–7% in SSP2, respectively. Note that the mitigation potential of BECCS is the contribution of captured and stored CO₂ to the cumulative avoided emissions (2015–2050) due to the replacement of fossil fuels. The avoided emissions were calculated from the difference between the net emissions of a given SSP scenario and the corresponding baseline (without mitigation target).

Economic implications of the bio-based economy

The total annual energy system cost by 2050 in the baseline scenarios (on the righthand side of Fig. 10) is projected to reach 31 and 43 billion \$/y in SSP1 and SSP3, respectively. With mitigation targets, the cost could increase to 36–47 billion \$/y in SSP1 and 47–48 billion \$/y in SSP3, owing to the additional investment in low carbon value chains required to comply with emission constraints.

Notably, the system cost in SSP1 is found to be lower than in SSP3, despite the higher mitigation target in the former. This could be explained by the rapid innovation of low carbon technologies in the SSP1 storyline, driven by strong international commitment to mitigation action. The international context was factored in by exogenous parameters,

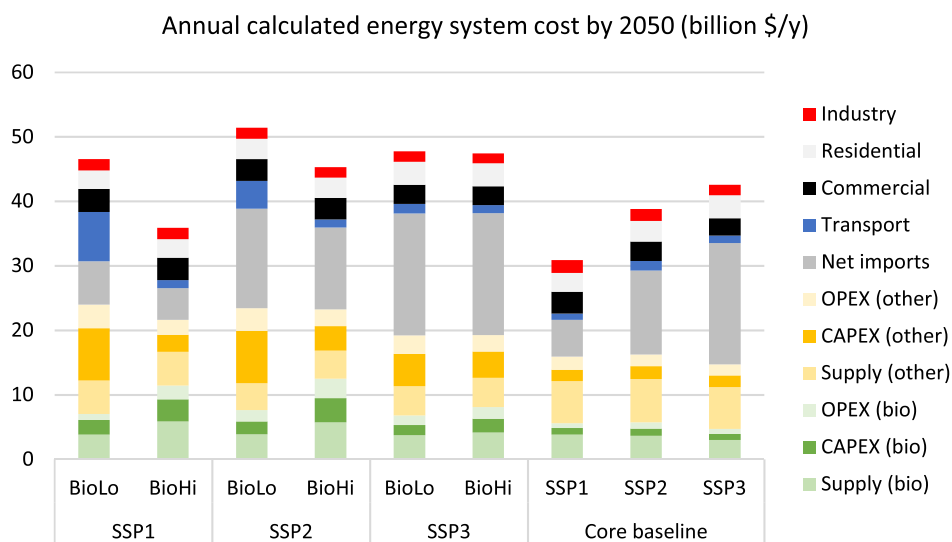


Figure 10. Annual calculated energy system cost by 2050 (billion \$/y) for the SSP scenarios and their baseline references (without mitigation targets), including the net imports and domestic supply of (bio and other) energy carriers, the CAPEX and OPEX of (bio and other) transformation processes, and the aggregated CAPEX and OPEX of demand processes per sector. The cost of energy for transport demand (in blue) represents the additional cost of powertrain components of new technologies (e.g. FCEV and BEV) compared with the reference (ICE) vehicles. This cost excludes non energy-related investments, such as the cost of vehicle gliders.

including lower cost of oil imports and steeper learning curves of low-carbon technologies, compared to SSP3. Note that since domestic reserves are projected to be depleted within a couple of decades, the supply of oil on the long-term could be more dependent on international prices. *These results show the effectiveness of early investment in new low carbon technologies.*

Concerning the influence of the biomass potential (*BioHi* vs *BioLo*), *achieving the same GHG mitigation targets without significant mobilization of biomass resources could incur higher costs; up to 11 billion \$/y in SSP1 and 6 billion \$/y in SSP2.* The difference is mainly attributed to the additional investment in vehicle powertrains (mainly BEV). In SSP1, these vehicle investments could be reduced by 83% when the deployment of biomass is higher (*BioHi*). Moreover, the cost of imports could be reduced by 26% due to the substitution of imported chemicals with bio-based alternatives. Furthermore, the investment in domestic energy supply and conversion to secondary products could be 10% less in SSP1-*BioHi* compared to SSP1-*BioLo*.

These domestic value chains were estimated to account for 52–60% of the total cost in SSP1 and 40–41% in SSP3. At high biomass availability (SSP1-*BioHi*), BBE value chains could cost 11 billion \$/y, mainly for the supply of energy crops as well as the CAPEX of FT biorefineries and BIGCC power plants. Moreover, non-bio value chains were costed at 10 billion \$/y, of which more than half is likely to be for mining gas and coal. By contrast, with limited biomass (SSP1-*BioLo*),

the cost of BBE value chains could be limited to 7 billion \$/y, mainly for crops, and BIGCC-CCS power. Further, non-bio value chains could cost 17 billion \$/y. The major share of this cost was determined to be the investment in power generation (hydro, wind and solar) and transmission grid infrastructure.

With regard to the economics of GHG mitigation, Fig. 11 illustrates the marginal CO₂ abatement cost curve (MACC) of the modeled energy system. Despite the limited number of scenarios, the trend indicates that the availability of biomass could reduce the cost of CO₂ abatement in the energy system. Moreover, such a reduction could be proportional to the mitigation target.

Discussion

The results were influenced by the uncertainty of input data and methodological limitations. We addressed the uncertainty via a sensitivity analysis for the most relevant parameters (Table 3), and we traced their impact on the lignocellulosic biomass flow per sector in SSP1-*BioHi* (Fig. 12).

The sensitivity analysis highlighted biomass gasification to electricity and liquid fuels as robust routes for achieving stringent emission mitigation; these technologies are especially noted for their capacity as BECCS. Although the tradeoff between gasification for transport fuels (FT-CCS) versus electricity (BIGCC-CCS) depended on the CAPEX of these technologies, the net change in the biomass conversion remained below ±2%. However, to reach the mitigation target

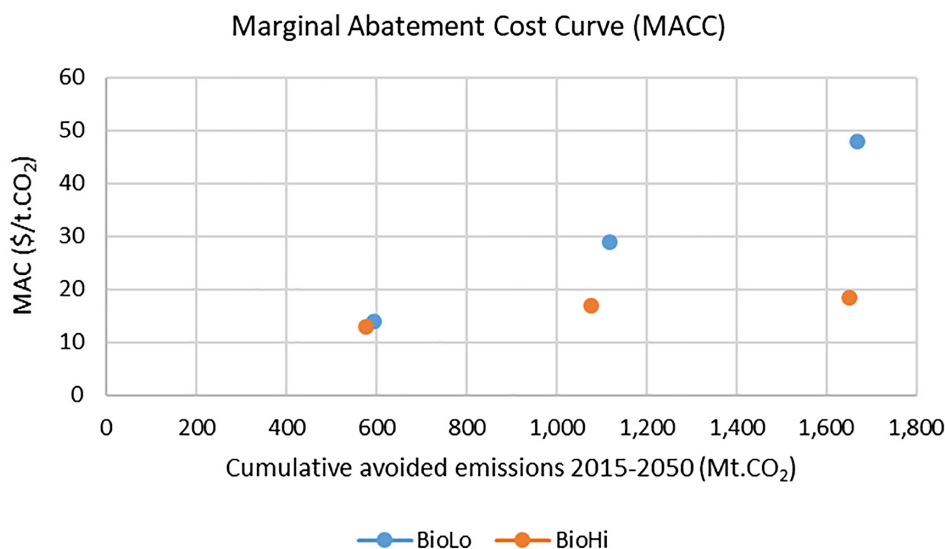


Figure 11. Marginal abatement cost curve (MACC). The marginal abatement cost (MAC) is estimated per each scenario in relation to its corresponding baseline (without emission constraints). The MAC is calculated as the difference in the total discounted system cost divided by the cumulative avoided emissions between 2015 and 2050.

Table 3. Parameters and data ranges used in the sensitivity analysis for SSP1 BioHi scenario by 2050.

Parameter	Low	Ref. scenario	High
Cost of lignocellulosic crops* (\$/GJ)	2.7	3.2	3.5
CAPEX**–BIGCC–CCS (\$/kW)	2800	4000	5200
CAPEX**–FT (\$/kW)	1950	2400	3250
Carbon storage potential***: Cumulative (Mt _{CO2})/annual (Mt _{CO2} /y)	500/100	4303/150	6497/200

*The lower, reference and upper ranges are based on the cost of eucalyptus reported by Jonker *et al.*,¹⁰⁴ Smeets and Faaij,⁷¹ and Lap *et al.*,²⁶ respectively.

**The CAPEX ranges for BIGCC and FT technologies are based on Tsiropoulos *et al.*¹⁰⁵ and IRENA,¹⁰⁶ respectively.

***The ranges of the annual storage potential are based on Lap *et al.*²⁶ For the cumulative potential, the upper limit is based on¹⁰⁰ (including enhanced oil recovery (EOR), depleted fields, coal bed methane (CBM), and saline aquifers). A recent assessment by Yáñez *et al.*¹⁰³ narrowed down the potential of EOR to 250 Mt (one fourth of the figure reported by Postic¹⁰⁰). Thus, we considered an aggregate figure of 500 Mt as a lower limit.

with a constrained CCS potential, the role of BIGCC-CCS is found to be prioritized, whereas FT-CCS is shown to shift towards co-production of FT road and aviation fuels without CCS. In this case, the overall demand for biomass would increase by 15%.

Concerning methodological limitations, least-cost optimization models assume perfect foresight of future markets; they furthermore neglect factors such as consumer behavior and the time required for technological change.^{107,108} This can be addressed by subjective constraints based on extensive specialized data. As our focus was on the conversion side, we applied systematic and simplified demand constraints, thereby excluding the demand-side competition for low carbon pathways.

Another limitation of the model is that its temporal resolution is too coarse to capture the need to balance

electricity supply and demand.¹⁰⁹ This can cause overestimation of intermittent power, and underestimation of the flexible capacity needs for grid stability.¹¹⁰ Lap *et al.*¹¹¹ have shown that such a mismatch can result in the underestimation of the total capacity by 7%. However, these dynamics could be further investigated by soft-linking energy system and power system models.

Further, our findings highlight the critical role of the biomass supply potential, which is strongly dependent on land availability. The assumed potential of carbon neutral biomass supply should be interpreted in the context of integrated land use management policies that strive to balance the impacts of land use change, food security, and conservation of biodiversity.^{112–114} Moreover, the aggregated costs of biomass supply and production may have underestimated the effect of spatial differentiation of

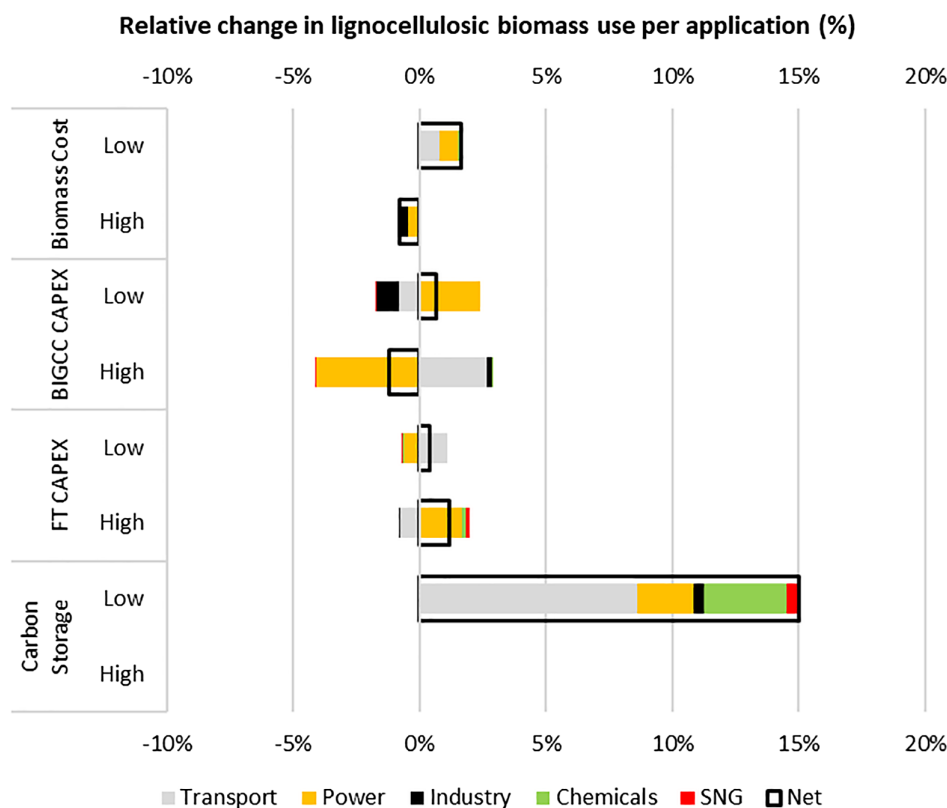


Figure 12. Relative change in lignocellulosic biomass use per sector with respect to SSP1-BioHi scenario by 2050. Parameters without corresponding bars show no relative change compared to the reference case.

resources, logistics, and transport infrastructure. A detailed land-use analysis fell outside of the scope of the current article but it will be tackled in follow up research.

Despite the limitations, our findings are consistent with relevant analyses of the bio-based economy. The finding on the need for a tradeoff between biomass use for industrial heat and advanced bio-based products in response to technological learning is in agreement with Tsiropoulos *et al.*⁸ The important role of BECCS gasification routes for power and fuels is in harmony with Lap *et al.*²⁶

In the case of Colombia, our results can be compared to those of IAMs and CGE models which investigated emission mitigation policies in Colombia^{30,31} (see Fig. 13). In our study, the median TPES is somewhat lower than in the literature, which can be related to the differences in conversion efficiencies and / or demand projections. Moreover, compared with other studies, our research shows lower projected fossil fuel use and higher on biomass use. This could be explained by the mitigation targets in our scenarios being higher than the sampled scenarios of reference literature. Furthermore, some of the reference low biomass / high fossil (CCS) scenarios were based on the Phoenix model, which did not include BECCS options.

Conversely, the reference upper quartile of biomass, which is within the range of our results, was based on the Global Change Assessment Model (GCAM), which projected the key role of BECCS. Finally, the prioritized role of biomass could be a result of the higher granularity of BBE value chains in our model compared to those used in other studies.

Conclusion

The purpose of this research was to explore the potential contribution of bio-based economy (BBE) options, including bioenergy with carbon capture and storage BECCS, to the supply of energy and chemicals, as well as GHG emission mitigation in emerging economies. An optimization modeling system analysis framework was demonstrated for the case of Colombia.

Our findings show that biomass can play an important, if variable, role in decarbonizing the energy system. Such a role would be competitive with, or complementary to, renewable electricity, depending on the country's GHG policy, capacity for technological learning, and the potential for biomass production and use. Electrification would

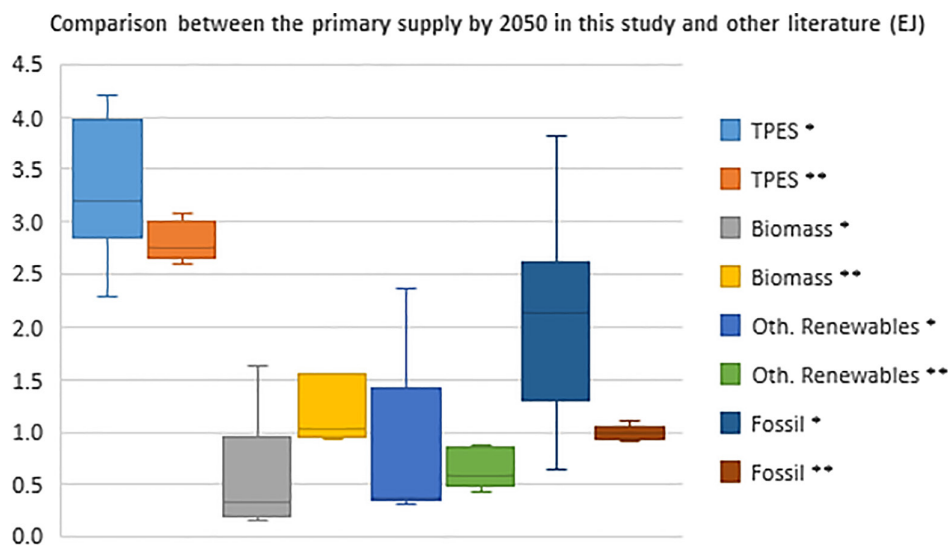


Figure 13. Boxplot showing the spread of the primary supply scenarios in reference literature (*) compared with our study (**). Reference literature included 22 scenarios from GCAM, TIAM-ECN and Phoenix models.³¹ Reference models covered a heterogeneous range of assumptions, methods, and scenario definitions, among others. Hence, comparisons of these trends should be treated with caution.

be more accessible for the built environment, but the competition between biomass and other renewable energy sources would be more pronounced in the industrial, transport, and power sectors.

Under conditions of modest GHG mitigation targets and slow technological learning (SSP3), the modern use of biomass could reach up to 435–525 PJ by 2050. In this scenario, biofuels could meet up to one third of the demand for fuel supplies for road transport. However, their share in the biomass portfolio could decline as new demand emerges; particularly for industrial heat and SNG in the gas grid.

With a stringent mitigation target and rapid technological learning (SSP1), the role of biomass could largely be determined by the resource potential. If available in sizeable quantities (SSP1-*BioHi*), the demand could be up to 1.7 times that of SSP3 (760 PJ). Biofuels could fulfill more than half the demand for road and aviation fuels combined. Moreover, biomass could shift from the industry and compete with other renewables, producing up to 27% of the electricity.

To achieve the same target in the absence of sufficient biomass resources (SSP1-*BioLo*), a substantial power capacity would be required to electrify the industry and transport sectors. Roughly 60% of the biomass could be necessary to complement hydro, wind, and solar power through BECCS. Almost half the demand for road mobility would need to be met by electric vehicles.

In such a case, the cost of the energy system could be 30% higher (additional 11 billion \$/y by 2050 compared to SSP1-*BioHi*), owing to the costlier investment in vehicle

powertrains and power generation and transmission infrastructure. Moreover, Colombia is projected to become a net oil importer within the next couple of decades. In this sense, biomass could reduce the reliance on imports and substitute them with domestic value chains for bio-based fuels and chemicals.

The cost differences between SSP1 and SSP3 scenarios, in relation to the rate of technological innovation, highlight the effectiveness of early investments in new technologies.

In terms of value chains, the most robust routes for cost-efficient deep decarbonization could be biomass gasification for producing power (BIGCC) and synthetic (FT) fuels. These routes are largely driven by their potential as net negative emitting technologies (BECCS). BECCS could contribute up to 24–29% of the cumulative mitigation potential of a deep decarbonization pathway. To pursue such pathway, the mobilization of biomass at large scale could reduce the MAC by more than 60%. Palm oil mills could economically contribute to this mobilization by valorizing residues *via* pellet production. Apart from energy, biomass could make a remarkable contribution to the chemical production. Sugarcane fermentation to ethylene (ETE) and biomass gasification to ammonia could be robust routes for biochemicals. Methanol-to-olefin (MTO) value chains could enable at least partial integration of biomass at feedstock level.

Overall, this modeling framework can analyze the potential of biomass value chains quantitatively with a high level of detail, and thereby explore possibilities for low carbon development in emerging economies. Further research should focus on the

implications of renewable electricity on grid stability and the attainability of biomass with low impact on land use change; this will facilitate the identification of feasible pathways for a BBE within an integrated systems analysis framework.

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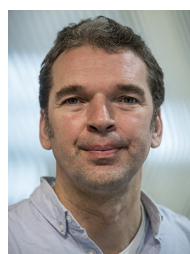
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