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

Ahmed Younis, René Benders, Ricardo Delgado, Tjerk Lap, Miguel Gonzalez-Salazar, Angela Cadena, André Faaij

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
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, Bioprod. Biorefin. 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. 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. Moreover, biomass can be used in diverse applications, including sectors with limited renewable substitutes for fossil fuels, such as aviation fuels and chemicals.

The terms ‘bio-based economy’ (BBE) and ‘bioeconomy’ have been used increasingly within different narratives. We refer to the transition from a fossil-based economy towards a bio-based economy, or the development of bioeconomy sectors, 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.’

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. Such a path may be viable for Latin American countries, and particularly Colombia, given the country’s potential for supplying biomass resources. Globally, it is in a strong position as a producer of first-generation (1G) biomass feedstock, and it also has a well-established biofuel industry.

Several roadmaps have recently been released to stimulate the development of novel bio-based value chains in Colombia. 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. Other alternatives for the supply of energy and chemicals, and the imperative for GHG mitigation, 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. 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. Moreover, their respective scopes may have overlooked the emerging roles of biomass in aviation fuels and biochemicals.

The transition towards a BBE can be addressed using energy system models (ESMs). Nevertheless, most of the published Colombian ESM studies have not focused on biomass; they have furthermore given only limited/no account of novel bio-based applications or the role of BECCS. Biomass-oriented ESMs have been applied to other case studies, as in the work of Tsipoulos et al., 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. amended an ESM of Brazil with a thorough depiction of biorefineries and BECCS technologies in the sugarcane sector. Significantly for other countries including Colombia, 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. 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:

$$\text{min} \left( NPV \right) = \sum_t \left( \sum_p \left( \sum_c \left( CRF \times CC \times IC + \sum_p FC \times IC \right) \right) + \sum_p VC \times E_{\text{out}} + \sum_c \left( P_{\text{imp}} \times E_{\text{imp}} \right) \right) - \left( P_{\text{exp}} \times E_{\text{exp}} \right)$$  \hspace{1cm} (1)

where the subscripts \(t, p, c, \text{imp}, \text{and exp}\) 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 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...
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. However, thorough analysis of future land use was not within the scope of this research. Jimenez 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 approach 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.) The database of existing technologies was based on the TIMES-CO-9 model, and was calibrated to the national energy balance year 2015. The bio-based data were drawn from various sources. Data on non-bio power oil refineries and hydrogen 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.
We then addressed them using scenario analysis 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 resolution 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

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

| Scenario                        | Present (kha) | BioLo (2050) | BioHi (2050) |
|---------------------------------|---------------|--------------|--------------|
| Land availability               | 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          |              |

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Note: Current land use corresponded to existing sugarcane and palm oil plantations. BioLo and BioHi estimates were based on future projection of historical trends and Jimenez, respectively. Current and future palm oil yields were based on Ramirez-Contreras et al. and the energy yield calculated from Garcia-Nunez et al. Current sugarcane yield was taken as an average figure for the last decade 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. 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) and the energy yield from Lap et al. and van den Broek et al. Agricultural and forestry residues 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. while sugarcane was based on average reported 7-year costs. 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. 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, 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 systems. 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 balance 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.
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,\textsuperscript{87–89} and that of ammonia by the demand for nitrogen-based fertilizers\textsuperscript{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,\textsuperscript{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,\textsuperscript{92} based on the shared socio-economic pathways (SSP) framework.\textsuperscript{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
The projections of population and gross domestic product in purchasing power parity are based on the SSP scenarios database. 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. 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. Longer-term targets (2050) were loosely inspired by the trends of Latin America in some SSP Representative Concentration Pathway (RCP) scenarios. 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.** The cumulative storage potential represents the capacity of geological formations, taken as the average of reported figures by Godec et al. and Postic. This includes Enhanced Oil Recovery (EOR), depleted fields, coal bed methane (CBM) and saline aquifers. The annual average is $2/10000$.

**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 CO2) by 2050 | Cumulative: 4303–annual: 150 by 2050 |
| Biomass supply per scenario | BioLo: 650–1000 PJ–BioHi: 6800–13900 PJ |

**Figure 3. Greenhouse gas emission mitigation scenarios.**

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...
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, and recent and upcoming investment and modernization plans of the national oil company, 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. 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. 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).](image-url)
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
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.
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,
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...
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

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**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\(^ {105}\)–BIGCC-CCS ($/kW) | 2800    | 4000           | 5200   |
| CAPEX\(^ {105}\)–FT ($/kW) | 1950    | 2400           | 3250   |
| Carbon storage potential**: Cumulative (Mt\(_{\text{CO}_2}\))/annual (Mt\(_{\text{CO}_2}/\text{y}\)) | 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 on\(^ {100}\) (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 Postic\(^ {100}\)). Thus, we considered an aggregate figure of 500 Mt as a lower limit.

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**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.
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.\textsuperscript{8}
The important role of BECCS gasification routes for power and fuels is in harmony with Lap et al.\textsuperscript{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\textsuperscript{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...
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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References

1. IPCC RK and Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, p. 151 (2014). https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcoever.pdf

2. Bruckner T, Bashmakov IA, Mulugetta Y, Chunn H, de la Vega Navarro A, Edmonds J et al., Energy Systems, in Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed. by Edenhofer O, Pachauri R, Sokona Y, Farahani E, Kadner S, Seyboth K et al. Cambridge University Press, Cambridge, pp. 527–532 (2014). Available: http://ipcc-wg3.gov/AR5/images/uploads/IPCC-WG3AR5-SPM_Approved.pdf

3. Chunn H, Faaji A, Moreira J, Bernides G, Dhamija P, Dong H et al., Bioenergy, in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, ed. by Edenhofer O, Pachauri R, Sokona Y, Seyboth K, Matschoss P, Kadner S et al. Cambridge University Press, Cambridge, pp. 209–332 (2011).

4. Rose SK, Kriegler E, Ribas B, Calvin K, Popp A, van Vuuren DP et al., Bioenergy in energy transformation and climate management. Clim Change 123(3–4):477–493 (2014). Available: http://link.springer.com/10.1007/s10584-013-0965-3.

5. Azar C, Lindgren K, Obersteiner M, Riahi K, van Vuuren DP, den Elzen KMGJ et al., The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). Clim Change 100(1):195–202 (2010). Available: http://link.springer.com/10.1007/s10584-010-9832-7.

6. Smith P, Bustamante M, Ahammad H and van Minnen J, Agriculture, Forestry and Other Land Use (AFOLU), in Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed. by Edenhofer O, Pachauri R, Sokona Y, Seyboth K, Matschoss P, Kadner S et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 811–922 (2014). Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf

7. Rogelj J, Popp A, Calvin KV, Luderer G, Emmerling J, Gernaey K et al., Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat Clim Chang 8(4):325–332 (2018). Available: http://www.nature.com/articles/s41558-018-0091-3.

8. Tsipoulopoulos I, Hoefnagels R, de Jong S, van den Broek M, Patel M and Faaji A, Emerging bioeconomy sectors in energy systems modeling - integrated systems analysis of electricity, heat, road transport, aviation, and chemicals: A case study for The Netherlands. Biofuel Bioprod Biorefin 12(4):665–693 (2018).

9. Gerssen-Gondelach SJ, Saygin D, Wicke B, Patel MK and Faaji APC, Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials. Renew Sustain Energy Rev 40:964–998 (2014).

10. de Jong S, Hoefnagels R, Faaji A, Slade R, Mourad R and Junginger M, The feasibility of short-term production strategies for renewable jet fuels - A comprehensive techno-economic comparison. Biofuel Bioprod Biorefin 9(6):778–800 (2015).

11. Vivien F-D, Nieddu M, Befort N, Debref R and Giampietro M, The hijacking of the bioeconomy. Ecol Econ 159:189–197 (2019). Available: https://linkinghub.elsevier.com/retrieve/pii/S0921800918308115

12. Staffas L, Gustavsson M and McCormick K, Strategies and policies for the bioeconomy and bio-based economy: an analysis of official National Approaches. Sustainability 5(6):2751–2769 (2013). Available: http://www.mdpi.com/2071-1050/5/6/2751.

13. Langeveld JWA, Dixon J and Jaworski JF, Development perspectives of the biobased economy: A review. Crop Sci 50:S-142–S-151 (2010). Available: http://doi.wiley.com/10.2135/cropsci2009.09.0529.

14. EC, Communication on Innovating for Sustainable Growth: A Bioeconomy for Europe. COM(2012) 60 final. Brussels, Belgium; 2012;

15. FAO, Assessing the Contribution of Bioeconomy to countries’ Economy - A Brief Review of National Frameworks. Food and Agriculture Organization of the United Nations, Rome, Italy, p. 65 (2018). Available: http://www.fao.org/publications/card/en/c/ibis8080E/

16. Trigo EJ, Henry G, Sanders J, Schurr U, Revel C et al., Towards bioeconomy development in Latin America and the Caribbean. Bioeconomy Work Pap 15:1-15 (2013). Available: http://agriport.cirad.fr/567934/1/document_567934.pdf.

17. Sasson A and Malpica C, Bioeconomy in Latin America. N Biotechnol 40:40–45 (2018). Available: https://linkinghub.elsevier.com/retrieve/pii/S1871678417300080.

18. Rodriguez AG, Mondaini AO and Hitchens MF, Bioeconomia en América Latina y el Caribe - Contexto global y regional y perspectivas. Comisión Económica para América Latina y el Caribe (CEPAL), Naciones Unidas, p. 65 (2018). Available: http://www.cepal.org/publicaciones/card/en/c/ibis8080E/

19. Henry G, Hadson E, Aramendis R, Trigo E and Rankin S, Bioeconomy: An engine for integral development of Colombia. Cali, Colombia International Center for Tropical Agriculture (CIAT), pp. 1–10 (2017). Available: https://cgspace.cgiar.org/handle/10568/92082?show=full.

20. Gonzalez-Salazar MA, Morini M, Pinelli M, Spina PR, Venturini M, Finkenrath M et al., Methodology for estimating biomass energy potential and its application to Colombia. Appl Energy 136:781–796 (2014).

21. FAO. Crops. 2019. Available: http://www.fao.org/faostat/en/#data/QC [14 August 2019]

22. Mateus CA, The Future of Biofuels in Colombia [Internet]. Bogotá; 2019. Available: https://www.iscc-system. wp-content/uploads/2017/02/3.-Carlos-Mateus-Fedebiombustibles.pdf
23. Biointropic, EAFIT, SILO. Estudio sobre la Bioeconomía como fuente de nuevas industrias basadas en el capital natural de Colombia - Fase II: Análisis de la situación y recomendaciones de política de bioeconomía [Internet]. Medellín; 2018. Available: https://www.dnp.gov.co/Crecimiento-Verde/Ejes-estrategicos/Paginas/Bioeconomia.aspx

24. NUMARK, UNC, MRI, Plan de negocios para el mejoramiento de la competitividad del sector de biocombustibles de Colombia: ATN/OC-10796-CO - ATN/KK-10795-CO - Informe Final. 2012.

25. Gonzalez-Salazar MA, Venturini M, Poganiert WR, Finkenrath M, Kirsten T, Acevedo H et al., Development of a technology roadmap for bioenergy exploitation including biofuels, waste-to-energy and power generation & CHP. *Appl Energy* **180**:338–352 (2016).

26. Lap T, Benders R, Kéberle A, van der Hillst F, Nogueira L, Szklo A et al., Pathways for a Brazilian biobased economy: Towards optimal utilization of biomass. *Biofuel Bioprod Biorefin* **13**(3):673–689 (2019).

27. Tsiropoulos I, Hoefnagels R, van den Broek M, Patel MK and Faaïj APC, The role of bioenergy and biochemicals in CO2 mitigation through the energy system - NDASH- a scenario analysis for The Netherlands. *GCB Bioenergy* **38**(1):42–49 (2017).

28. Tsiropoulos I, Emerging Bioeconomy: Assessing the Implications of Advanced Bioenergy and Biochemicals with Bottom-Up and Top-Down Modelling Approaches. Utrecht, the Netherlands: Utrecht University, (2016). http://dspace.library.uu.nl/handle/1874/340360.

29. Daigioiu W, Wicke B, Faaïj APC and van Vuuren DP, Competing uses of biomass for energy and chemicals: Implications for long-term global CO2 mitigation potential. *GCB Bioenergy* **7**(6):1321–1334 (2015).

30. van der Zwaan BCC, Calvin KV and Clarke LE, Climate mitigation in Latin America: implications for energy and land use: Preface to the special section on the findings of the CLIMACAP-LAMP project. *Energy Econ* **56**:495–498 (2016).

31. Calderón S, Alvarez AC, Loboguerrero AM, Arango S, Calvin K, Kober T et al., Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets. *Energy Econ* **56**:575–586 (2016).

32. Postic S, Selosse S and Maïzi N, Energy contribution to Latin American INDCs: Analyzing sub-regional trends with a TIMES model. *Energy Policy* **101**:170–184 (2017). Available: https://linkinghub.elsevier.com/retrieve/pii/S030142151630619X.

33. IDB and DDPLAC, Getting to Net-Zero Emissions: Lessons from Latin America and the Caribbean. Washington, DC: Inter-American Development Bank (2019). http://dx.doi.org/10.18235/0002024.

34. Binsted M, Iyer G, Edmonds J, Vogt-Schilb A, Arguello R, Cadena A et al., Stranded asset implications of the Paris agreement in Latin America and the Caribbean. *Environ Res Lett* **15**(4):044026 (2020). Available: http://iopscience.iop.org/article/10.1088/1748-9326/ab506d.

35. Wicke B, van der Hillst F, Daigioiu V, Banse M, Beringer T, Gerssen-Gondelach S et al., Model collaboration for the improved assessment of biomass supply, demand, and impacts. *GCB Bioenergy*. **7**(3):422–437 (2015).

36. Daigioiu V, Faaïj APC, Saygin D, Patel MK, Wicke B and van Vuuren DP, Energy demand and emissions of the non-energy sector. *Energy Environ Sci* **7**(2):482–498 (2014).

37. Mawhood R, Gazis E, de Jong S, Hoefnagels R and Slade R, Production pathways for renewable jet fuel: A review of commercialization status and future prospects. *Biofuel Bioprod Biorefin* **10**(4):482–484 (2016).

38. Cadena A and Haurie A, Modelling the implications of the Kyoto protocol for a developing country. *OPSEARCH*. **38**(1):1–21 (2001).

39. Delgado R, Álvarez C, Cadena A, Calderón S, Modelling the Socio Economic Implications of Mitigation Actions in Colombia: Working Paper for the CDKN Project On Linking Sectoral and Economy Wide Models. Bogotá; 2014.

40. Botero S, Cadena A, Vesa G, Betancur L. Regulatory feasibility analysis of policy mechanisms to foster renewable energy in the Colombian power sector. In: 32nd IAEE International Conference Energy, Economy, Environment: The Global View. 2009. Available: https://repositorio.uniandes.edu.co/handle/1992/9612.

41. Diaz A, Cadena A. Identificación y evaluación de un conjunto de medidas para incentivar la penetración de energía renovable en la generación de electricidad en Colombia [Internet]. Universidad de los Andes; 2007. Available: https://biblioteca.uniandes.edu.co/visor_de_tesis/web/?SessionID=L1Rlc2lzXzIwMDdfc2VndW5kb19zZW51c3tyZ58wMDBAaMxMyOSSwZGY%3D

42. Winkler H, Delgado R, Palma-Behnke R, Pereira A, Vásquez Baos T, Moyo A et al., Information for a developmental approach to mitigation: Linking sectoral and economy-wide models for Brazil, Chile, Colombia, Peru and South Africa. *Clim Dev* **9**(6):559–570 (2017).

43. Gonzalez-Salazar MA, Venturini M, Poganiert WR, Finkenrath M, Kirsten T, Acevedo H et al., A general modeling framework to evaluate energy, economy, land-use and GHG emissions nexus for bioenergy exploitation. *Appl Energy* **178**:223–249 (2016).

44. Gonzalez-Salazar MA, Venturini M, Poganiert W-R, Finkenrath M and Leal MRLV, Combining an accelerated deployment of bioenergy and land use strategies: Review and insights for a post-conflict scenario in Colombia. *Renew Sustain Energy Rev* **73**:159–177 (2017).

45. Clarke D, Jablonski S, Moran B, Anandarajah G and Taylor G, How can accelerated development of bioenergy contribute to the future UK energy mix? Insights from a MARKAL modelling exercise. *Biotechnol Biofuels* **2**(1):13 (2009). Available: http://www.scopus.com/inward.record.url?eid=2-s2.0-67849110458&partnerId=I2Otx3y1.

46. Jablonski S, Strachan N, Brand C and Bauen A, The role of bioenergy in the UK’s energy future formulation and modelling of long-term UK bioenergy scenarios. *Energy Policy*. **38**(10):5799–5816 (2010).

47. McDowell W, Anandarajah G, Dodds PE and Tomei J, Implications of sustainability constraints on UK bioenergy development: Assessing optimistic and precautionary approaches with UKMARKAL. *Energy Policy* **47**:424–436 (2012).

48. Forsell N, Guerassimoff G, Athanassiadis D, Thivolle-Casat A, Lorne D, Millet G et al., Sub-national TIMES model for analyzing future regional use of biomass and biofuels in Sweden and France. *Renew Energy* **60**:415–426 (2013).

49. Börjeson M, Athanassiadis D, Lundmark R and Ahlgren EO, Bioenergy futures in Sweden - system effects of CO2 reduction and fossil fuel phase-out policies. *GCB Bioenergy* **7**(5):1118–1135 (2015).

50. Börjeson Hagberg M, Pettersson K and Ahlgren EO, Bioenergy futures in Sweden - modeling integration scenarios for biofuel production. *Energy*. **109**:1026–1039 (2016).

51. Panos E and Kannan R, The role of domestic biomass in electricity, heat and grid balancing markets in Switzerland. *Energy* **112**:1120–1138 (2016).

52. van Meijl H, Smeets E, van Dijk M, Powell J, Tabeau A, Macro-Economic Impact Study for Bio-Based Malaysia. LEI Report 2012–042. The Hague, 2012. Available: https://www.wur.nl/en/project/Macro-economic-Impact-Study-MES-for-Biobased-Malaysia.htm.
53. Arrieta FRP, Teixeira FN, Yáñez E, Lora E and Castillo E, Coceneration potential in the Colombian palm oil industry: Three case studies. Biomass Bioenergy. 31(7):503–511 (2007).

54. Gutiérrez LF, Sánchez OJ and Cardona CA, Process integration possibilities for biodiesel production from palm oil using ethanol obtained from lignocellulosic residues of oil palm industry. Bioresour Technol 100(8):1227–1237 (2009).

55. Rincón LE, Moncada J and Cardona CA, Analysis of potential technological schemes for the development of oil palm industry in Colombia: A biorefinery point of view. Ind Crops Prod 52:457–465 (2014).

56. Moncada J, Tamayo J and Cardona CA, Evolution from biofuels to integrated biorefineries: Techno-economic and environmental assessment of oil palm in Colombia. J Clean Prod 81:51–59 (2014).

57. Salomón M, Gomez MF and Martin A, Technical polygeneration potential in palm oil mills in Colombia: A case study. Sustain Energy Technol Assessments 3:40–52 (2013). Available: https://linkinghub.elsevier.com/retrieve/pii/S2213188113000349.

58. Garcia-Nunez JA, Ramirez-Contreras NE, Rodriguez DT, Silva-Lora E, Frea CS, Stockle C et al., Evolution of palm oil mills into bio-refineries: Literature review on current and potential uses of residual biomass and effluents. Resour Conserv Recycl 110:99–114 (2016).

59. Garcia-Nunez JA, Rodriguez DT, Fontanilla CA, Ramirez NE, Silva Lora EE, Frea C et al., Evaluation of alternatives for the evolution of palm oil mills into biorefineries. Biomass Bioenergy 95:310–329 (2016).

60. Daza Serna LV, Solarte Toro JC, Serna Loaiza S, Chacón Pérez Y and Cardona Alzate CA, Agricultural waste management through energy producing biorefineries: The Colombian case. Waste Biomass Valorizat 7(6):789–798 (2016). Available: http://link.springer.com/10.1007/s12649-016-9576-3.

61. Loulou R, Remme U, Kanudia A, Lehtilä A, Goldstein G, Documentation for the TIMES model part I [internet]. IEA Energy Technol Syst Anal Program 2005. Available: www.etsap.org/tools.htm

62. Farzaneh H, Energy Systems Modeling: Principles and Applications. Springer, Singapore, p. 168 (2019). Available: http://link.springer.com/10.1007/978-981-13-6221-7.

63. Loulou R, Lehtilä A, Kanudia A, Remme U, Goldstein G, Documentation for the TIMES Model PART II: Reference manual. Energy Technol Syst Anal Program. 2016. p. 384. Available: https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-II_July-2016.pdf.

64. Giannakidis G, Karlsson K and Labriet M, Limiting Global Warming to Below 2 °C: Energy System Modelling and Policy Development. Lecture Notes in Energy, Vol. 64. Springer International Publishing, Cham, p. 423 (2016). Available: http://link.springer.com/10.1007/978-3-319-74424-7.

65. Jimenez Morales CE. Palm Oil Biodiesel in Colombia. A GIS Based Experatory Study on its Potential and Scenarios for the Future. (Master thesis). Utrecht University; 2012. Available: https://dspace.library.uu.nl/handle/1874/252962

66. Ramirez-Contreras NE, Munar-Florez DA, Garcia-Nuñez JA, Mosquera-Montoya M and Faaíj APC, The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives. J Clean Prod 258:120757 (2020). Available: https://linkinghub.elsevier.com/retrieve/pii/S0956052020308040.

67. Asocarha, Aspectos Generales Del Sector Agroindustrial De La Caña. Asocarha, Cali (2018). Available: https://www.asocarha.org/documentos/862018-E148DE81-00FF00,000A000,87B877, C3C3C3,0F00FF,B4B4B4,F00FF,2D2D2D,A3C4B5.pdf.

68. PROFOR. Situación actual y potencial de fomento de plantaciones forestales con fines comerciales en Colombia. Bogotá, 2017.

69. van den Broek R, van den Burg T, van Wijk A and Turkenburg W, Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua: A comparison with fuel oil electricity generation on the basis of costs, macro-economic impacts and environmental emissions. Biomass Bioenergy 19(5):311–335 (2000). Available: https://linkinghub.elsevier.com/retrieve/pii/S0961953400000349.

70. DANE, Cuenta satelital piloto de la agroindustria del cultivo de caña de azucar 2005–2012. Bogotá, Colombia: Departamento Administrativo Nacional de Estadistica (DANE) (2012). Available: https://www.dane.gov.co/files/investigaciones/pib/agroindustria/GuiaProceimientosResultadosCSACana2005_2012.pdf.

71. Smeets EMW and Faaij APC, The impact of sustainability criteria on the costs and potentials of bioenergy production - Applied for case studies in Brazil and Ukraine. Biomass Bioenergy 34(3):319–333 (2010).

72. Mai–Moulin T, Visser L, Fingerman KR, Elbersen W, Elbersen B, Nabuurs GJ et al., Sourcing overseas biomass for EU ambitions: Assessing net sustainable export potential from various sourcing countries. Biofuel Bioprod Biorefin 13(2):293–324 (2019).

73. Beddoes JC, Bracmont KS, Burns RT, Lazarus WF. An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U. S. Livestock Production Facilities. Washington DC, USA: 2007. Available: https://www.agmrc.org/media/cms/manuredigesters_FC5C31F0F7B78.pdf

74. Batidzirai B, Smeets EMW and Faaij APC, Harmonising bioenergy resource potentials – methodological lessons from review of state of the art bioenergy potential assessments. Renew Sustain Energy Rev 16(9):6998–6630 (2012).

75. Searle S and Malins C, A reassessment of global bioenergy potential in 2050. GCB Bioenergy 7(2):328–336 (2015).

76. Smeets E, Faaij A, Lewandowski I and Turkenburg W, A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci 33(1):56–106 (2007). Available: https://linkinghub.elsevier.com/retrieve/pii/S0360128506000359.

77. Popp A, Calvin K, Fujimori S, Havlík P, Hurnepaëder F, Stehfest E et al., Land-use futures in the shared socio-economic pathways. Glob Environ Chang 42:331–345 (2017). Available: https://linkinghub.elsevier.com/retrieve/pii/S099098716303399.

78. Ereev SY and Patel MK, Standardized cost estimation for new technologies ( SCENT ) - methodology and tool. J Bus Chem 9(1):31–48 (2012). Available: http://www.businesschemistry.org/article/?article=150.

79. UPME. Balance Energetico Colombiano - BECO 1975–2015: Ver.12 Rev.03, 2017. Available: http://www1.uperme.gov.co/InformacionCifras/Paginas/BalanceEnergetico.aspx [10 December 2018]

80. Tews IJ, Zhu Y, Drennan C, Elliott DC, Snowden-Swan LJ, Onarheim K et al., Biomass Direct Liquefaction Options. TechnoEconomic and Life Cycle Assessment. Richland, WA: Pacific Northwest National Lab. (PNNL) (2014). Available: http://www.osti.gov/servlets/purl/1184983/.

81. Batidzirai B, Schotman GS, van der Spek MW, Junginger M and Faaij APC, Techno-economic performance of sustainable international bio-SNG production and supply chains on short and longer term. Biofuel Bioprod Biorefin 13(2):325–357 (2019).
A Younis et al.  
Modeling and Analysis: System analysis of the bio-based economy in Colombia

82. de Vita A, Kielichowska I, Mandatowa P, Capros P, Dimopoulou E, Evangelopoulou S, et al. ASSET project: Technology pathways in decarbonisation scenarios [Internet]. 2018. Available: https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27\_technology_pathways\_finalreportmain2.pdf

83. IEA ETSAP. Technology Brief P04 - Oil Refiners. 2014. Available: https://iea-etsap.org/E-TechDS/PDF/P04_OilRef\_KV_Apr2014\_GSOK.pdf

84. Bolat P and Thiel C, Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: Techno-economic inputs for hydrogen production pathways. *Int J Hydrogen Energy* 39(17):8898–8925 (2014).

85. Blanco H, Nijs W, Ruf J and Faaij A, Potential for hydrogen and power-to-liquid in a low-carbon EU energy system using cost optimization. *Appl Energy* 232:617–639 (2018 Dec).

86. XM. Informe de Operación del SIN y Administración del Mercado 2015. Medellin; 2016. Available: http://informesanuales.xm.com.co/2017/SitePages/operacion/Default.aspx

87. Acoplasticos, *Plásticos en Colombia 2017–2018*. Bogotá, Colombia: Acoplasticos (2018). Available: https://www.acoplasticos.org/index.php/tnu-nos/tnu-ppry/tnu-ppry-pi.

88. Neelis ML, Patel M, Gielen DJ and Blok K, Modelling CO2 emissions from non-energy use with the non-energy use emission accounting tables (NEAT) model. *Resour Conserv Recycl* 45(3):226–250 (2005 Nov). Available: https://linkinghub.elsevier.com/retrieve/pii/S0921344950000728.

89. OECD/IEA. Energy Technology Transitions for Industry: Strategies for the Next Industrial Revolution. Paris, France; 2009. Available: http://www.oecd-library.org/energy/energy-technology-transitions-for-industry_9789264068612-en

90. IFA. International Fertilizer Industry Association Data. 2018. Available: http://ifadata.fertilizer.org/ [11 March 2019]

91. de Wit M, Junginger M, Lapsu K, Londo M and Faaij A, Competition between biofuels: Modeling technological learning and cost reductions over time. *Biomass Bioenergy* 34(2):203–217 (2010). Available: https://linkinghub.elsevier.com/retrieve/pii/S0961953409001445.

92. Swart R, Raskin P and Robinson J, The problem of the future: Sustainability science and scenario analysis. *Glob Environ Chang* 14(2):137–146 (2004). Available: https://linkinghub.elsevier.com/retrieve/pii/S0959378003000670.

93. O’Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR et al., A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim Change* 122:387–400 (2014). Available: http://link.springer.com/10.1007/s10584-013-0905-2.

94. Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O’Neill BC, Fujimori S et al., The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob Environ Chang* 42:153–168 (2017). Available: https://linkinghub.elsevier.com/retrieve/pii/S0959378016300681.

95. KC S and Lutz W, The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob Environ Chang* 42:181–192 (2017). Available: https://linkinghub.elsevier.com/retrieve/pii/S0959378014001095.

96. OECD/IEA, *World Energy Outlook* 2016. Paris, France: International Energy Agency (IEA) (2016). Available: https://webstore.iea.org/world-energy-outlook-2016.

97. OECD/IEA, *Outlook for Natural Gas: Excerpt from World Energy Outlook* 2017. International Energy Agency, Paris, p. 761 (2018). Available: https://www.iea.org/publications/freepublications/publication/WEEO2017Excerpt_Outlook_for_Natural_Gas.pdf

98. Gobierno de Colombia. Colombia’s Intended Nationally Determined Contribution (INDC) [Unofficial English Translation] [Internet]. 2015. Available: http://www4.unfccc.int/submissions/INDC/PublishedDocuments/Colombia/1/ ColombiaINDCUnofficialtranslationEng.pdf

99. Godec ML, Jonsson H and Basava-Redi L, Potential global implications of gas production from shales and coal for geological CO2 storage. *Energy Prog* 37:6656–6666 (2013). Available: https://linkinghub.elsevier.com/retrieve/pii/S1876610213000842.

100. Postic S, Long-Term Energy Prospective Modeling for South America – Application to International Climate Negotiations. Paris, France: MINES ParisTech, (2015). Available: https://pastel.archives-ouvertes.fr/tel-01303955/file/52144\_POSTIC\_2015\_archive.pdf.

101. UPME, *Plan Energetico Nacional 2020–2050 - Documento de consulta*. Bogotá D.C., Colombia: Unidad de Planeacion Minero Energetica (UPME) (2019). Available: https://www1.upme.gov.co/Paginas/Plan-Energetico-Nacional-2050.aspx.

102. Ecopetrol. Actualización Plan de Negocio 2020–2022. Bogotá; 2020.

103. Yáñez E, Ramirez A, Núñez-López V, Castillo E and Faaij A, Exploring the potential of carbon capture and storage-enhanced oil recovery as a mitigation strategy in the Colombian oil industry. *Int J Greenh Gas Control* 94:102938 (2020).

104. Jonker JGG, Junginger M, Posada J, Ioart CS, Faaij APC and Hilsf E, Economic performance and GHG emission intensity of sugarcane- and eucalyptus-derived biofuels and biobased chemicals in Brazil. *Biofuel Bioprod Biorefin* 13(4):950–977 (2019 Jul 11). Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.1986.

105. Tsipoulopoulos I, Tarvydas D, Zucker A. Cost Development of Low Carbon Energy Technologies - Scenario-Based Cost Trajectories to 2050 [Internet]. 2017 Editi. JRC Science and Policy Reports (EUR 29034 EN). Publications Office of the European Union, Luxembourg: 2018. 71 p. Available from: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC109894/cost_development_of_low_carbon_energy_technologies_v2.2_final_online.pdf

106. IRENA, *Innovation Outlook: Advanced Liquid Biofuels*. Bonn, Germany: International Renewable Energy Agency (2016). Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Innovation_Outlook_Advanced_Liquid_Biofuels_2016.pdf.

107. Herbst A, Toro F, Reitz F and Jochem E, Introduction to energy systems modelling. *Swiss J Econ Stat* 148(2):111–135 (2012). Available: https://sjes.springeropen.com/articles/10.1007/BF03393363.

108. Weijermars R, Taylor P, Bahn O, Das SR and Wei Y-M, Review of models and actors in energy mix optimization – can leader visions and decisions align with optimum model strategies for our future energy systems? *Energy Strateg Rev* 1(1):5–18 (2012). Available: https://linkinghub.elsevier.com/retrieve/pii/S2211467X11000022.

109. Pfenninger S, Deane JP, Poneclet K, Panos E, Pietzcker RC, Delarue E et al., Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renew Sustain Energy Rev* 33:74–86 (2014). Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032114000872.

110. Collins S, Deane JP, Poneclet K, Panos E, Pietzcker RC, Delarue E et al., Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renew Sustain Energy Rev* 76:839–856 (2017).

111. Lap T, Benders R, van der Hilt F and Faaij A, How does the interplay between resource availability, intersectoral competition and reliability affect a low-carbon power generation mix in Brazil for 2050? *Energy* 195:116948
(2020). Available: https://linkinghub.elsevier.com/retrieve/pii/S0360544220300554.

112. Popp A, Rose SK, Calvin K, Van Vuuren DP, Dietrich JP, Wise M et al., Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. Clim Change 123(3–4):495–509 (2014). Available: http://link.springer.com/10.1007/s10584-013-0926-x.

113. Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J, Trade-offs of different land and bioenergy policies on the path to achieving climate targets. Clim Change 123(3–4):691–704 (2014). Available: http://link.springer.com/10.1007/s10584-013-0897-y.

114. Smith P, Haberl H, Popp A, Erb K, Lauk C, Harper R et al., How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob Chang Biol 19(8):2285–2302 (2013).

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