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Exploring the spatiotemporal evolution of bioenergy with carbon capture and storage and decarbonization of oil refineries with a national energy system model of Colombia

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ABSTRACT

Bioenergy combined with carbon capture and storage (BECCS) has a high mitigation potential of greenhouse gases in the energy system. However, the feasibility of its deployment depends on co–location of suitable storage basins and biomass resources with low-carbon stocks. Moreover, national transition analyses towards low–carbon energy systems have often given little attention to the mitigation potential of existing oil refineries, which are major components of current energy systems. We parametrized and incorporated these knowledge gaps into an energy system optimization model and used it analyze mitigation pathways towards carbon neutrality of the Colombian energy system by midcentury.

Our results show that modern bioenergy could contribute 0.8–0.9 EJ/y (48–51 %) to the final energy consumption by 2050 at a system cost of 29–35 B$/y. BECCS value chains could deliver a mitigation potential of 37–41 % of the cumulative avoided emissions between 2030 and 2050. Low–carbon retrofitting of existing oil refineries could contribute up to 19 % of the total biofuel production and 10 % of the total CO_2 capture by 2050. The Andes and Caribbean could be promising regions for BECCS because of their high potential for biomass supply and carbon sinks. In contrast, Orinoquía has a high potential for bioenergy and more uncertainty of CCS, depending on the access to nearby carbon sinks.

This framework could be used to harmonize between the visions of the energy and agricultural sectors, national government and the oil sector, and national and regional governments, towards integrated planning for low-carbon development.

1. Introduction

Bioenergy combined with carbon capture and storage (BECCS) is projected to significantly contribute to net atmospheric carbon dioxide removal (CDR) in climate change mitigation pathways that seek to limit mean global temperature increases to well below 2 °C above preindustrial levels by the end of the 21st century [1,2]. The importance of BECCS in low-carbon development pathways has been demonstrated in Colombia, as an example of an emerging economy [3,4]. However, the mitigation potential and feasibility of the large-scale deployment of BECCS depend on the co-location of suitable storage basins and biomass resources with low-carbon stocks, among other factors [5,6].

Global-scale integrated assessment models (IAMs) have often analyzed the role of BECCS using aggregated data, which makes them less suitable for national–scale assessments. National–level bottom–up studies deploying spatially–explicated matching between carbon sources and sinks have either focused on existing (non–biogenic) carbon sources [7,8], overlooking the dynamic evolution of the energy system, or focused on BECCS supply chains [5,9,10], in isolation from the wider scope of the energy system. Other studies integrated a national-level energy system optimization model (ESOM) with a spatially–explicit model for a detailed analysis of the evolution of carbon capture and storage (CCS) infrastructure [11–13]. Nevertheless, these studies have

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Abbreviations

1G	First-generation
2G	Second-generation
BECCS	Bioenergy combined with carbon capture and storage
BEV	Battery electric vehicle
BIGCC	Biomass integrated gasification combined cycle
BioC	Bio-oil co-processing in existing oil refineries
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
EEM	Energy efficiency measures in existing oil refineries
ESOM	Energy system optimization model
FCEV	Fuel cell electric vehicle
FT	Fischer-Tropsch
GCM	Global circulation model
GHG	Greenhouse gas
IAM	Integrated assessment model
MMB	Middle Magdalena Basin
MTM	Miscellaneous technological measures in existing oil refineries
NET	Negative emission technology
OPEX	Operational expenditure
SSP	Shared Socioeconomic Pathways scenario analysis framework
TIMES	The Integrated MARKAL-EFOM System
TFC	Total final consumption
TOC	Total cost of ownership
TPES	Total primary energy supply

not considered the impact of the spatial variability of biomass supply on the optimal energy mix and the share of BECCS in that mix.

The spatial heterogeneity of biomass has been widely analyzed in the context of supply-side resource assessments [14] and the optimization of the location and size of biomass processing plants [15]. Despite the growing interest in enhancing the regional disaggregation of national ESOMs, little has been done to apply these multi-regional ESOMs to address the heterogeneity of the biomass supply [16]. Forsell et al. [17] is one of the rare instances that considers subnational biomass cost-supply potential in national ESOMs. However, this study focused only on biomass value chains. Therefore, it relied on exogenous demand for bioenergy and neglected the competition between biomass and other value chains. Moreover, the study excluded the role of CCS.

Lap et al. [18] reconciled the heterogeneity of biomass supply in a national ESOM. However, this framework differentiates the supply potential of biomass resources based on their associated emissions from land use change, rather than their geographical distribution and its effects on production and transportation costs. In a follow-up study, Lap et al. [19] amended the framework with a spatially disaggregated assessment of the geological storage potential of carbon dioxide (CO_2) and associated costs. However, the scope of this study could not capture the limitations of biomass supply logistics.

Articulating the heterogeneity of biomass resources can provide a more realistic account of the role of biomass in energy systems. Additionally, regionalizing the model can help identify any potential regional specializations in the biomass and BECCS value chains.

Most studies assessing the role of biomass (with CCS) and other mitigation options in national energy systems have focused on establishing dedicated greenfield biorefineries. Little attention has been given to the decarbonization of oil refineries within the wider decarbonization scope of national energy systems [20]. Yáñez [21] analyzed the decarbonization potential of an existing oil refinery, including biomass co-processing [22], CCS [8], energy efficiency measures [23], electrification and green hydrogen production [24]. However, these studies focused on a facility-level perspective. Analyzing these options in a national ESOM can determine their competitiveness compared with dedicated biorefineries and the role of plant retrofitting of oil refineries in low-carbon pathways.

The aim of this study is to analyze the role of biomass and CCS value chains in a low-carbon national energy system with enhanced spatial resolution at the regional administrative division level for biomass sources and at the basin level for carbon sinks. Through enhancement, detailed aspects can be analyzed that otherwise are not captured in an aggregated scope. These aspects include the regional specialization of particular biomass and CCS value chains, the limitations of infrastructure development, and the competitiveness of greenfield biorefineries with decarbonization options in existing oil infrastructure.

2. Methods

2.1. Modeling framework

Fig. 1 provides an overview of the modeling framework. The core of the framework was founded on an instance of The Integrated MARKAL-EFOM System (TIMES) model which was designed to analyze the role of the bio-based economy in Colombia, thereafter referred to as TIMES–CO–BBE. The structure of the model is described in detail elsewhere [3,4] and summarized in Section 2.1.1.

To manage the trade-offs between enhancing spatial, temporal, and technological granularity and the associated computational complexity [15], we introduced a targeted regionalization of biomass sources and carbon sinks based on the principles and network typology described in Section 2.1.2.

We also introduce a regionalized biomass supply module based on data from Ref. [14] and the approach described in Section 2.2.1. We modified the cost of biomass transport based on [25] as described in Section 2.2.2.

We updated the geological CO_2 storage potential based on prior studies [8,26], cost data and the modeling approach as proposed by Lap et al. [19], and described in Section 2.3. Considering CO_2 transport, distances were estimated following the approach described in Section 2.4 and cost data based on a previous study [27].

Regarding conversion technologies, Section 2.5.1 lists the greenfield BECCS technology options available in the model. Section 2.5.2 explains the approach used to parameterize the decarbonization of existing oil refineries based on published data [8,22–24].

Finally, we conduct a scenario analysis based on the Shared Socioeconomic Pathways (SSP) framework [28]. We adapted this framework considering Colombia's uncertainties in biomass supply potential, geological CO_2 storage potential, technological development, climate policy and socioeconomic factors. Moreover, we compared nationally aggregated and regionalized versions of the model. Finally, we compare investment pathways for decarbonizing existing oil refineries to baseline cases in which oil refineries were shut down in the absence of any investment.

The novel contributions of this study are summarized as follows:

- An approach to integrate spatially–differentiated sub–national biomass cost-supply potential into a national ESOM, including a representation of land–use competition between different energy crops within each region.
- A network typology to incorporate the matching of carbon sources and sinks into a national ESOM, considering the limitations and costs associated with CO_2 transport distances.

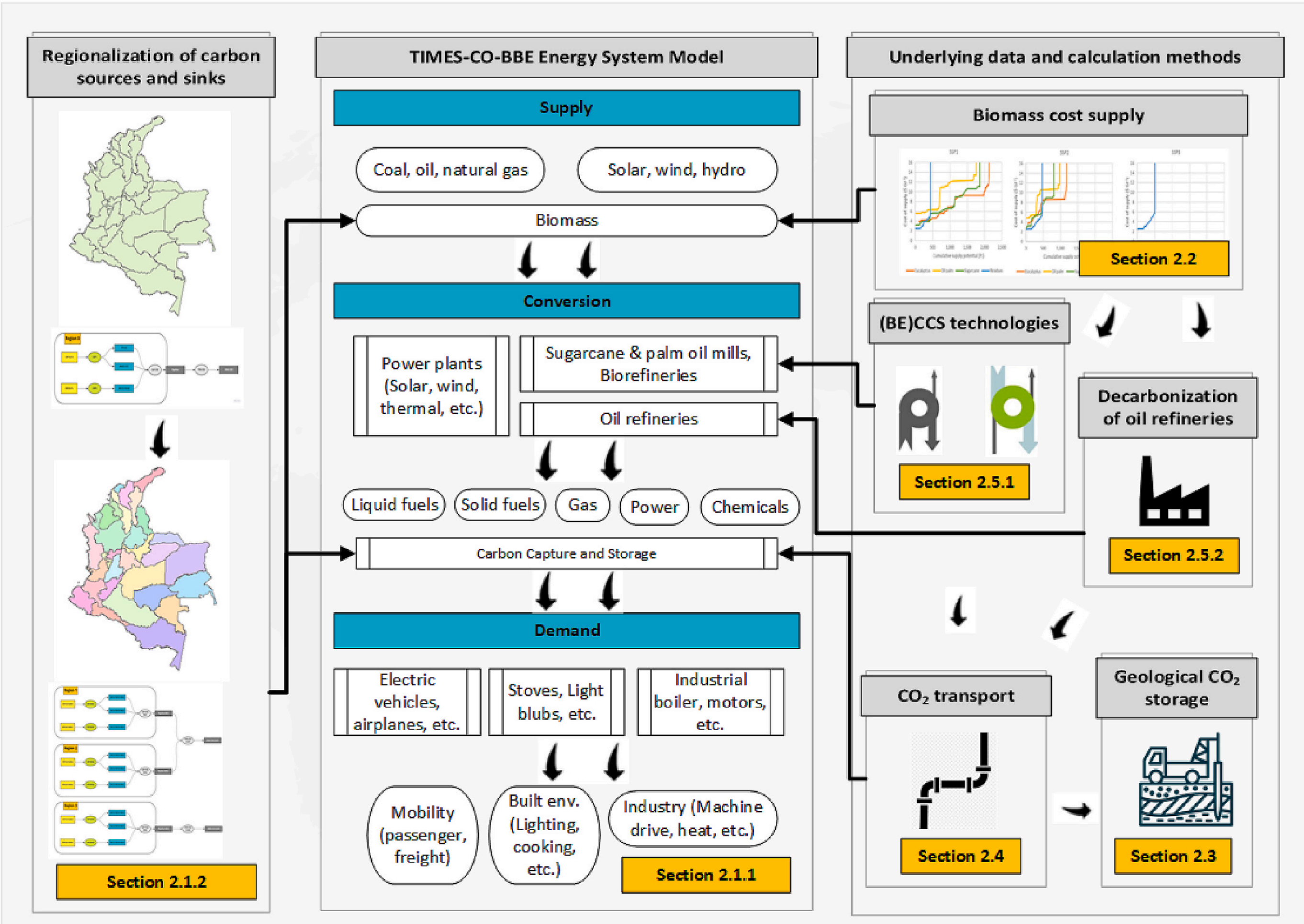

Fig. 1. Overview of the modeling framework, underlying data, and calculation methods.

- Parametrization of mitigation pathways of oil refineries in a national ESOM, making the outcome of facility–level studies useful for national–level ESOM–based analyses.
- Improved estimation of geological CO_2 storage potential in Colombia.
- Improved estimation of biomass cost by incorporating the transport cost of energy crops.
- Improved representation of low–carbon technologies compared to previous versions of TIMES–CO–BBE.

2.1.1. *TIMES–CO–BBE*

TIMES is a dynamic bottom-up linear optimization energy system model generator. TIMES aims at minimizing the total discounted system cost subject to technical, market, and policy constraints [29]. TIMES–CO–BBE v1 model was calibrated to the national energy balance of Colombia considering 2015 as a base year [30] and enriched with a detailed representation of bioenergy and BECCS value chains. The BBE database includes five types of biomass feedstock and more than 50 biorefinery configurations that can produce multiple products, including fuel, heat, electricity, and base chemicals. TIMES–CO–BBE has been used to analyze the role of biomass in achieving midcentury GHG mitigation goals subject to scenarios of technological development, socioeconomic drivers and biomass supply potential [3].

In the present analysis, we modified an updated version of the model, TIMES–CO–BBE v2, which features enhanced temporal resolution based on approximating the joint probability of electricity load and supply of intermittent renewable energy sources, and an intermediate projection of hydroclimatic variability and its impact on hydropower in Colombia [4]. However, in contrast to a previous study [4], the scope of this analysis excludes soft-linking the ESOM to a power system simulation model.

The current TIMES–CO–BBE v3 incorporates updated technoeconomic assumptions of battery electric vehicles (BEV) and hydrogen fuel cell electric vehicles (FCEV). We also expanded the diffusion of advanced biofuels beyond the road transport and aviation sectors to include marine transport [31] and other demand sectors (e.g., commercial, agriculture, and construction). Appendix A summarizes the differences among the three versions of the model.

2.1.2. *Regionalization approach*

To enhance the spatial resolution of the model with manageable complexity, the regionalization of the model was applied only to the (BE)CCS value chains, that is, biomass supply and CO_2 transport and storage, while other energy conversion and demand technologies were considered at the national level. In this regard, we assumed that the demand for biorefinery products is within proximity to the supply centers. This is a reasonable assumption, given that the transport of products constitutes a minor factor.

As shown in Fig. 2, the spatial resolution of the model includes 32 administrative departments for biomass supply [14] (Section 2.2) and four clusters of carbon sinks [8] (Section 2.3). Biomass processing was assumed to occur within the same supply regions. Each carbon source was assigned to the nearest sink cluster within a feasible distance for CO_2

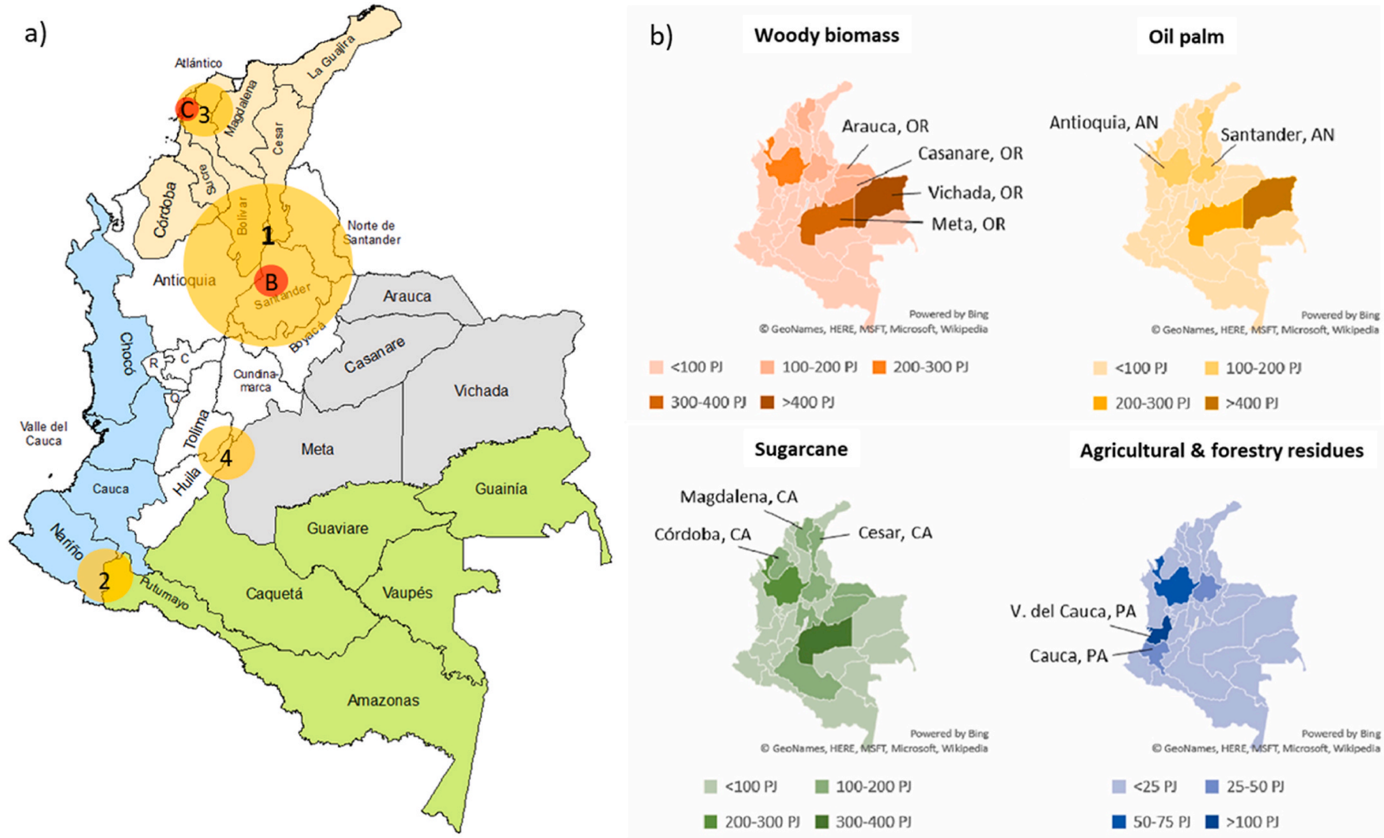

Fig. 2. a) Map showing Colombia's main land departments (administrative divisions), color-coded according to Colombia's five natural regions: Caribbean (CA) in yellow, Pacific (PA) in blue, Amazonia (AM) in green, Orinoquía (OR) in grey and Andes (AN) in white. The figure shows representative locations of the four carbon sink clusters considered in the analysis as yellow circles. The sizes of the circles reflect their relative storage capacities. The red circles B and C represent locations of Barrancabermeja and Cartagena oil refineries, respectively. b) Maps showing the supply potential of four types of biomass per department in shared socioeconomic pathway 1 (SSP1) scenario (see Section 2.6), adapted from Ref. [14]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

transport (Section 2.4).

For carbon sinks, representative coordinates were estimated for each of the four clusters proposed by Yáñez et al. [8] based on the weighted mean center of all storage sites within the cluster (Fig. 2a). The weighting factor was the CO_2 storage potential per location. The scope of geological CO_2 storage considered in the analysis was limited to mature oil fields. Storage in these oilfields was selected because of the availability of subsurface data, accessibility to existing infrastructure, and proximity to existing carbon sources. For biomass sources, representative coordinates were based on the centroid of each administrative department. The scope of regionalized biomass feedstock included three types of energy crops and agricultural and forestry residues.

To illustrate how the regionalized spatial resolution is nested into the model, Fig. 3 presents an example of the network typology used in the analysis. Here, Crop 1 in Region 1 is available as feedstock for BECCS Technologies 1 and 2. Moreover, Crop 2 in the same region can supply feedstock to BECCS Technology 3. Here, BECCS technology refers to the processes for biomass conversion and CO_2 capture. All captured CO_2 from this region is transported via pipeline to the nearest carbon sink in Cluster 1. Likewise, carbon sources in Region 2 are also linked via a pipeline process to the same sink cluster, whereas Region 3 is connected to the nearest sink Cluster 2. In the model, each region has a unique code which distinguishes the biomass and CO_2 commodities produced in this region from those produced in other regions. The same applies to the processes for biomass supply (e.g., plantations) and conversion (i.e., BECCS). The actual model is disaggregated into 9 plantation types (see Fig. 5), three supply types of residues, and 11 BECCS technologies (Table 1) for each region. In this regard, the aggregated model includes 847 processes and 249 commodities, whereas the regionalized model includes 2778 processes and 815 commodities.

2.2. Biomass supply

2.2.1. Land use and biomass supply potential

Previous analyses of the BECCS in the Colombian energy system have relied on an aggregated representation of biomass resources [3] based on estimates from previous studies [32,33]. This representation consisted of flat costs and yield levels per biomass type for the entire national territory. The spatial heterogeneity of land availability, resource productivity for different land qualities, and biomass supply logistics were not adequately captured by this level of aggregation.

To address this limitation, we expanded the biomass supply module based on data from a recent resource assessment [14] that estimated the cost-supply potential of three bioenergy crops and agricultural and forestry residues at the subnational level (Fig. 4). Younis et al. [14] analyzed three scenarios of the Colombian land–use system based on the shared socioeconomic pathways (SSP) framework [28] (the framework is further explained in section 2.6). In SSP1 scenario, the agricultural productivity could increase at a high rate, meeting the growing demand for food with lower land footprint, thus freeing up 'surplus land' of about 14 Mha by 2050 that could be available for energy crop production. In SSP2, an intermediate increase in agricultural productivity could free up to 8 Mha of surplus land by 2050. The supply potential of biomass in these scenarios is determined by the available land and corresponding yields. The underlying preconditions include food first principles and sustainable agricultural intensification, for example, through

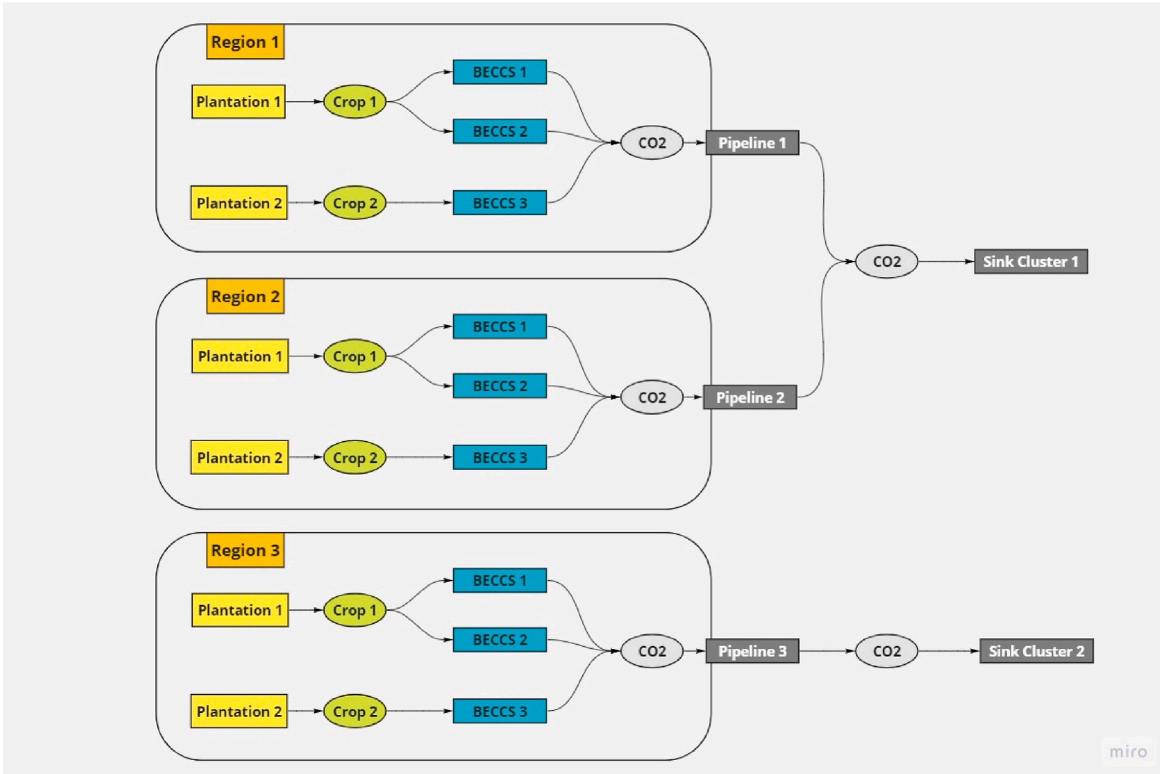

Fig. 3. An illustrative example of a hypothetical network typology which includes three biomass supply regions, two types of biomass, three types of processes for biomass conversion and CO_2 capture (BECCS technologies), and two carbon sink clusters.

Table 1
Techno-economic parameters of greenfield (BE)CCS technologies available in the TIMES–CO–BBE model.

Technology[a]	Feedstock[b]	Main product	Conversion efficiency (GJ_{out}/GJ_{in})	CAPEX ($/kW)	OPEX ($/kWy)	CO_2 capture (kg/GJ_{out})	Ref[c]
BIGCC	BM	Electricity	0.40	3200	68	150	1,2
FT	BM	Biofuels	0.49	2450	107	96	3,4
BG	BM	Hydrogen	0.66	1700	58	135	4
EtOH-Ann	SC	Sugar/EtOH	0.47	747	75	11	5
EtOH-Aut	SC	EtOH	0.47	981	98	28	6
EtOH-Imp	SC	EtOH	0.58	1300	130	26	7
IGCC – pre-combustion	Coal	Electricity	0.41	3150	109	191	8
PC – oxyfuel	Coal	Electricity	0.38	2580	133	209	8
CCGT – post-combustion	NG	Electricity	0.49	1435	60	100	8
CCGT – oxyfuel	Natural gas	Electricity	0.50	1620	65	100	8
SMR	Natural gas	Hydrogen	0.71	382	15	53	9

[a] Biomass integrated gasification combined cycle (BIGCC), Fischer Tropsch (FT) synthesis, Biomass gasification (BG), Annexed ethanol distillery (EtOH-Ann), Autonomous ethanol distillery (EtOH-Aut), Improved ethanol distillery (EtOH-Aut), Integrated gasification combined cycle (IGCC), Pulverised coal -supercritical (PC), Combined cycle gas turbine (CCGT), Steam methane reforming (SMR).
[b] Lignocellulosic biomass (BM), Sugarcane (SC), Natural gas (NG).
[c] 1- [42], 2- [43], 3- [44], 4- [45], 5- [46], 6- [47], 7- [48], 8- [49], 9- [50]. Note: The cost of CO_2 storage and transport was subtracted from the CAPEX of fossil CCS power plants in Ref. [49] to avoid double counting.

agroforestry systems, refraining from agricultural expansion into natural forests and sensitive ecological zones. In the SSP3 scenario, the growing demand for food and low agricultural productivity, without changes in self-sufficiency patterns, are likely to direct all available land to food production, with the risk of persistent deforestation. Under these conditions, expanding the production of energy crops is considered unsustainable. Accordingly, the biomass potential in this scenario is limited to the residues and byproducts of food and forestry production activities. Further details on the underlying approach and corresponding data are presented in Appendix B and Supplementary Material, respectively.

The aforementioned assessment was resource-focused, meaning that the assimilated cost-supply curves represented the potential for each crop individually, with all surplus land allocated to that crop. In practice, the market potential of different types of biomass crops may involve a degree of competition for the same land base. This competition can be addressed using demand-driven methods, such as energy system models [34].

Fig. 5 illustrates the biomass supply module for a given region. Upstream *Available Land* $_{s,r,y}$ processes were defined to manage the allocation of available surplus land for biomass production, distinguished by suitability class (*s*) and region (*r*) in year (*y*). Downstream, *Biomass Plantation* $_{s,r,b,y}$ processes were defined using *Allocated Land* $_{s,r,y}$ as the input and *Biomass Crop* $_{b,r,y}$ production as the output. These plantations were parameterized according to yield, production cost, and lifetime per biomass type (*b*).

Competition between different bioenergy crops within the same

Table 2
Refinery decarbonization options and the corresponding time frames, costs, modeling principles and allocation to scenarios (Section 2.6).

#[a]	Mitigation option type[a]	Target process[b]	Description[c]	Time frame[d]	Capital cost[e,f] [M $_{2015}$]	Economic life[e,f] [y]	Modeling principle[f]	Scenario analysis[g]		
								SSP1	SSP2	SSP3
1	EEM-2	CHP	LPG and NGL recovery from refinery gas	S	43.6	10	Reduce Specific Energy Consumption (SEC) of the oil refinery by 17 % (−14 MJ_{fuel}/GJ_{crude}) compared to baseline	X	X	X
2	EEM-2	CHP	Tuning (excess air value, burner maintenance)	S	2.0	5		X	X	X
3	EEM-1	Flaring	Steam-to-air assist flares	S	0.9	10		X	X	X
4	EEM-2	CHP	Improved management of steam losses	S	0.2	5		X	X	X
5	EEM-1	Flaring	Improved management of flares by optimizing flare purge gas and reducing purge rates	S	0.1	5		X	X	X
6	EEM-3	FCC	Waste heat recovery to produce low-pressure steam	M	0.9	20	Reduce SEC by 1 % (−0.7 MJ_{fuel}/GJ_{crude})	X	X	X
7	CCS-1	FCC + CHP	CO_2 capture in FCC and CHP units using a combined stack	M	1717	25	Capture 2.5 kg_{CO2}/GJ_{crude}	X		
8	CCS-2	HDT	CO_2 capture in the largest hydrotreatment unit	M	225	25	Capture 0.1 kg_{CO2}/GJ_{crude}	X		
9	CCS-3	HDT	CO_2 capture from a combined stack that integrates hydrotreatment, hydrocracking, and delayed coking units (future revamping project)	L	1531	25	Capture 2.3 kg_{CO2}/GJ_{crude}	X		
10	CCS-4	HDT	CO_2 capture in a combined stack from two small and old hydrogen generation units	M	14	25	Capture 0.1 kg_{CO2}/GJ_{crude}	X	X	
13	BioC-1	HDT	Co-processing vegetable oil	S	499	25	Substitute 1.7%$_e$ of crude oil input with bio-oil	X	X	
18	BioC-3	FCC	Co-processing fast pyrolysis oil	M	597	25	Substitute 1.6%$_e$ of crude oil input with bio-oil	X	X	
19	BioC-4	HDT	Co-processing catalytic pyrolysis oil	L	499	25	Substitute 8%$_e$ of crude oil input with bio-oil	X		
23	BioC-6	–	Onsite FT synthesis	L	3291	25	Substitute 10%$_e$ of oil products with biofuels	X		
24	MTM-GH_2	HDT	Green H_2 from electrolysis using national grid to supply current units	L	61	25	Substitute 2 MJ of fuel consumption with 4 MJ of grid electricity per unit crude throughput	X		
25	MTM-GE-GT	CHP	Green electricity from national grid to replace GT	M	–	25	Substitute 2 MJ of fuel consumption with 1 MJ of grid electricity per unit crude throughput	X	X	
32	MTM-GH_2-BioC-4	BioC-4	Green H_2 from Electrolysis using national grid to supply BioC-4	L	364	25	Substitute 23 MJ of fuel consumption with 23 MJ of grid electricity per unit crude throughput	X		
34	MTM-GE-Eboiler	CHP	Replace a share of steam production using e-boilers	L	75	15	Substitute 24 MJ of fuel consumption with 20 MJ of grid electricity per unit crude throughput	X		

[a] The numbering system follows that described in Ref. [24] to ease tracing them back to the source. Energy Efficiency Measures (EEM), Carbon Capture and Storage (CCS), co-processing of biomass with oil (BioC), Miscellaneous Technological Measures (MTM), Grid electricity (GE), Green hydrogen (GH_2), Gas turbine (GT).
[b] Combined Heat and Power (CHP), Fluid Catalytic Cracking (FCC), Hydrotreatment (HDT).
[c] Liquified Petroleum Gas (LPG), Natural Gas Liquid (NGL).
[d] Short-term (S), Medium-term (M), Long-term (L).
[e] The annualized CAPEX of mitigation options was modelled as a change in the annual fixed operational cost (FIXOM) of the refinery. Accounting to Yáñez et al. [24], the annualized cost was calculated by the capital investment, economic lifetime, and a discount rate of 12 %. The corresponding OPEX was taken as 2 % of the CAPEX.
[f] Techno-economic data for mitigation options were based on reference [23] for EEM [8], for CCS [22], for BioC, and [24] for MTM. The modeling principle represented own calculations based on these references, where all changes were normalized to the refinery level throughput (i.e. per unit crude oil input).
[g] The mitigation measures were structurally grouped into three deployment pathways based on reference [24], namely Maximum CO_2 avoidance, intended nationally determined contribution (INDC) and baseline. We matched these pathways to SSP1, SSP2, and SSP3 scenarios, as described in Section 2.6.

region is managed using crop- and non-crop-specific limits. The crop-specific limits corresponding to the maximum supply potential per crop include all suitable land available for a crop to be entirely allocated to that crop. These bounds were determined by Ref. [14]. Non-crop-specific limits were applied to the *Available Land* per suitability class for all crops within the region, assuming that the suitability of land for different crops within a region largely overlapped. These bounds were calculated according to the steps in Appendix C).

With respect to the supply potential of residues, a similar approach was used, where each region included a three-step cost-supply potential covering agricultural field, agro-industrial, and forestry residues. In contrast to Younis et al. [14], the residues from the sugarcane and palm oil sectors were excluded from the module to avoid double counting. These were endogenously calculated using the production of sugarcane and oil palm in the land use module.

2.2.2. Biomass transport

The processing of biomass supplied from each region was assumed to occur within its boundaries. The average biomass transport cost from the farm gate to the plant gate (C_{Do}) was calculated as described by Wright and Brown [25] (Equation (1)):

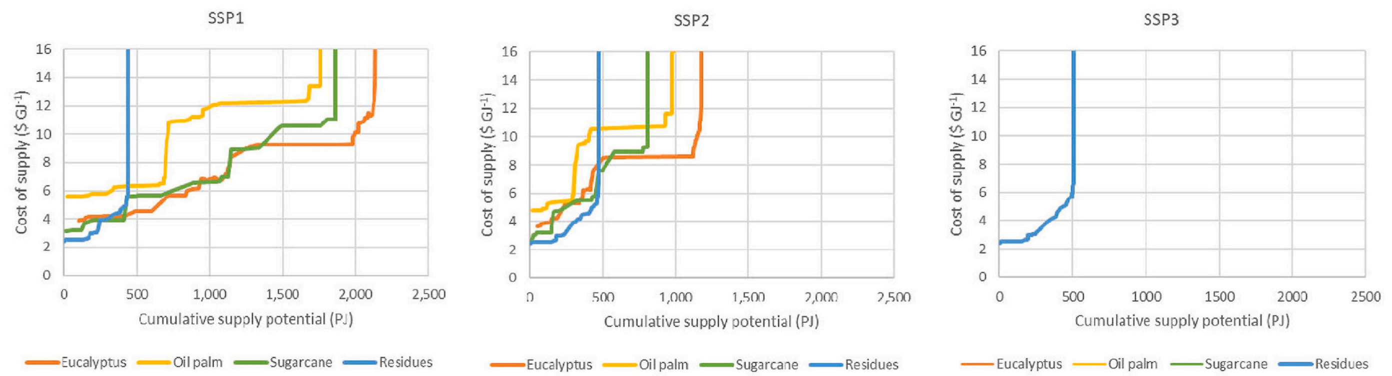

Fig. 4. Midcentury cost-supply potential of biomass from agricultural and forestry residues and three energy crops that can be sustainably grown on surplus land given food first and no deforestation principles. The three shared socioeconomic pathway (SSP) scenarios reflect different assumptions on socioeconomic drivers and agricultural technology (see Section 2.6). This figure is adapted from Ref. [14].

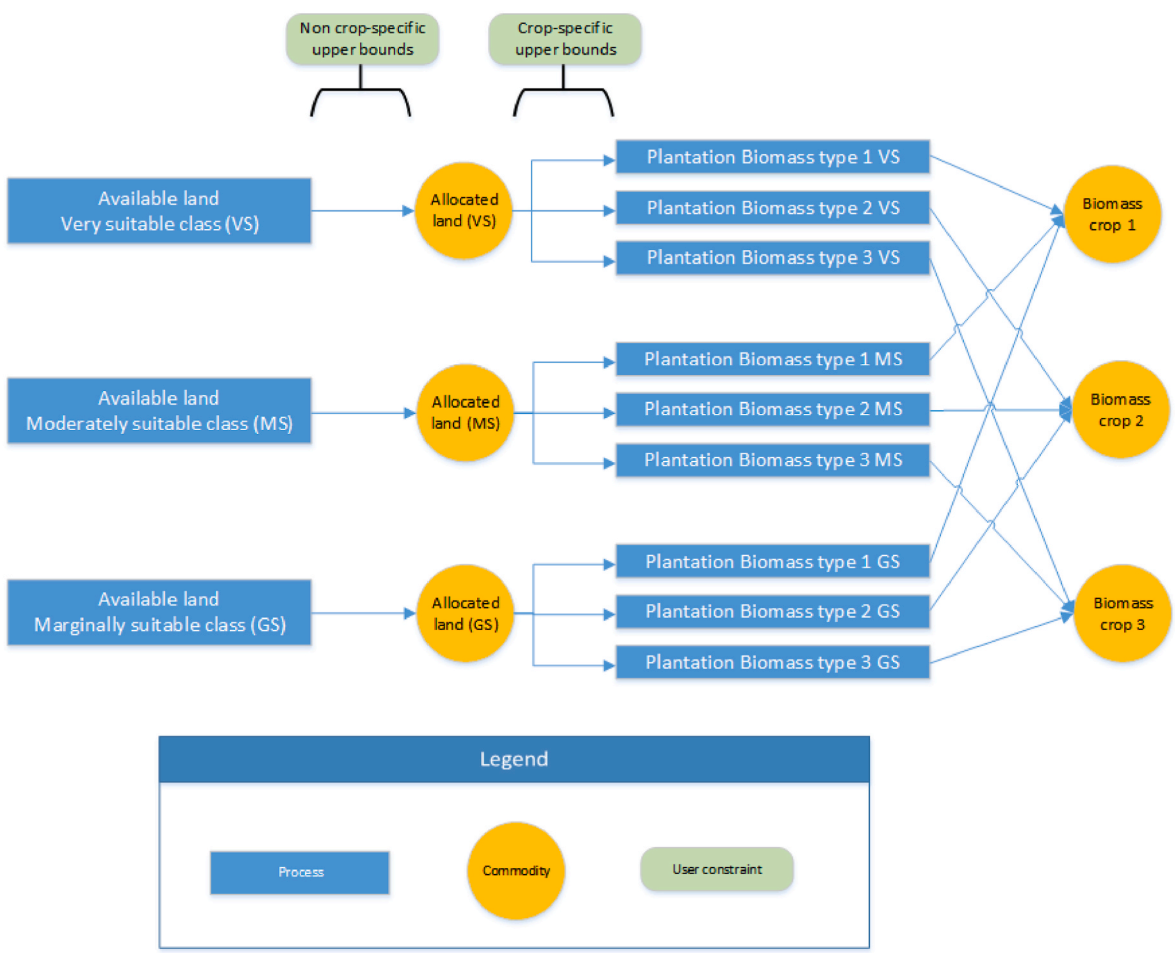

Fig. 5. An illustration of the land allocation module for a specific region, which includes three land suitability classes and three types of energy crops.

$$C_{D_o} = C_{DU} \times D \times F \qquad \text{Equation 1}$$

where C_{DU} is the unit cost for feedstock delivery (dollars per ton per kilometer), D is the average delivery distance of the feedstock, and F is the amount of feedstock delivered annually to the plant. The unit cost of feedstock delivery for lignocellulosic biomass is $0.44 ton^{-1} kilometer^{-1}.

D was estimated using Equation (2), assuming that the biomass was uniformly distributed around the processing location:

$$D = \frac{2}{3} \times \tau \times \sqrt{\frac{F}{\pi \times f \times Y}} \qquad \text{Equation 2}$$

where f is the fraction of the acreage around a plant used for feedstock production (taken as 60 %, based on [25]), Y is the annual feedstock yield, and τ is a 'tortuosity factor' to account for the difference between the actual distance traveled by a truck and the radial distance calculated by this approach. The tortuosity factor depends on the nature of the road network and can be as low as 1.2 for developed agricultural regions where roads are laid out in rectangular grids and as high as 3.0 for less developed regions. In this analysis, τ was assigned to departments in inverse proportion to population density, as previously proposed [35]. Appendix D presents a descriptive analysis of biomass transport distances and costs.

2.3. CO_2 sinks

The main parameters used to model the geological storage of CO_2 in an energy system model are cumulative storage potential, the annual CO_2 injection rate, and the cost of storage.

2.3.1. Geological CO_2 storage potential

Previously reported estimates of the geological storage potential of CO_2 in Colombia, for example [36,37], have shown high divergence in scope and magnitude, pronounced aggregation, and in some cases a lack of transparency of the underlying methods (see review in Appendix E).

Here we combined two previously detailed geological storage assessments [8,26]. Yáñez et al. [8] identified four geographical clusters that are feasible for CCS projects (Fig. 2a). However, the scope of this study was limited to optimizing enhanced oil recovery (EOR), which has limited potential.

Cardozo et al. [26] calculated the theoretical CO_2 storage potential in the central sector of the Middle Magdalena Basin (MMB) in Colombia, which falls within Cluster 1, as defined by Yáñez et al. [8]. Based on the method of Bachu et al. [38] for oil and gas reservoirs, the authors estimated the theoretical CO_2 storage potential at 9 Gt (see Appendix E).

The present analysis is based on the four clusters of CO_2 sinks defined by Yáñez et al. [8]. However, instead of matching carbon sinks to existing CO_2 sources only, our modeling framework explored the dynamic evolution of new sources over time. Another difference is that we considered the potential for storage in mature oil and gas fields.

Storage potential was determined in three steps. First, the potential estimated by Cardozo et al. [26] for the MMB was considered as a proxy for Cluster 1. This theoretical potential does not consider the possible risks related to seal characterization for CO_2 retention and trapping, CO_2 mineralization, fluid interaction, or injectivity. In the second step, these uncertainties were addressed by applying confidence ranges to the chance of success (*COS*) of the trap, reservoir, and seal integrity (Equation (3)). The corresponding probabilities (*P*) for trap, reservoir, and seal integrity were assumed to range between 0.4 and 0.7, 0.8–1.0, and 0.5–0.7, respectively. Accordingly, the COS_{CO2} (Equation (3)) was predicted to range between 0.16 and 0.49, leading to a technical storage potential of 1.44–4.41 Gt.

$$COS_{CO_2} = P_{trap} \times P_{reservoir} \times P_{seal\ integrity} \qquad \text{Equation 3}$$

finally, we used the ratio between the CCS-EOR potential in Cluster 1 calculated by Yáñez et al. [8] and the corresponding potential in mature fields estimated by Cardozo et al. [26] to predict the potential of mature fields in other clusters based on their respective EOR potentials. The resulting estimates per cluster ranged between 7 and 8% of the potential in Cluster 1.

2.3.2. Cost of CO_2 storage

The cost structure of a CO_2 storage project includes capital expenditures on drilling and injection equipment, site characterization, operation and maintenance costs and site closure [39]. The capital cost depends on the number of wells required to reach the annual target injection rate of CO_2. The number of wells required depends on the injectivity per well, which is determined by geological factors, such as the permeability of the target formation, dynamic viscosity of CO_2, density of CO_2 at the formation depth, and pressure build-up at the injection well. Given the large scope of this study and the lack of sufficient data to quantify these factors in detail, we adopted the levelized cost of CO_2 storage reported by Lap et al. [19] for a geological formation in Brazil. This cost range (7–20 $/t) sufficiently covers the uncertainty of CO_2 storage economics in the present study (Table 3). The target injection rate per cluster was calculated from the storage potential, considering an economic lifetime of 25 years [8].

2.4. CO_2 transport

The cost of CO_2 transport via pipelines depends on the length and size of the pipelines, which are related to the distance and annual flow rates of CO_2 transport, respectively. We assumed a simplified network structure, in which each administrative department is directly connected to the nearest carbon sink. The scope of this study was limited to continental onshore systems.

2.4.1. CO_2 transport distances

Yáñez et al. [8] used a bottom-up approach to project a techno-economically feasible CO_2 transport network to match carbon sources and sinks in Colombia. The network layout considered the capacities and proximities of carbon sources, sinks, and existing infrastructure corridors. The application of such networks can be challenging in TIMES–CO–BBE because of the different methodologies and broader and more dynamic scope of carbon sources used in our analysis.

Alternatively, the CO_2 transport distance was determined in a three-step process. First, we calculated the Euclidean straight-line distances between all the carbon sources and sinks to match each source to the closest sink.

Second, the road distances between the coordinates of the sources and sinks were retrieved using Google Maps. The distance traveled on roads provides a better proxy for topological constraints and proximity to infrastructure corridors.

Third, the tortuosity factor for an administrative department was calculated as the ratio of the road distance to the corresponding Euclidean distance. No road distances between the coordinates were identified for some departments in the Caribbean and Pacific regions. The corresponding pipeline distances were calculated by multiplying the Euclidean lengths by the highest tortuosity factors within the same region (Fig. 2a).

In Amazonia, no road distances were identified for any of the departments in the region because of the rural nature and limited infrastructure. The corresponding pipeline lengths were calculated using the Euclidean distances and highest tortuosity factor for the entire dataset.

The resulting distances ranged from 112 km to 1748 km (see Appendix F). A cut-off limit was set for departments beyond 800 km for any carbon sink. Within this limit, the average national transport distance is estimated to be 305 km. The cutoff value was assumed to be based on the longest CO_2 pipeline currently installed worldwide, the Cortez project [40]. As an exception, the Vichada Department was assumed to fall within this range, although the estimated distance was 856 km, because this department exhibited a small deviation from the threshold distance, while it was projected to contribute significantly to the supply potential of biomass (Fig. 2b).

2.4.2. CO_2 transport cost

We based the CO_2 transport cost on Smith et al. [27], who reported the costs of CO_2 transport across various distances (160 and 800 km) and scales (1.0, 3.2, 6.0 and 15.0 Mtpa). We considered a location factor of 1.08 for South America, based on van der Spek et al. [41]. For each distance calculated in the previous section, the corresponding CO_2 transport cost per ton was calculated using linear interpolation. Cost uncertainty was explored through a scenario analysis based on different scales of CO_2 transport (Table 3 and Appendix F).

2.5. Energy conversion and CO_2 capture

The scope of the technological details presented in this study is limited to regionalized technologies that are connected to CO_2 sinks,

Table 3
Key variables explored through scenario analysis using the shared socioeconomic pathways framework.

	SSP1	SSP2	SSP3
Socioeconomic drivers[a]			
Population by 2050 (million)	56	62	69
Gross domestic product by 2050 (billion $)	1996	1837	1504
CO_2 mitigation target			
Net emissions by 2050 (Mt), compared to 88 Mt in 2015[b]	0	32	52
Biomass supply			
Total surplus land potentially available by 2050[c] (Mha)	14	8	–
Yields of bioenergy crops by 2050[d] (GJ/ha)			
• Woody crops	283	265	–
• Oil palm	176	157	–
• Sugarcane	382	315	–
Supply potential of biomass by 2050[e] (PJ/y)			
• Woody crops	3260	1640	–
• Oil palm	1946	981	–
• Sugarcane	1862	680	–
• Agricultural and forestry residues	302	308	313
Cost of biomass supply by 2050[f] ($/GJ)			
• Woody crops	7.2	7.2	–
• Oil palm	13.2	13.6	–
• Sugarcane	9.2	9.2	–
• Agricultural and forestry residues	3.6	3.7	3.8
Conversion technology			
Technological learning[g]	High	Intermediate	Low
Oil refinery[h]	DP-3: Maximum CO2 avoidance	DP-4: INDC	DP-1: Baseline
CO_2 transport and storage			
CO_2 storage potential (Gt)[i]	5.4	1.8	0.2
CO_2 injection rate (Mt/y)	218	71	10
Cost of storage ($/$t_{CO2}$)[j]	7	14	20
CO_2 transport rate (Mt/y)[k]	15	6	3.2
Cost of transport ($/$t_{CO2}$)[k]	2.3	4.3	6.1

[a] The socioeconomic drivers are based on previous studies [51,52]. The corresponding demand for energy services and food is reported in Refs. [3,14], respectively.

[b] The SSP framework separates between socioeconomic drivers and the efforts exerted towards climate change mitigation and adaption. However, for the purpose of this study, we limited the scope to one mitigation target per SSP scenario. The mitigation targets for SSP2 and SSP3 are consistent with those presented previously [3]. By contrast, the climate policy in SSP1 scenario was updated to reflect increased ambitions to achieve 51 % GHG reduction by 2030, relative to the official baseline scenario, and carbon neutrality by midcentury [53].

[c] Not all available land is suitable for crop production. The variation of land suitability per type of bioenergy crop is discussed elsewhere [14].

[d] Energy yields were based on the lower heating value. The yields of sugarcane and oil palm included the energy content of the main product (vegetable oils and sugars) and residues available for valorization such as sugarcane trash, empty fruit bunches, shells, and kernels of oil palm fruits. Projected yields and potentials of sugarcane and oil palm were based on Younis et al. [14], while projected yields of woody crops were based on Lap et al. [18].

[e] The supply potentials of energy crops were calculated by the projected yields and the potentially available land per crop per land suitability class [14]. The supply potential of agricultural and forestry residues refers to the available potential of byproducts of non-energy food and forestry products, after considering other uses and ecological constraints [14].

[f] For energy crops, the cost of biomass supply included farm gate production costs based on reference [14] and transport costs estimated in this study as described in Section 2.2.2. The cost of residues represents an average of field residues and agro-industrial residues based on reference [14].

[g] Technological learning included the availability (i.e., introduction year) and learning rates (i.e., efficiency improvement and cost reduction over time) of technologies. For the underlying datasets per technology, please refer to Ref. [3]. On average, the projected reduction in CAPEX of bio-based technologies was −2.2 %/y, −1.2 %/y, and −0.3 %/y in SSP1, SSP2, and SSP3, respectively.

[h] GHG mitigation pathways and corresponding naming conventions were based on reference [24]. The technology options per deployment pathways are reported in Section 2.5.2 (Table 2). In summary, the SSP3 scenario included EEM measures only, SSP2 scenario included EEM, co-processing of vegetable bio-oil, and limited application of CCS, and the SSP1 scenario included the full span of measures to achieve maximum CO_2 avoidance in the refinery, including advanced biofuel production, electrification, and green hydrogen.

[i] The geological storage potential in SSP1 and SSP2 scenarios corresponded to the upper and lower ranges of the technical potential in depleted oil and gas fields, while that of the SSP3 scenario was based on the CCS-EOR potential only. The storage potential in clusters 1, 2, 3, and 4 corresponded to 81 %, 6 %, 6 %, and 7 % of the total values reported in the table, respectively (Section 2.3.1).

[j] The cost of CO_2 storage per ton was based on the assessment of Lap et al. [19] for an onshore saline aquifer in Brazil. The assessment followed methods from McCoy [39], considering data for the capital expenditure on drilling and injection equipment per well from Tayari et al. [54], site characterization and closure cost from McCoy [39] and ZEP [55], and operation and maintenance cost as suggested by Kanudia et al. [56].

[k] For the cost of CO_2 transport, the values reported in this table reflect the national averages. The cost data per administrative division is reported in Appendix F. The cost of CO_2 transport was based on the size and length of the pipelines. The lengths were determined by the distances between sources and sinks (Section 2.4.1). The flow rates represented three scenarios of CCS development. The associated costs were adapted from Smith et al. [27].

namely greenfield BECCS technologies and the oil refinery sector. An exhaustive list of all the technologies in the TIMES–CO–BBE model is presented elsewhere [3].

2.5.1. Greenfield (BE)CCS technologies

Several (BE)CCS technologies are included in the model for producing electricity, hydrogen, and liquid biofuel. Table 1 lists the greenfield (BE)CCS technology options included in this analysis and their respective techno-economic parameters. Technological learning is subject to scenario analysis (Section 2.6) based on data presented elsewhere [3].

2.5.2. Decarbonization of exiting oil refineries

The standard parametrization of oil refineries in a TIMES model and the corresponding data for the refinery sector in Colombia are reported in Appendix G. For the parameterization of decarbonization pathways, four types of GHG mitigation options were considered within the oil refinery sector: energy efficiency measures (EEM) [23], co-processing routes of biomass in oil refineries (BioC) [22], carbon capture and storage (CCS) through EOR [8], and miscellaneous technological measures (MTM). The latter includes green hydrogen and renewable electricity use [24] (Fig. 6).

These measures were organized into three deployment pathways (see scenario analysis in Section 2.6) considering the capacity to implement multiple options simultaneously and the path dependency for short-, medium-, and long-term investments [24].

To analyze these deployment pathways within the context of a national energy system model, we propose the parameterization presented in Fig. 6 and the modeling principle in Table 2. EEM was represented by a reduction in refinery fuels (auxiliary inputs) for the same throughput. In contrast, MTM involves partial substitution of refinery fuels with (low-carbon) electricity from the grid for electrification and onsite green hydrogen production. BioC was achieved through partial substitution of crude oil with bio-based feedstock and partial substitution of refinery products with biofuels. CCS measures were included by linking captured CO_2 from the refinery to the relevant CO_2 pipeline and sink clusters.

For the national scope of this analysis, we extrapolated the scope of mitigation pathways of Yáñez et al. [24] from the Barrancabermeja refinery to the sector level, assuming homogeneity in techno-economic characteristics (e.g., complexity, age). Although this approach provides a preliminary indication, a detailed investigation of the mitigation potential of the Reficar refinery is beyond the scope of this analysis. The

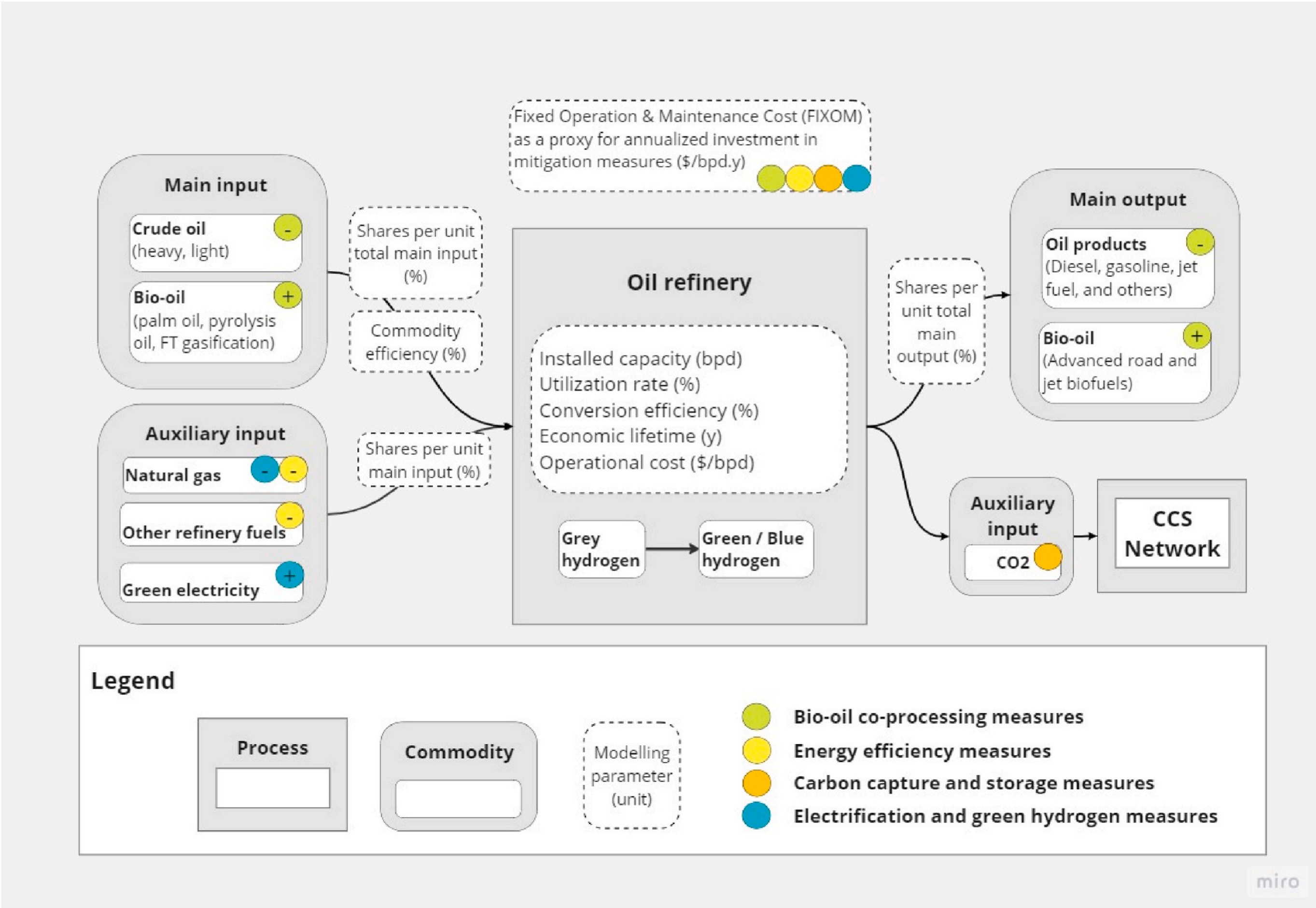

Fig. 6. Proposed parametrization to model the deployment of GHG mitigation options in an existing refinery.

locations of the two refineries are shown in Fig. 2.

2.6. Scenario analysis

In this study, we followed the shared socioeconomic pathway (SSP) scenario analysis framework based on the SSP1, SSP2, and SSP3 narratives [28]. SSP1 reflects a future in which global collaboration fosters a transition towards sustainable development. This future will manifest in the rapid advancement and upscaling of low-carbon energy and agricultural technologies. This scenario indicates lower population growth and higher welfare. By contrast, SSP3 depicts a scenario of global fragmentation with a national focus. This scenario is characterized by high population growth, low economic welfare, and slow technological progress in the energy and agricultural sectors. SSP2 corresponds to a middle-of-the-road scenario where the current progress towards sustainable development goals continues slowly. Table 3 presents the key variables explored. Further details are presented elsewhere [3,4].

For each SSP scenario, two aspects were analyzed, yielding four variations. First, modeling BECCS value chains at a nationally aggregated resolution was compared with a regionally disaggregated resolution. Second, the investment in the decarbonization of oil refineries was compared with the case where the Barrancabermeja and Reficar refineries were projected to close by 2030 and 2040, respectively. The scenarios were compared in terms of CO_2 balance, total energy supply and demand, biomass supply and land use, annual system cost, and spatial details of the regionalized model.

3. Results

3.1. Total energy supply and consumption

Fig. 7a and b shows the projected total primary energy supply (TPES) and total final consumption (TFC), respectively, given alternative investment options in the oil refinery sector and levels of aggregation of BECCS value chains. TPES and TFC are projected to grow more in SSP1 than in SSP3 under the effect of demand drivers. SSP3 represents higher projected population growth, which reflects higher residential demand than SSP1. However, SSP1 represents higher economic growth, which reflects a higher demand for transportation, industrial, and commercial sectors than SSP3.

Currently, oil is the main energy source for domestic supply and exports in Colombia. Should the oil sector invest in retrofitting refineries, domestic crude reserves will be depleted in the short-to medium-term. The co-processing of bio-oil in existing refineries can have a modest effect on reducing the demand for crude input. In the absence of investment in upstream exploration and sizeable discoveries, maintaining the operation of refineries requires crude oil imports. Alternatively, if oil refineries retire in the medium-term, the supply of primary oil and imports of secondary oil products are expected to be phased out by the midcentury.

Given the declining role of oil, the growing demand for energy services, and emission mitigation targets, the supply of biomass and other renewable energy sources is projected to increase.

Considering the demand for the transportation industry, advanced biofuels are expected to be the most economical alternative for

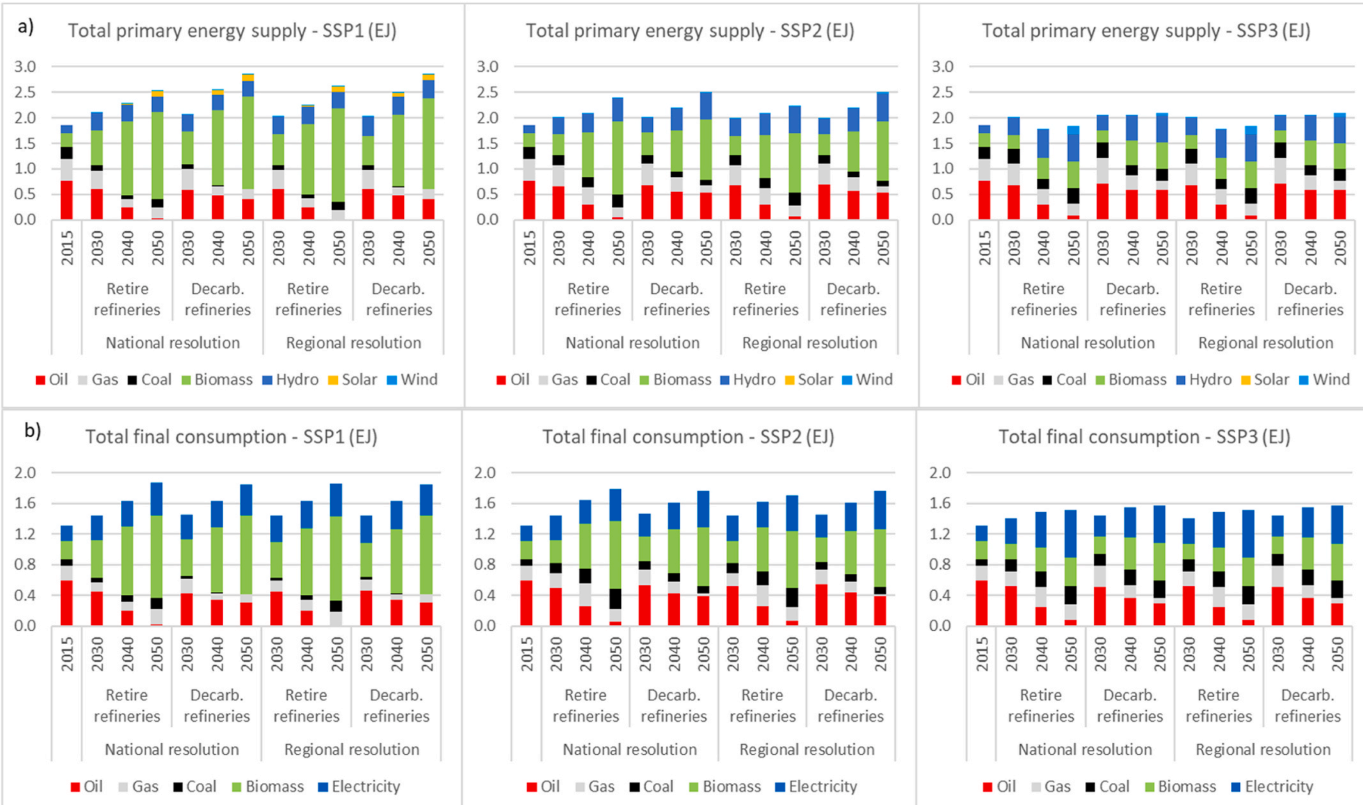

Fig. 7. a) Total primary energy supply (EJ) and b) total final consumption of the projected scenarios of the Colombian energy system. These figures include energy demand for non-energy purposes (e.g., base chemicals) and exclude the use of sugar and vegetable oil as food and oleochemical products.

decarbonizing the transport sector, especially in the SSP1 and SSP2 scenarios (Fig. 8), where high biomass potential and technological progress constitute favorable conditions. Second-generation (2G) fuels can be produced in dedicated biorefineries and co-produced in existing first-generation (1G) biorefineries through the valorization of residues. In SSP1, many of these fuels are expected to be produced through BECCS technologies, which are expected to be crucial in attaining carbon neutrality by midcentury (Section 3.2). Moreover, the co-processing of biomass in existing oil refineries could supply up to 19 % of total biofuel production in the SSP1 scenario.

In SSP3, a larger role for BEVs is projected, given the high limitations on sustainable biomass supply and the slow technological development of bioenergy technologies. The high efficiency of BEVs can limit the growth in energy demand for transport (Fig. 8) and TFC (Fig. 7b).

In a built environment, electrification is likely to be the most suitable low-carbon solution. Fig. 9 shows the expected dominance of renewable sources in power production. The expansion of hydropower reservoirs can help balance the large-scale integration of intermittent solar and wind power. However, previous research has shown that additional measures such as energy storage or flexible power generation capacity, may be required to safeguard the reliability of power systems, which can increase energy system cost by 2–5% [4]. By 2050, solar power is anticipated to be more competitive than wind power in SSP1 at levelized costs of 0.010 $/kWh and 0.017 $/kWh, respectively. The opposite is true for SSP3 where the costs are expected to be 0.027 $/kWh and 0.024 $/kWh by 2050, respectively. While the learning rates for solar and wind power are higher for SSP1 than for SSP3, the relative difference is more favorable to solar power in SSP1. The underlying data are reported in Ref. [3] and adapted to the current scenario analysis framework based on the scenarios reported in Ref. [57] and the resource potential

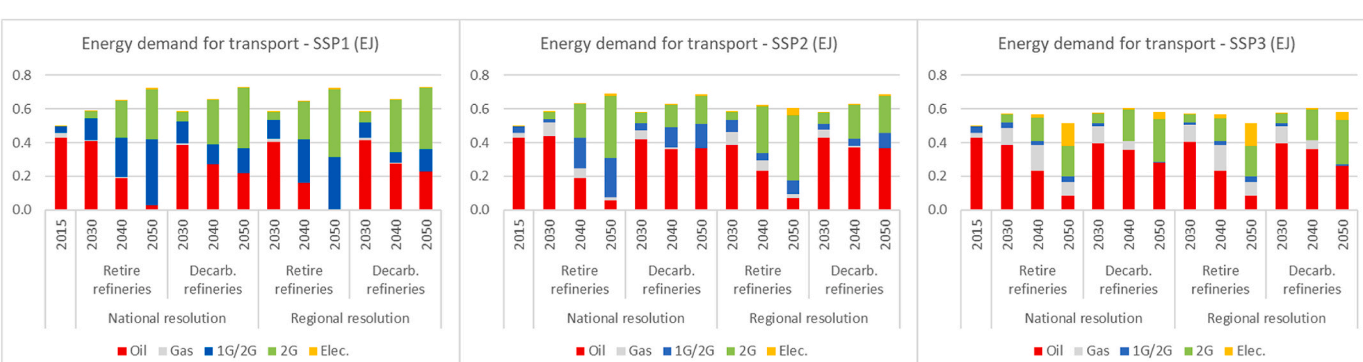

Fig. 8. Energy demand for transport (EJ), in which oil products include gasoline, diesel, jet, and heavy fuel oil. 1G includes first-generation bioethanol and biodiesel. 2G includes advanced second-generation road and jet biofuels.

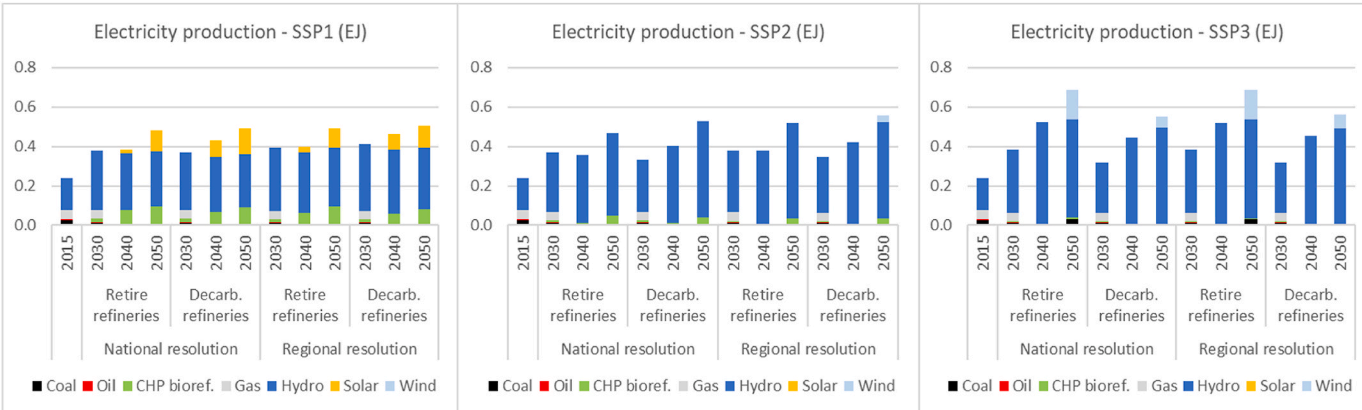

Fig. 9. Electricity production (EJ), where combined heat and power (CHP) refers to the surplus electricity injected into the grid which exceeds the endogenous energy demand of biorefineries biorefineries.

categories reported in Ref. [49].

A mix of solid biomass, electricity, and natural gas is expected to meet the demand of the industrial sector. In the SSP3 scenario, coal is projected to be the main industrial fuel given the abundance of domestic low-cost feedstock and low emission targets. Remarkably, a growing role for coal is projected in the net-zero emission SSP1 scenarios with the retirement of oil refineries. In this regard, negative emission technology (NET) deployment can stimulate positive emissions in heavy industries while meeting the system-level mitigation target cost-efficiently. To prevent CDR technologies from providing such incentives, refined mitigation targets must be defined for each sector.

3.2. CO_2 balance and contribution of BECCS

Fig. 10a shows the projected CO_2 balance of the Colombian energy system for each of the three SSP scenarios.

In SSP1, the large-scale availability and development of BECCS technologies for advanced biofuels are anticipated to play a crucial role in achieving carbon neutrality by midcentury. As a source of negative emissions, BECCS can offset the growing emissions in other sectors. This

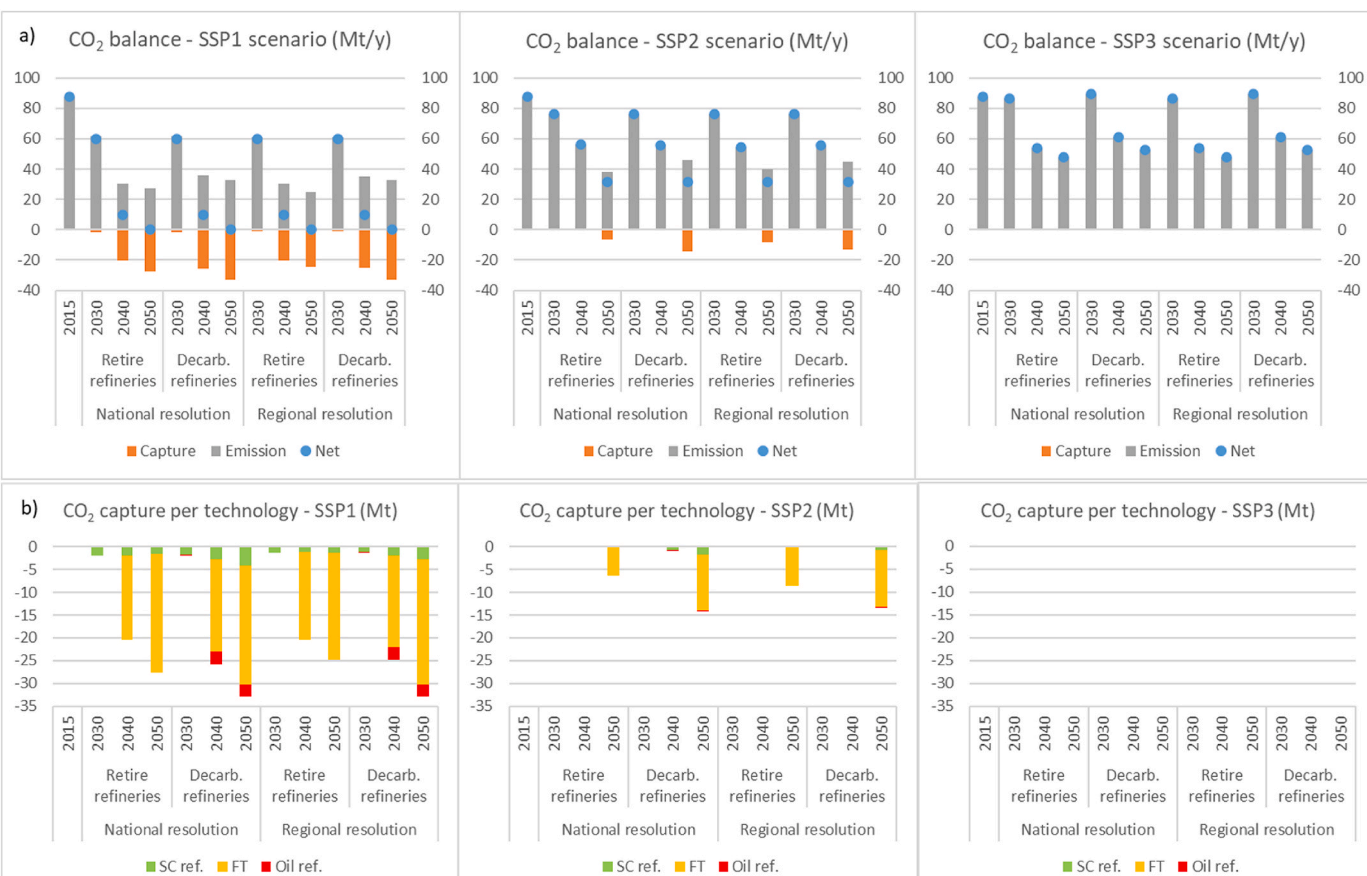

Fig. 10. a) CO_2 balance of the projected national energy system in Colombia. In each scenario, the respective decarbonization pathway of the oil refineries was compared to their retirement. Moreover, modeling the system at nationally aggregated and regionalized resolutions were compared. b) Breakdown of captured CO_2 per type of process, where SC ref., FT, and Oil ref. refer to sugarcane refineries, Fischer-Tropsch synthesis facilities, and oil refineries, respectively (Mt/y).

trend is consistent regardless of the spatial resolution of the BECCS value chains or investment decisions in the oil sector. Such trajectories will require total CO_2 injection rates of 25–33 Mt/y by the midcentury with a cumulative injection of 340–470 Mt between 2030 and 2050. These rates are not expected to be linear because early stage deployment is expected to be small and grow substantially over time. The cumulative avoided emissions between 2030 and 2050 in the SSP1 scenario, i.e., net emissions compared with the SSP1 reference scenario without emission constraints, are anticipated to range between 0.9 and 1.2 Gt. Accordingly, the mitigation potential of BECCS in the same period, i.e., the share CO_2 capture to the total avoided emissions, can reach 37–41 %.

Based on the sensitivity analysis, the absence of CCS is likely to increase the demand for biomass, whereas the limitation on biomass can greatly increase the demand for electrification and system cost (Section 4 and Fig. 14).

In SSP2, the role of BECCS in curbing the emissions of the energy system to 30 Mt/y by midcentury is expected to become relevant in the longer term. By 2050, the cumulative CO_2 storage requirement could range between 32 and 83 Mt. In SSP3 conditions, CCS is unlikely to play any significant role given the modest mitigation target and low development of these technologies. Thus, the low storage potential considered in this analysis is not a limiting factor for CCS deployment in the SSP3 scenario.

Fig. 10b shows the breakdown of captured CO_2 per process. In SSP1, sugarcane biorefineries can lead to the early deployment of BECCS. However, their capacity is likely to remain limited to 1–4 Mt/y considering the low corresponding CO_2 capture rates. By 2040, the development of CCS in existing oil refineries can increase CO_2 capture by an additional 2.8 Mt/y (9–10 % of the total capture). However, the major deployment of BECCS is expected from biomass gasification and Fischer-Tropsch synthesis, which can provide drop-in road and aviation transport fuels and bio-naphtha as feedstock for base chemicals. Similar technologies are expected in SSP2, but at a smaller scale and with a later deployment.

3.3. Land use and biomass supply

Fig. 11a shows the projected land allocation for energy crops, including the demand for sugar and oil as food. Fig. 11b shows the supply of biomass for modern applications. Total land use in the agricultural sector, including livestock production, has been reported previously [14].

Currently, approximately 500 kha of land is allocated to sugarcane and oil palm for the production of food and first-generation (1G) biofuels. The allocation of sustainable biomass production in SSP1 can reach 3 Mha to achieve a carbon neutral energy system by midcentury. This land conversion represents 21–23 % of the total surplus land available for sustainable biomass production under the SSP1 scenario.

Under the SSP2 scenario, the land requirement for sustainable biomass production can reach 2.3–3.2 Mha by 2050. This conversion corresponds to 29–40 % of the surplus land available for sustainable biomass production under SSP2 [14]. In the SSP3 scenario, the potential of biomass is limited to the residues and byproducts of food and forestry activities, where no surplus land could be sustainably available for biomass production (see section 2.2.1).

Although the projected supply of biomass in SSP2 is lower than that in SSP1, the corresponding land uses are comparable in the long-term, which can be explained by differences in yield and land availability. The higher availability of surplus land in SSP1 can accommodate much of the biomass supply on lands of higher quality, consequently resulting

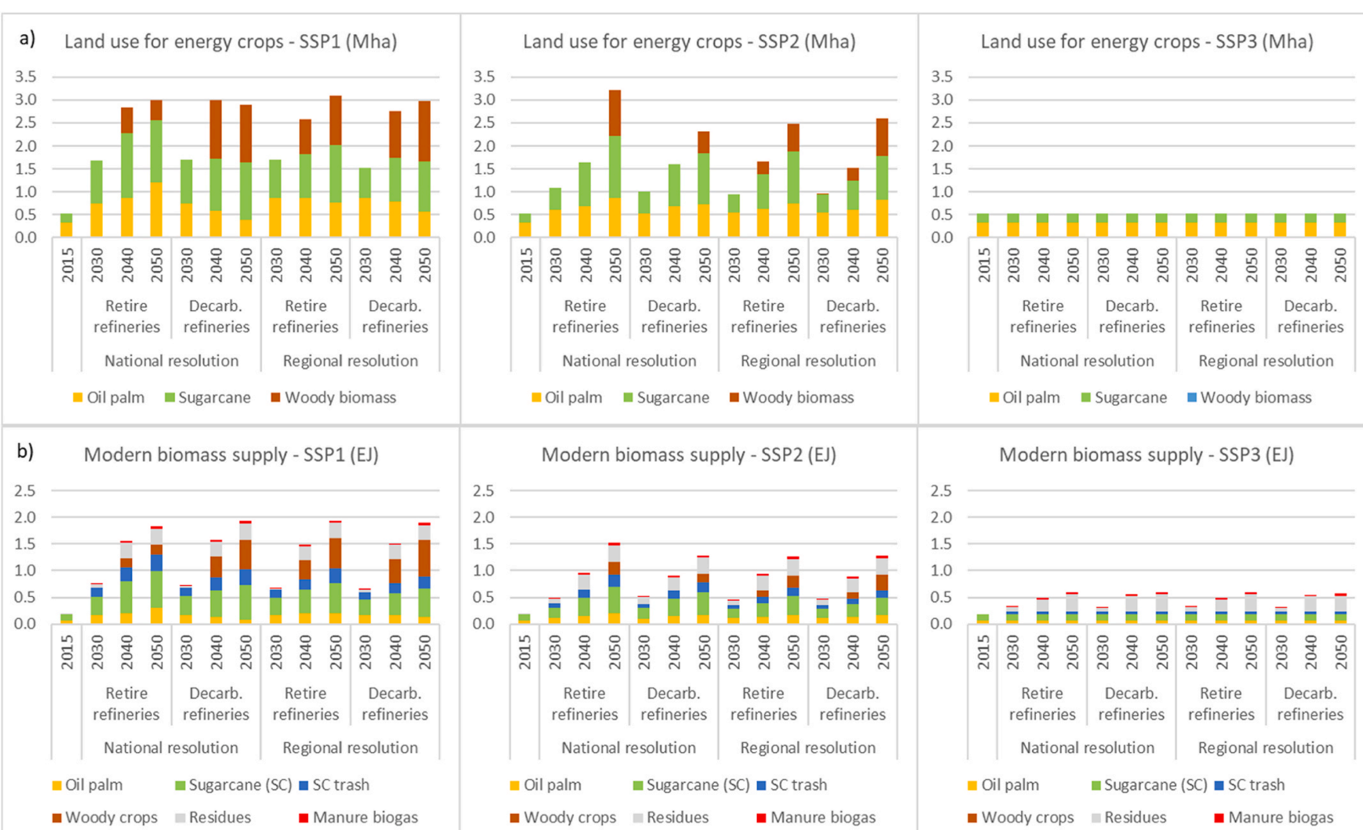

Fig. 11. a) Land use for energy crops (Mha), including current allocation to co-production of biofuels, sugar, and vegetable oil. b) Modern biomass supply, excluding edible oil and sugar and the traditional use of firewood for heating and cooking (EJ). Sugarcane includes the energy content of sugar and bagasse, oil palm includes the energy content of crude palm oil and residues (fresh fruit bunch, shell, and kernel), and residues include other residues associated with the agricultural and forestry sectors.

in higher yields. In contrast, the saturation of high-quality land in SSP2 could push more biomass production from lignocellulosic crops to be grown on lower-quality land, resulting in a lower yield.

Currently, the biomass supply for modern applications is approximately 0.2 EJ. The demand for biomass by 2050 is projected to grow to 1.8–1.9 EJ in SSP1 and 1.3–1.5 EJ in SSP2. Sugarcane is expected to play a significant role in these scenarios. The energy content of bagasse, which can be efficiently valorized in biorefineries for the co-production of heat and power, is a major component of sugarcane. Moreover, part of the associated field residue (i.e., sugarcane trash) can be pretreated and valorized within sugarcane mills or in standalone biorefineries. Key applications of sugarcane include the production of sugar, biofuels, biochemicals, surplus electricity, solid residues, and CDR.

In addition to sugarcane, woody biomass from dedicated plantations is projected to significantly contribute to the SSP1 and SSP2 scenarios. The projected demand for agricultural and forestry residues corresponds to their ecological potential. Key applications of lignocellulosic biomass include advanced road and aviation biofuels, biochemicals, surplus electricity, industrial heat, and CDR.

In the oil palm sector, key applications include for non-energy oleochemical products and biofuel production, whether in dedicated biorefineries or through co-processing in existing oil refineries. Moreover, the primary supply of palm oil includes residues that contribute to the demand for lignocellulosic biomass.

3.4. Annual system cost

Fig. 12 shows the projected total annual energy system costs by 2050. Investment in road mobility, which is factored into cost optimization, is based on the total cost of ownership (TCO) of vehicles. However, from an energy system perspective, the cost of powertrains is a more relevant indicator. To provide a proxy for the cost of powertrains in road mobility, we considered internal combustion engine vehicles (ICEVs) as reference vehicles with no additional CAPEX or OPEX, and accounted for the cost of powertrains in BEVs as the difference in TCO between BEVs and the corresponding reference ICEVs. In this sense, a negative OPEX for BEVs indicates net savings in OPEX compared with the reference ICEVs.

The cost of bioresources includes biomass production and transport. The supply of other resources includes the mining of natural gas and coal, whereas the net imports are mainly crude oil. The biorefining cost includes the annualized CAPEX and OPEX of standalone biorefineries for producing fuel, surplus electricity, and base chemicals. The cost of refining includes OPEX and investment in retrofitting existing oil refineries. The power costs include CAPEX and OPEX for the production and transmission of electricity. The CCS cost represents the cost of CO_2 transport and storage. The cost in the demand sector reflects the CAPEX and OPEX of the equipment that delivers energy services.

The system cost in SSP1 (29–35 B$/y) is projected to be lower than in SSP3 (35–40 B$/y), with net savings of 5–6 B$/y. The projected mitigation target in SSP1 is higher than that in SSP3, as is the size of the economy. The cost savings in SSP1 can be explained by the decreased import prices for fossil fuels and improved BECCS value chain conditions. These conditions include the cost and availability of biomass, the efficiency and scalability of bioenergy technologies, and the value of NETs, which can provide low-cost fuels with a negative emission balance that can lower emission mitigation efforts elsewhere in the energy system.

The supply of resources constitutes a major share of system cost (27–52 %). In the absence of significant upstream discoveries and associated investments in exploration, crude oil imports of to operate refineries are likely to expose the energy system to the uncertainty of global oil prices. Net imports reached 14 % of the system cost at an oil price of 13 $/GJ in SSP1 and 38 % at an oil price of 26 $/GJ in SSP3. In this regard, investments in domestic renewable resources can alleviate economic risks and increase self-reliance.

The improvement in agricultural productivity in SSP1 can reduce the cost of biomass supply by up to 8 % compared to SSP3. According to the sensitivity analysis in Section 4, advanced biofuels may offer a more affordable decarbonization alternative to electrification.

3.5. The impact of enhancing the spatial resolution

Figs. 7–12 show that enhancing the spatial resolution of the model resulted in small deviations from the aggregated resolution at the national level. The largest differences between the two resolutions are observed in the SSP2 scenario without retrofitting the oil refineries. Using the aggregated resolution, the supply of biomass is overestimated

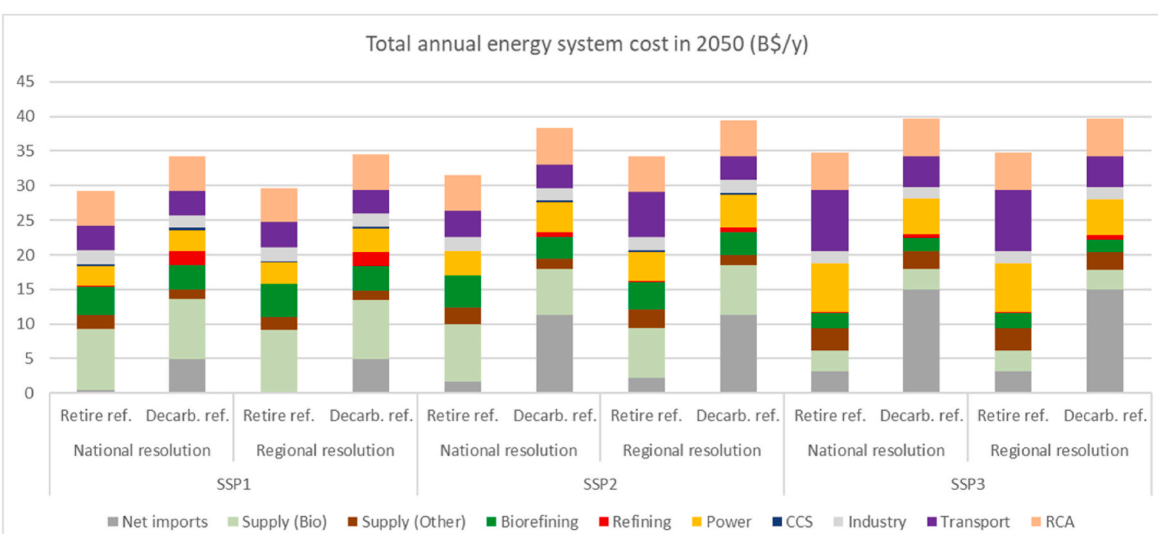

Fig. 12. Total energy system cost by 2050 (B$/y). Net imports: International trade of energy carriers. Supply: domestic extraction of bioresources (bio) and fossil resources (other). Biorefining: CAPEX and OPEX of dedicated biorefineries. Refining: CAPEX and OPEX of retrofitting existing oil refineries and other fossil fuel processing. Power: CAPEX and OPEX of power plants and transmission grid. CCS: CO_2 transport and storage infrastructure. Demand sectors, e.g., industry and transport, include energy equipment that produces final energy services. RCA denotes residential, commercial, agricultural, and other sectors. Transport costs include powertrains relative to reference vehicles and not the whole cost of the fleet.

by 20 % compared with the regionalized model, especially for sugarcane (Fig. 11b). In this case, ethanol was expected to play a greater role in the transport sector (Fig. 8). In contrast, considering the regional differentiation of biomass potential and costs, the transport sector is expected to rely more on electric vehicles and advanced biofuels (Fig. 8) with a higher deployment of CCS (Fig. 10b). Moreover, the system cost in the aggregated model is underestimated by 8 % compared to the spatially detailed model (Fig. 12). These differences show that representing the spatial variability of the biomass cost–supply potential in the model could capture some of the limitations on BECCS value chains, hence limiting their deployment at the expense of costlier alternatives. Another advantage of the spatially disaggregated model is its capacity to highlight the regional conditions for BECCS value chains and the contributions of different regions to the national goal, as discussed in section 3.6.

3.6. Regional distribution of BECCS value chains

The previous sections revealed that the spatially aggregated and disaggregated versions of the model demonstrated comparable results at the national level in terms of energy supply, CO_2 balance, land use, and system costs. Nevertheless, we demonstrate that the regionalized model provides more details on the evolution of BECCS value chains at the regional level. Fig. 13a and b shows the regional distribution of biomass supply per source and CO_2 capture per technology, respectively. The maps focus on SSP1 midcentury projections with retrofitting of oil refineries, where the highest deployment of BECCS is anticipated.

The Andes, Orinoquía, Caribbean, and Pacific regions account for 35 %, 34 %, 19 %, and 11 % of the projected biomass supply, respectively. More than half of the projected biomass supply is concentrated in four departments across three regions: Meta (Orinoquía region), Antioquia and Santander (Andes region), and Cesar (Caribbean region). Together with Valle del Cauca (Pacific region), Magdalena (Caribbean region), Casanare, and Arauca (Orinoquía region), these eight departments hosted 80 % of the projected biomass supply.

Although a previous finding revealed that the Vichada Department can host one-third of the surplus land availability [14] and has the highest biomass supply potential (Fig. 2 b), the corresponding economic potential determined by this demand-driven framework is rather low because of the high cost of biomass and CO_2 transport owing to its remoteness and lack of access to infrastructure. In general, the Orinoquía region has a high potential for the deployment of bioenergy, but its contribution to BECCS is limited by its lack of proximity to geological carbon sinks. Although the Meta Department has a high potential for BECCS, the feasibility of such a deployment should be further investigated in more detail, especially if the required distances for CO_2 transport via pipelines can exceed 500 km.

In terms of BECCS deployment, the Andes, Orinoquía, and Caribbean regions account for 59 %, 18 %, and 17 % of the total economic potential, respectively. The Andes region is expected to prevail because it hosts the largest carbon sink cluster identified in this analysis. The key departments supporting the potential of BECCS are Antioquia and Santander (Andes) for CO_2 sink Cluster 1, Meta (Orinoquía) for sink Cluster 4, and Magdalena and Cesar (Caribbean) for sink Cluster 3. The selection of these departments is determined by their proximity to CO_2 sinks (see the clusters in Fig. 2a) and, hence, the low cost of CO_2 transport, along with an adequate supply of biomass resources.

CO_2 captured from oil refineries is bound to existing sources in the Barrancabermeja and Reficar refineries in Santander and Bolívar, respectively. By contrast, CO_2 capture in sugarcane biorefineries, the dedicated gasification of lignocellulosic biomass, and FT synthesis reflect the dynamic evolution of greenfield BECCS facilities over time.

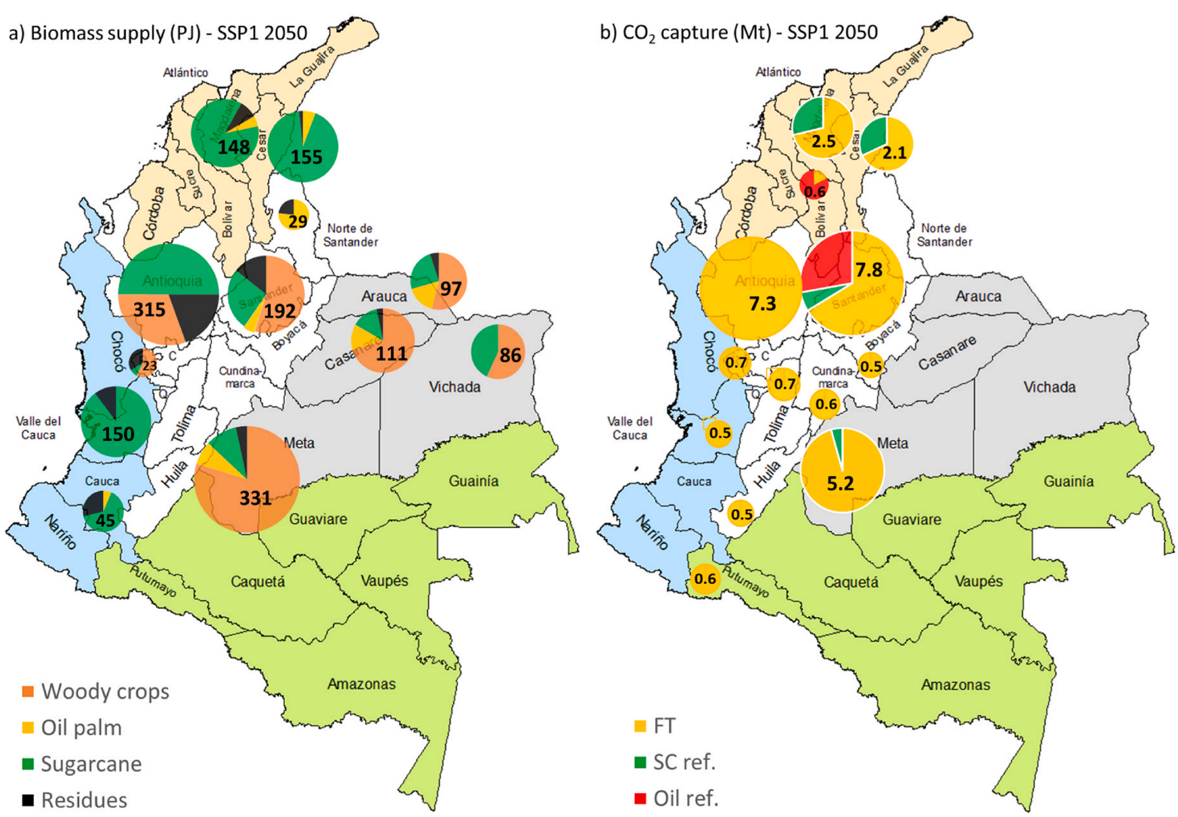

Fig. 13. a) Projected biomass supply by 2050 in the SSP1 scenario (PJ) for modern bioenergy and biochemicals, with and without CCS (top 90 % administrative departments). Sugarcane includes sugar, bagasse, and sugarcane trash. Oil palm includes crude palm oil, fresh fruit bunch, kernel, and shell. The supply of residues includes other agricultural and forestry residues; b) CO_2 capture (Mt) by 2050 for the SSP1 scenario (top 90 % departments) for dedicated Fischer-Tropsch (FT) synthesis, sugarcane (SC) biorefineries, and existing oil refineries.

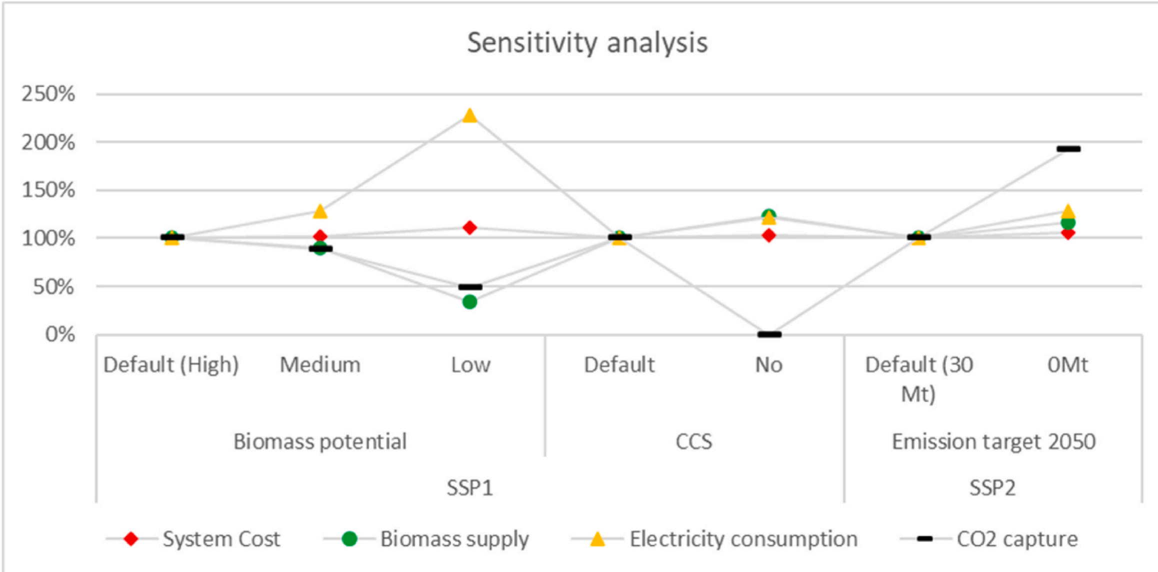

Fig. 14. Results of sensitivity analysis. Change in total discounted system cost, primary biomass supply per year by 2050, total final electricity consumption per year by 2050, and CO_2 capture per year by 2050 relative to the default scenarios. The default SSP1 and SSP2 scenarios correspond to the national resolution scenarios with refinery retirement presented in the results section. For biomass potential, the medium and low scenarios correspond to a case where the supply potentials of SSP2 and SSP3 scenarios would be the limitation for achieving climate neutrality in SSP1 scenario.

4. Discussion

The insights of this study are bound by limitations in terms of scope, methods, and data. The major sources of uncertainty include the supply potential of sustainable biomass, CO_2 storage potential, and technical advancement in low-carbon technologies. Through a narrative-based approach, we structured these uncertainties into three storylines. However, a deeper understanding can be obtained by investigating the overlap between these factors.

A sensitivity analysis explored the limitations of sustainable biomass supply by running the SSP1 scenario with the land availability of the SSP2 and SSP3 scenarios (i.e., medium and low supply potentials, respectively). Moreover, we investigated the capacity to reach a net-zero target in SSP1 without any CCS development. Finally, we investigated the capacity to reach the net-zero target given the technological learning levels in the SSP2 scenario. We traced the impacts of these additional scenarios on primary biomass supply, final consumption of (renewable) electricity, and CO_2 capture rate by 2050, including the total discounted system cost, relative to the default scenarios.

In the absence of land available for bioenergy, the net-zero target could still be achieved using one-third of the biomass supply and half the CDR projected in the default SSP1 scenario (Fig. 14). However, the corresponding demand for electricity is expected to be 2.3 times the default value because of increasing demand in the transport and industrial sectors. Moreover, the corresponding system cost was 11 % higher than the default cost. Without CCS, the net-zero target in SSP1 can also be reached. However, the corresponding demand for biomass and renewable electricity is likely to increase by 23 % and 21 %, respectively, and the system cost will be 3 % higher than that in the default scenario. Finally, attaining a net-zero target at the technological learning levels of SSP2 will require doubling the CO_2 capture rate, 28 % more electricity, and 17 % more biomass supply than the default at a 6 % higher system cost.

These results highlight that the most critical factor in attaining a cost-effective net-zero transition is the capacity to supply sustainable biomass resources. The lower the learning curve of bioenergy technologies, the greater the need for CDR in the long term. The more constraints on BECCS value chains, the higher the requirement for investment in electrification and at a higher cost.

Our results deviate from a previous study [3], which projected a steady demand for oil in all scenarios and a steady role for the BECCS in the power sector in the SSP1 and SSP2 scenarios. Conversely, this study anticipated a higher demand for biofuels at the expense of bioelectricity. In addition to the improved representation of biomass supply, CO_2 transport and storage, and revised mitigation targets, this deviation can be attributed to the representation of the operation of oil refineries, market constraints on advanced technologies and their diffusion to demand sectors. For example, we considered flex-fuel engine vehicles as an option in this study, whereas the diffusion of biofuels in the previous study was constrained by blending limits. Moreover, we extended access to advanced biofuels for marine transport and the commercial, agricultural, and construction sectors. Accordingly, the system cost in SSP1 by 2050 (29–35 B$/y) is lower than the range projected (36–47 B$/y) in Ref. [3], where the present study exhibited less requirement for crude oil imports and more demand for advanced biofuels at the expense of costlier electrification.

Compared to Delgado et al. [58], the projected contribution of biomass is higher in this study and that of solar power is lower. Moreover, Delgado et al. [58] also projected BEVs to play a major role in passenger mobility, while this study projected advanced biofuels to be more competitive. These differences could be explained by the underlying methods and levels of detail. Delgado et al. [58] used a dynamic recursive partial equilibrium model, i.e., GCAM, which balances the energy markets at each time step. By contrast, TIMES identifies optimal solutions to minimize system cost throughout the entire time horizon. Moreover, TIMES–CO– BBE has a more detailed temporal representation of variable renewable energy [4], which could limit the penetration of solar power in the system. TIMES–CO– BBE also has a higher technical detail of bio–based options and multi–output biorefineries feeding multiple sectors. Given the higher level of detail and optimization nature of our model, advanced biofuels could be more competitive option than electrification of mobility.

The scale of BECCS anticipated in this analysis (<0.5 Gt) was well below the maximum cumulative potential for BECCS in Colombia, which Asibor et al. [59] estimated at 2.17 Gt. However, our analysis was limited to the contribution of NETs to the mitigation efforts required until 2050. Future analyses should consider long-term solutions for the remainder of the century.

Considering the shortcomings of these methods, the biomass supply module suffers from the inadequacies of the underlying source [14], which assumes that the biomass supply from surplus land is carbon neutral. Ramirez-Contreras et al. [60] estimated the GHG balance of biomass production on surplus land. Lap et al. [18] introduced dynamic emission-supply curves for biomass into the ESOM. However, this study did not investigate the spatial effects of biomass logistics. Further research can reconcile the spatial details of the biomass supply with improved GHG emissions.

The technology portfolio in this study lacks some emerging low-carbon options, especially in the demand sectors. Future analyses can address the role of (BE)CCS in heavy industries within an ESOM framework, drawing on conclusions from bottom-up studies [8,61]. Further amendments can include technological options for transport and industry and expand the application of hydrogen.

The deployment of BECCS in the potentially biomass-rich Orinoquía region depends on access to carbon sinks. Meta and Casanare include mature oil and gas fields and saline aquifers that can constitute potential sinks. However, the geological storage potential of this region has only been studied qualitatively [62]. Further research can quantify the CO_2 storage potential in the Orinoquía region and its contribution to national emissions mitigation efforts.

The present study addressed CO_2 transport via a simplified network typology, in which each biomass source and carbon sink region were connected via dedicated pipelines. More complex networks that apply clustering principles [8] and the modeling of CCS networks in dynamic ESOMs [11] may serve as inspiration for future studies.

5. Conclusion

This study presents two novel approaches: a) enhance the spatial resolution of a national ESOM to analyze the regional conditions for BECCS value chains; b) evaluate the investment in decarbonization of existing oil refineries within the wider context of GHG mitigation options in the national energy system.

Our results show that modern bioenergy can contribute 0.8–0.9 EJ/y (48–51 %) to the final energy consumption in SSP1 scenario by 2050 at a system cost of 29–35 B$/y. Advanced biofuel production through BECCS can play an important role in achieving thorough decarbonization in Colombia, with a mitigation potential of up to 37–41 % of the cumulative avoided emissions between 2030 and 2050. Although enhancing the spatial detail of a national energy system model did not result in radical deviation from the aggregated model at the national level, the disaggregated model can provide valuable details on the spatiotemporal evolution of BECCS value chains at the regional level.

The Andes and Caribbean regions have the highest potential for BECCS value chains. Although the Orinoquía region has the highest potential for biomass supply, most of this potential is suitable for bioenergy production without CCS because of its lack of proximity to CO_2 sinks and infrastructure. The development of BECCS in this region is likely to be limited to the Meta Department and is subject to long-distance pipelines.

By 2050, the retrofitting of existing oil refineries through mitigation measures, including biomass co-processing and CCS, can be part of a national GHG mitigation pathway, contributing up to 19 % of total biofuel production and 10 % of total CO_2 capture. This could partially alleviate the challenge of building several large-scale advanced biorefineries within a short period of time. However, the persistent demand for crude oil in the absence of sufficient upstream discoveries and corresponding investments can expose the Colombian economy to the burden of oil imports and its vulnerability to international oil prices.

The results of this study have important policy and methodological implications. From a policy perspective, this study has three contributions: First is a proposed link between the national strategic planning of energy and land use systems for a country with promising potential for BECCS value chains. This could be relevant for Colombia and other countries where sectoral climate change mitigation efforts seem to be fragmented. This framework could facilitate identifying opportunities for synergies and setting harmonized goals. Second, regions and value chains are identified where the techno-economic and ecologically sound implementation potential of BECCS value chains is worth investigating in further detail. Further efforts should validate the implementation potential for specific locations and mobilize the policy, resources, and know–how to demonstrate these value chains. Third, the findings demonstrate an analytical framework and scenario analysis tool to facilitate discussion and alignment between the national and regional governments regarding the regional contributions to national climate goals. The tool could also capture the interaction between emission mitigation goals of the oil sector and the wider energy system. This could be used to facilitate a discussion and align the decarbonization visions of both the national government and the oil sector, and the contribution of the latter to the national low-carbon development strategy.

From a methodological perspective, this study presents two approaches: The first is an approach to improving the capacity of energy system models to address the spatiotemporal complexity of the energy transition by combining the temporal enhancement presented in Ref. [4] with the spatial enhancement presented in this study. The second is an approach to soft-link supply-oriented [14] and demand-driven [3] methods for an integrated system analysis assessment of a bio-based economy.

CRediT authorship contribution statement

Ahmed Younis: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Tjerk Lap:** Conceptualization, Methodology, Software, Writing – review & editing. **Edgar Yáñez:** Methodology, Investigation. **Lorena Suarez:** Methodology, Investigation, Writing – review & editing. **René Benders:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **André Faaij:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ahmed Younis reports financial support was provided by Netherlands Enterprise Agency. Edgar Yanez, Lorena Suarez reports a relationship with Ecopetrol that includes: employment.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101232.

Appendix A Comparison between current and previous versions of TIMES–CO–BBE

Table A 1
Comparison between previous versions of TIMES–CO–BBE model and the version used in the present analysis.

	TIMES–CO–BBE v1 [3]	TIMES–CO–BBE v2 [4]	TIMES–CO–BBE v3 (This study)
Time slices	40 (5 daily × 2 weekly x 4 seasonal)	• D12 (3 daily x 4 seasonal) • V36 (3 daily x 4 seasonal x 3 joint probability of load and variable renewables)	V36 (3 daily x 4 seasonal x 3 joint probabilities of load and variable renewables)
Hydroclimatic variability	Baseline (no variability)	• Baseline • Median projection based on CESM1–BGC global circulation model (GCM) • Dry projection based on CNRM–CM5 GCM	Median projection (CESM1–BGC GCM)
Soft-linking	none	Power system simulation model (PowerPlan) [a]	Land–use analysis/biomass resource assessment model
Mitigation target SSP1 by 2050	16 Mt (−80 % relative to 2015)		Carbon neutral (0 Mt)
Biomass supply potential by 2050	• BioLo (0.6–1 EJ) BioHi (7–14 EJ)		• SSP1 (2.3–3.6 EJ) • SSP2 (1–1.9 EJ) • SSP3 (0.3 EJ)
Biomass supply spatial resolution	National (aggregated potential)		Regionalized (32 departments, i.e. administrative divisions)
Biomass logistics cost	Farm gate		Factory gate
Geological CO_2 storage potential	4.3 Gt		• SSP1: 5.4 Gt • SSP2: 1.8 Gt • SSP3: 0.2 Gt
Geological storage spatial resolution	National (aggregated capacity)		• Four regions/basins.
CCS cost	Capture only		Capture, transport, and storage
Existing oil refineries	Constant operation		• Investment in decarbonization pathways • Retirement profile
Existing first-generation biorefineries	Constant operation		Retirement profile
Diffusion of advanced biofuels	Transport sector (Road and aviation)		• Transport sector (Road, aviation and marine) • Commercial and others (e.g. agriculture, construction)
Transport technologies	• Constant location factor 1.3 for Battery Electric Vehicles (BEV) and Hydrogen Fuel Cell Electric Vehicles (FCEV) • Technical limit on Renewable Jet Fuel (RJF) up to 50 %		• Location factor linearly converging to 1.0 b y midcentury for BEV and FCEV • No technical limit on RJF

[an] Energy storage in hydropower dams is represented in TIMES–CO–BBE by static quarterly capacity factors based on actual operation data. In PowerPlan Colombia, energy storage is simulated dynamically considering the reservoir capacities and monthly inflow patterns [4].

Appendix B Regionalized biomass cost-supply approach

Younis et al. [14] used a regionalized two-step approach to determine the cost-supply potential of bioenergy crops and agricultural and forestry residues at the subnational level.

In the first step, they used statistical land-use balancing to project the potential availability of surplus land for biomass in each of the 32 Colombian departments (administrative divisions). Those projections were subject to future scenarios of socio-economic drivers and agricultural productivity by 2030 and 2050. The balancing routine was founded upon a) food, feed, and fiber first principle, b) compliance with the land zoning for agricultural activities and exclusion of protected areas as defined by the Colombian government, and c) redistribution of surpluses and deficits of agricultural production between departments, in resemblance of domestic trade, based on the relative capacities of the departments to resolve these imbalances of production and consumption.

In the second step, they matched the surplus land per department with crop-specific land suitability classes, following the agroecological zoning methodology [63]. This spatially explicit classification was retrieved from the Colombian rural agricultural planning information system (SIPRA) [64], which distinguishes between three classes: very suitable (VS), moderately suitable (MS), and marginally suitable (GS) land. The scope of the assessment included three types of biomass crops, namely sugarcane, oil palm and commercial forestry plantations, as well as agricultural and forestry residues. The results of this approach in terms of data for land availability, energy yield and cost are reported in Supplementary Information spreadsheet.

Appendix C. Calculation steps of non-crop-specific bounds

The non-crop-specific bounds were determined for each region in a given year in three steps (see Table C. 1). First, the upper bound per suitability class for any crop (A_s) was determined by the maximum land availability (LA_{bs}) per suitability class (s) for any crop (b), as per Eq. C. 1. Accordingly, the sum of A_s for each crop constituted the upper bound for all suitability classes per crop (A), as per Eq. C. 2 (see A in Table C. 1).

. Second, the upper bound of total suitable land for any crop (B) was determined by the maximum of the total available suitable land for any crop, as per Eq. C. 3 (see B in Table C. 1). Third, the sum obtained in A was compared to that in B. If the former was higher, the upper bounds per suitability class were scaled down according to the ratio between the sum in A and the total in B, so that the upper bound of the total suitable land of any crop remains intact (see Eq. C. 4).

$$A_s = max[LA_{bs}] \quad \text{Eq. C 1}$$

$$A = \sum_s A_s \quad \text{Eq. C. 2}$$

$$B = max\left[\sum_s LA_b\right] \quad \text{Eq. C 3}$$

$$C_s = \begin{cases} A_s \forall A \leq B \\ A_s \times B/_A \forall A > B \end{cases} \quad \text{Eq. C 4}$$

Table C 1
Calculation steps of non-crop-specific bounds for Colombia as one aggregated region.

Biomass type (*b*) per region (*r*: Colombia)	Suitability class (*s*)	Maximum area [Mha]	
		2030	2050
Woody crops	Very suitable	1730	5171
	Moderately suitable	1502	4185
	Marginally suitable	2437	5891
	Total	5670	15,246
Oil palm	Very suitable	1404	3486
	Moderately suitable	2631	5757
	Marginally suitable	1470	4021
	Total	5505	13,264
Sugarcane	Very suitable	600	1192
	Moderately suitable	1050	1911
	Marginally suitable	1979	3554
	Total	3629	6657
A. Upper bound per suitability class for any crop	Very suitable	1730	5171
	Moderately suitable	2631	5757
	Marginally suitable	2437	5891
	Sum	6798	16,818
B. Upper bound of Total suitable land for any crop		5670	15,246
C. Scaled non-crop-specific upper bounds	Very suitable	1443	4687
	Moderately suitable	2194	5219
	Marginally suitable	2033	5340
	Total	5670	15,246

Appendix D. Descriptive analysis of biomass transport distances and cost

Table D. 1 shows the tortuosity factors (τ) used to calculate the biomass transport distances and cost. A sample of the results of this calculation are summarized below – for each biomass crop type (all suitability classes combined) in SSP1 scenario by 2050. The average transport distance ranged between 21 and 27 km for the three crop types. However, about four departments reported distances higher than 50 km. Some outliers reported distances exceeding 120 kms. These were mainly from Vichada department, which is characterized by being a remote region, with large area, the highest biomass potential, and poor infrastructure.

Considering the biomass transport cost, the average cost ranged between 0.6 and 2.4 $/GJ for the three biomass types (see Figure D. 1). Vichada department exhibited high transport costs for oil palm and eucalyptus >3.4 $/GJ. By contrast, Smeets et al. [65] estimated the cost of transporting lignocellulosic biomass in Europe by truck over a distance of 100 km to range between 0.6 and 1.1 €/GJ.

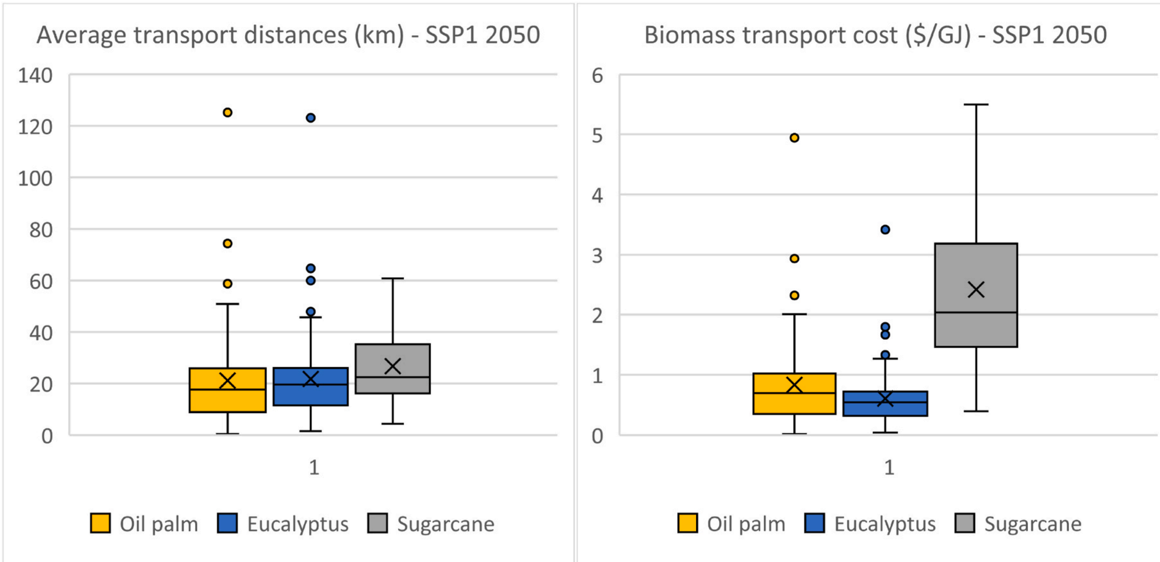

Fig. D 1. Boxplots of the average biomass transport distance (km) and biomass transport cost ($/GJ) for the 32 administrative divisions considered in the analysis in SSP1 scenario by 2050.

Table D 1
Normalized population density and tortuosity factors per administrative region for biomass transport cost.

Departments	*Normalized population density*	*τ SSP1 scenario*	*τ SSP2 scenario*
Amazonas	0.007	2.17	2.72
Antioquia	0.607	1.04	1.30
Arauca	0.024	1.77	2.21
Atlántico	0.231	1.22	1.53
Bolívar	0.197	1.25	1.57
Boyacá	0.114	1.36	1.70
Caldas	0.089	1.42	1.77
Caquetá	0.045	1.60	2.00
Casanare	0.034	1.68	2.10
Cauca	0.128	1.34	1.68
Cesar	0.097	1.41	1.76
Chocó	0.047	1.59	1.99
Córdoba	0.163	1.30	1.62
Cundinamarca	1.000	0.96	1.20
Guainía	0.004	2.40	3.00
Guaviare	0.011	2.04	2.55
Huila	0.109	1.38	1.73
La Guajira	0.097	1.43	1.79
Magdalena	0.118	1.36	1.70
Meta	0.094	1.43	1.79
Nariño	0.164	1.29	1.62
Norte de Santander	0.125	1.35	1.68
Putumayo	0.033	1.69	2.11
Quindío	0.052	1.56	1.94
Risaralda	0.087	1.43	1.78
San Andres[a]	0.007	2.17	2.71
Santander	0.187	1.26	1.57
Sucre	0.079	1.45	1.82
Tolima	0.127	1.34	1.67
Valle del Cauca	0.431	1.10	1.38
Vaupes	0.004	2.38	2.97
Vichada	0.007	2.19	2.74

Appendix E. Review of Geological CO_2 storage in Colombia

To the best of our knowledge, no comprehensive assessment of the geological storage potential of CO_2 in Colombia has been published. First order estimates were reported in studies of global or regional scope [36,37]. However, the divergence of these figures reflects their high uncertainty (see Figure E. 1). Moreover, the high level of aggregation and/or lack of transparency of these estimates and underlying methods makes them difficult to be compared or used for detailed analysis.

Godec et al. [36] assessed the global CO_2 storage potential through conventional and enhanced recovery of coalbed methane from coal seams (CBM and ECBM, respectively). The authors estimated the potential of (E)CBM and the associated theoretical CO_2 storage potential in Colombian basins at

0.3 Tcm and 2.1 Gt, respectively. These figures corresponded to <0.5 % of the global potential estimated in the same study.

Postic [37] used a global multi-regional energy system model to analyze climate change mitigation options in Latin America and Caribbean countries, where Colombia was represented by a separate region. The author reported the geological CO_2 storage potential in CBM, deep saline aquifers, enhanced oil recovery (EOR), and depleted oil and gas fields. The total potential in Colombia was estimated at 6.5 Gt, which was scaled down from more aggregated estimates [66].

Mariño-Martínez and Moreno-Reyes [62] identified Carbonera formation in Colombia as a suitable location for CO_2 storage; however, the approach of that study was rather qualitative.

Yáñez et al. [8] and Cardozo et al. [26] presented two of the most recent and detailed geological storage assessments. Yáñez et al. [8] conducted a bottom-up techno-economic assessment of CO_2 source-sink matching and infrastructure development in Colombia. The authors identified four main geographical clusters with feasible economic potential for CCS projects (Fig. 2a). However, the scope of that study was limited to optimizing enhanced oil recovery (EOR), which limited the technical potential to 500 Mt of CO_2 and the economic potential 250 Mt when matched to CO_2 sources (see Figure E. 1). Note that the study focused on preselected CO_2 sources and hence excluded the dynamic evolution of the energy system.

Cardozo et al. [26] presented one of the few attempts to estimate the CO_2 storage potential in Colombia at a regional scale. The study area of that analysis covered the central sector of the Middle Magdalena Basin (MMB), which falls within cluster 1 as defined by Yáñez et al. [8] (Fig. 2a). This selection was based on the proximity of the basin to existing oil and gas infrastructure and emission sources such as the Barrancabermeja refinery and cement plants. Moreover, it is a mature basin where most of the oil and gas fields are located, and hence extensive subsurface information is available. Further, the potential for commercial EOR in the basin could offset the cost.

The calculation was based on Bachu et al. [38] method for oil and gas reservoirs (see Eq. (E. 1)), using data from 70 wells and seismic interpretation of more than 4000 km of 2D seismic. The authors estimated a theoretical CO_2 storage potential in unit T2 (Mugrosa formation) of about 9 Gt.

$$M_{CO_2t} = \rho_{CO_2r}\left[R_f A h \varphi (1 - S_W)\right] \tag{E 1}$$

where M_{CO2t} is the theoretical mass storage capacity for CO_2 storage in a reservoir at in situ conditions, ρ_{CO2r} is the CO_2 density at reservoir conditions, R_f is the recovery factor, A, h, φ, and S_w are reservoir area, thickness, porosity, and water saturation, respectively. In contrast to Bachu et al. [38], the volumes of injected and produced water were neglected because water injection has not been implemented for most of the fields within the study area [26].

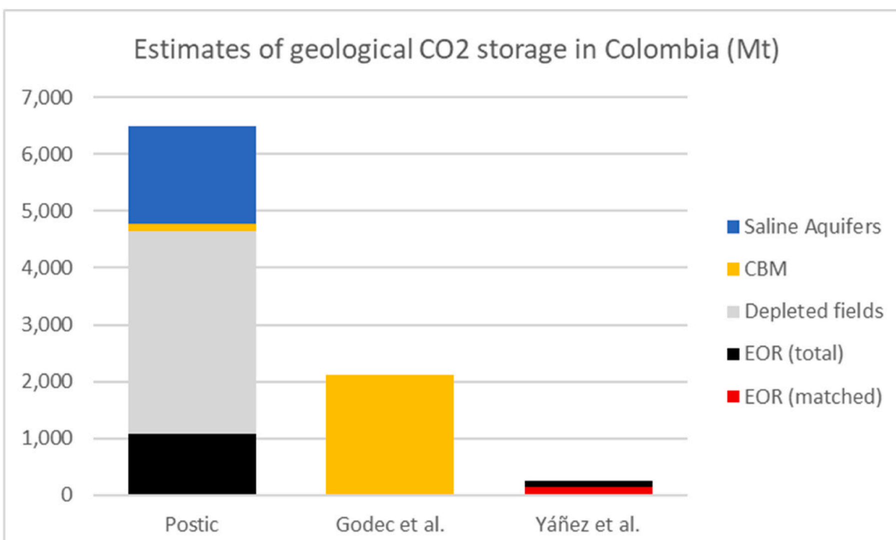

Fig. E 1. Estimates of geological storage potential of CO_2 in Colombia [8,36,37].

Appendix F. CO_2 transport distances and cost

Table F 1
CO2 transport distances via pipelines (km) and associated cost ($/t) per administrative region per SSP scenario.

Departments	*Distance*	Cost SSP1	Cost SSP2	Cost SSP3
Amazonas	1748	n/a	n/a	n/a
Antioquia	395	2.96	5.57	7.94
Arauca	599	4.49	8.40	12.05
Atlántico	269	2.02	3.82	5.40
Bolívar	123	0.92	1.77	2.46
Boyacá	346	2.60	4.89	6.95
Caldas	379	2.84	5.35	7.61
Caquetá	656	4.92	9.20	13.20
Casanare	634	4.76	8.89	12.75
Cauca	378	2.84	5.33	7.59
Cesar	247	1.85	3.51	4.95
Chocó	818	n/a	n/a	n/a

(continued on next page)

Table F 1 (*continued*)

Departments	*Distance*	Cost SSP1	Cost SSP2	Cost SSP3
Córdoba	300	2.25	4.25	6.02
Cundinamarca	268	2.01	3.80	5.38
Guainía	1468	n/a	n/a	n/a
Guaviare	782	5.86	10.95	15.74
Huila	137	1.03	1.97	2.74
La Guajira	511	3.83	7.18	10.27
Magdalena	152	1.14	2.19	3.04
Meta	513	3.85	7.21	10.32
Nariño	372	2.79	5.25	7.47
Norte de Santander	318	2.39	4.50	6.38
Putumayo	313	2.35	4.43	6.29
Quindío	226	1.70	3.22	4.53
Risaralda	317	2.38	4.48	6.36
San Andres	n/a	n/a	n/a	n/a
Santander	130	0.98	1.87	2.60
Sucre	112	0.84	$1.61	2.24
Tolima	120	0.90	1.73	2.40
Valle del Cauca	367	2.75	5.18	7.37
Vaupes	1236	n/a	n/a	n/a
Vichada	856	6.00	11.20	16.10
National average	305	2.29	4.32	6.13

Appendix G. Parametrization of oil refineries

Typically, an oil refinery is represented in TIMES model by a process linked to input and output commodities (see Fig. 6). A distinction is made between the main flows, such as crude feedstock that is directly converted into main products, and the auxiliary flows, such as inputs that supply energy to the production process, or outputs such as captured CO_2 emissions.

For each refinery, the installed capacity describes the maximum processing capacity of crude oil input. The utilization rate indicates the actual throughput in a given year, in relation to the installed capacity. The conversion rate represents the ratio between the sum of main outputs and that of main inputs. The total outputs and total inputs are broken down into multiple products via shares that add up to one. Rate and share parameters can be expressed in lower and upper ranges to reflect the operational flexibility of the refinery. An economic lifetime or retirement profile is used to project the installed capacity throughout the time horizon of the analysis. Variable operational and maintenance cost (VAROM) reflects the cost of refining per unit input of crude oil. For the scope of this analysis, fixed operational and maintenance cost (FIXOM) per unit of capacity is used to capture the annualized investment cost in upgrading the refinery through different mitigation technologies (see section 2.5.2).

The refinery sector in TIMES–CO–BBE is represented by Barrancabermeja and Reficar refineries, which represent 62 % and 37 % of the 405 thousand barrel per day refining capacity in Colombia, respectively [67]. Unless otherwise specified, we modelled each refinery as a single process, without detailed distinction between the operation of different units. Similar to Younis et al. [3], the inputs and outputs of the refinery sector was calibrated to the national energy balance in the base year 2015 [30]. As such, commodities reported in the national energy balance, like natural gas, were included as auxiliary inputs. On the other hand, fuels produced and consumed within the refinery were implicitly considered, such as hydrogen. The production of base chemicals was modelled by a separate process which links the non-energy products from the energy balance to the production of olefins required for the downstream chemical industry [3]. In this study, we introduced more operational distinction between the two refineries based on recent data from Ecopetrol reports [67–69], as summarized in Table G. 1.

Table G 1
Standard technoeconomic parameters for the largest two oil refineries in Colombia.

Refinery	Barrancabermeja	Reficar
Installed capacity [a] [PJ]	562	337
Utilization rate [b] [%]	71–92	78–95
Conversion rate [c] [%]	75–85	75–85
Breakdown of oil products [d] [%]		
• Diesel	19–30	36–58
• Gasoline	27–30	31–34
• Kerosene/Jet fuel	7–11	5–6
• Fuel oil	13–29	2–22
• LPG	5–6	3–5
• Non-energy	2–3	0–2
• Other	5–16	<1
Specific energy consumption (SEC) [e] [MJ/GJ]	73	73
• Natural gas	55	55
• LPG	18	18
Variable Operational cost (VAROM) [f] [$\$_{2015}$/GJ]	0.7	0.7

[a] The effective crude oil processing capacity included an allocation of the capacity of other refineries (1 %) to the two refineries represented in the model based on their weighted average contribution to the total [68]. The capacity was expressed on energy basis using a conversion factor of 6.09 GJ/bbl crude oil [30].

[b] The utilization rate represents the actual throughput in proportion to the nameplate capacity. The utilization rates were adapted from Ecopetrol annual reports [67,69]. Note that the utilization rate in Reficar was exceptionally low (7 %) in 2015 because of an expansion project. In that year, the total throughput of all refineries was estimated at 542 PJ [30], while our estimated throughput for all refineries

under normal operation conditions of Reficar ranged between 663 and 837 PJ.

[c] The conversion rate (amount of oil products with respect to crude oil throughput) in the base year was estimated in energy terms at 75 % based on the national energy balance [30]. Standard conversion rate beyond the base year was taken as 86 % based on [22]. The latter is more in line with the rates reported by Ecopetrol [67,69].

[d] The shares of oil products were adapted from recent reports issued by Ecopetrol [67,69].

[e] SEC of the refinery sector was retrieved from the base year energy balance and assumed the same for both refineries [30]. This value is lower than the estimate of Yáñez et al. [23] for Barrancabermeja refinery (85 MJ/GJ). This could be explained by differences in system boundaries and operational assumptions.

[f] Variable refining cost was based on Yáñez et al. [22] ($€_{2018}$/bbl 5) applying relevant standardization factors.

References

[1] IPCC, Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in: The Context of Strengthening the Global Response to the Threat of Climate Change, 2018.

[2] S.V. Hanssen, V. Daioglou, Z.J.N. Steinmann, J.C. Doelman, D.P. Van Vuuren, M.A. J. Huijbregts, The climate change mitigation potential of bioenergy with carbon capture and storage, Nat. Clim. Change 10 (2020) 1023–1029, https://doi.org/10.1038/s41558-020-0885-y.

[3] A. Younis, R. Benders, R. Delgado, T. Lap, M. Gonzalez-Salazar, A. Cadena, et al., System analysis of the bio-based economy in Colombia: a bottom-up energy system model and scenario analysis, Biofuels, Bioprod Biorefining 15 (2021) 481–501, https://doi.org/10.1002/bbb.2167.

[4] A. Younis, R. Benders, J. Ramírez, M. de Wolf, A. Faaij, Scrutinizing the intermittency of renewable energy in a long-term planning model via combining direct integration and soft-linking methods for Colombia's power system, Energies 15 (2022) 7604, https://doi.org/10.3390/en15207604.

[5] E. Baik, D.L. Sanchez, P.A. Turner, K.J. Mach, C.B. Field, S.M. Benson, Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States, Proc. Natl. Acad. Sci. USA 115 (2018) 3290–3295, https://doi.org/10.1073/pnas.1720338115.

[6] P.A. Turner, K.J. Mach, D.B. Lobell, S.M. Benson, E. Baik, D.L. Sanchez, et al., The global overlap of bioenergy and carbon sequestration potential, Clim. Change 148 (2018) 1–10, https://doi.org/10.1007/s10584-018-2189-z.

[7] K. Li, S. Shen, J.-L. Fan, M. Xu, X. Zhang, The role of carbon capture, utilization and storage in realizing China's carbon neutrality: a source-sink matching analysis for existing coal-fired power plants, Resour. Conserv. Recycl. 178 (2022), 106070, https://doi.org/10.1016/j.resconrec.2021.106070.

[8] E. Yáñez, A. Ramírez, V. Núñez-López, E. Castillo, A. Faaij, 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 (2020), 102938, https://doi.org/10.1016/j.ijggc.2019.102938.

[9] M. Freer, C. Gough, A. Welfle, A. Lea-Langton, Carbon optimal bioenergy with carbon capture and storage supply chain modelling: how far is too far? Sustain. Energy Technol. Assessments 47 (2021), 101406 https://doi.org/10.1016/j.seta.2021.101406.

[10] M. Freer, C. Gough, A. Welfle, A. Lea-Langton, Putting bioenergy with carbon capture and storage in a spatial context: what should go where? Front Clim 4 (2022) 1–21, https://doi.org/10.3389/fclim.2022.826982.

[11] M. van den Broek, E. Brederode, A. Ramírez, L. Kramers, M. van der Kuip, T. Wildenborg, et al., Designing a cost-effective CO2 storage infrastructure using a GIS based linear optimization energy model, Environ. Model. Software 25 (2010) 1754–1768, https://doi.org/10.1016/j.envsoft.2010.06.015.

[12] H. Tang, S. Zhang, W. Chen, Assessing representative CCUS layouts for China's power sector toward carbon neutrality, Environ. Sci. Technol. 55 (2021) 11225–11235, https://doi.org/10.1021/acs.est.1c03401.

[13] H. Tang, W. Chen, S. Zhang, Q. Zhang, China's multi-sector-shared CCUS networks in a carbon-neutral vision, iScience 26 (2023), 106347, https://doi.org/10.1016/j.isci.2023.106347.

[14] A. Younis, Y. Trujillo, R. Benders, A. Faaij, Regionalized cost supply potential of bioenergy crops and residues in Colombia: a hybrid statistical balance and land suitability allocation scenario analysis, Biomass Bioenergy 150 (2021), 106096, https://doi.org/10.1016/j.biombioe.2021.106096.

[15] R. Martínez-Gordón, G. Morales-España, J. Sijm, A.P.C. Faaij, A review of the role of spatial resolution in energy systems modelling: lessons learned and applicability to the North Sea region, Renew. Sustain. Energy Rev. 141 (2021), 110857, https://doi.org/10.1016/j.rser.2021.110857.

[16] V. Aryanpur, B. O'Gallachoir, H. Dai, W. Chen, J. Glynn, A review of spatial resolution and regionalisation in national-scale energy systems optimisation models, Energy Strategy Rev. 37 (2021), 100702, https://doi.org/10.1016/j.esr.2021.100702.

[17] N. Forsell, G. Guerassimoff, D. Athanassiadis, A. Thivolle-Casat, D. Lorne, G. Millet, et al., Sub-national TIMES model for analyzing future regional use of biomass and biofuels in Sweden and France, Renew. Energy 60 (2013) 415–426, https://doi.org/10.1016/j.renene.2013.05.015.

[18] T. Lap, V. Daioglou, R. Benders, F. van der Hilst, A. Faaij, The impact of LUC emissions on the potential of bioenergy as climate change mitigation option for a Brazilian low-carbon energy system, GCB Bioenergy (2021), https://doi.org/10.1111/gcbb.12901.

[19] T. Lap, R. Benders, F. van der Hilst, A. Faaij, BECCS as climate mitigation option in a Brazilian low carbon energy system: estimating potential and effect of gigatonne scale CO2 storage, Int. J. Greenh. Gas Control 128 (2023), 103945, https://doi.org/10.1016/j.ijggc.2023.103945.

[20] C. Bergman-Fonte, G. Nascimento da Silva, M. Império, R. Draeger, L. Coutinho, B. S.L. Cunha, et al., Repurposing, co-processing and greenhouse gas mitigation – the Brazilian refining sector under deep decarbonization scenarios: a case study using integrated assessment modeling, Energy 282 (2023), 128435, https://doi.org/10.1016/j.energy.2023.128435.

[21] E. Yanez, Greenhouse Gas Mitigation Strategies for the Oil Industry - Bottom-Up System Analysis on the Transition of the Colombian Oil Production and Refining Sector, [Thesis fully internal (DIV), University of Groningen]. University of Groningen, 2021, https://doi.org/10.33612/diss.158071720.

[22] É. Yáñez, H. Meerman, A. Ramírez, É. Castillo, A. Faaij, Assessing bio-oil co-processing routes as CO2 mitigation strategies in oil refineries, Biofuels, Bioprod Biorefining 15 (2021) 305–333, https://doi.org/10.1002/bbb.2163.

[23] E. Yáñez, A. Ramírez, A. Uribe, E. Castillo, A. Faaij, Unravelling the potential of energy efficiency in the Colombian oil industry, J. Clean. Prod. 176 (2018) 604–628, https://doi.org/10.1016/j.jclepro.2017.12.085.

[24] É. Yáñez, H. Meerman, A. Ramírez, É. Castillo, A. Faaij, Fully integrated CO2 mitigation strategy for an existing refinery: a case study in Colombia, Appl. Energy 313 (2022), 118771, https://doi.org/10.1016/j.apenergy.2022.118771.

[25] M. Wright, R.C. Brown, Establishing the optimal sizes of different kinds of biorefineries, Biofuels, Bioprod Biorefining 1 (2007) 191–200, https://doi.org/10.1002/bbb.25.

[26] C. Cardozo, E. López, L. Suárez, C. Patiño, A. Ortiz-Karpf, Estimation of Geological Storage Capacity of CO2: Regional Pilot in the Central Sector of the Middle Magdalena Valley Basin. ICE 2022 Cart. 19-22 April 2022, Cent. Conv. Cart. India., 2022.

[27] E. Smith, J. Morris, H. Kheshgi, G. Teletzke, H. Herzog, S. Paltsev, The cost of CO2 transport and storage in global integrated assessment modeling, Int. J. Greenh. Gas Control 109 (2021), 103367, https://doi.org/10.1016/j.ijggc.2021.103367.

[28] B.C. O'Neill, E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, et al., A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Clim. Change 122 (2014) 387–400, https://doi.org/10.1007/s10584-013-0905-2.

[29] R. Loulou, U. Remme, A. Kanudia, A. Lehtila, G. Goldstein, Documentation for the TIMES Model Part I, 2005.

[30] UPME. Balance Energético Colombiano - BECO 1975 - 2015: Ver.12 Rev.03 2017. http://www1.upme.gov.co/InformacionCifras/Paginas/BalanceEnergetico.aspx (accessed December 10, 2018)..

[31] A. Mukherjee, P. Bruijnincx, M. Junginger, Techno-economic competitiveness of renewable fuel alternatives in the marine sector, Renew. Sustain. Energy Rev. 174 (2023), 113127, https://doi.org/10.1016/j.rser.2022.113127.

[32] C.E. Jimenez Morales, Palm Oil Biodiesel in Colombia, a GIS Based Exploratory Study on its Potential and Scenarios for the Future, Master thesis, Utrecht University, 2012.

[33] M.A. Gonzalez-Salazar, M. Morini, M. Pinelli, P.R. Spina, M. Venturini, M. Finkenrath, et al., Methodology for biomass energy potential estimation: projections of future potential in Colombia, Renew. Energy 69 (2014) 488–505, https://doi.org/10.1016/j.renene.2014.03.056.

[34] B. Batidzirai, E.M.W. Smeets, A.P.C. Faaij, Harmonising bioenergy resource potentials - methodological lessons from review of state of the art bioenergy potential assessments, Renew. Sustain. Energy Rev. 16 (2012) 6598–6630, https://doi.org/10.1016/j.rser.2012.09.002.

[35] V. Daioglou, E. Stehfest, B. Wicke, A. Faaij, D.P. van Vuuren, Projections of the availability and cost of residues from agriculture and forestry, GCB Bioenergy 8 (2016) 456–470, https://doi.org/10.1111/gcbb.12285.

[36] M.L. Godec, H. Jonsson, L. Basava-Reddi, Potential global implications of gas production from shales and coal for geological CO2 storage, Energy Proc. 37 (2013) 6656–6666, https://doi.org/10.1016/j.egypro.2013.06.598.

[37] S. Postic, Long-term Energy Prospective Modeling for South America – Application to International Climate Negotiations, MINES ParisTech, 2015.

[38] S. Bachu, D. Bonijoly, J. Bradshaw, R. Burruss, S. Holloway, N.P. Christensen, et al., CO2 storage capacity estimation: methodology and gaps, Int. J. Greenh. Gas Control 1 (2007) 430–443, https://doi.org/10.1016/S1750-5836(07)00086-2.

[39] S.T. McCoy, The Economics of CO2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs, Carnegie Mellon University, 2008.

[40] K. Balaji, Carbon-Dioxide Pipeline Infrastructure Route Optimization and Network Modeling for Carbon Capture Storage and Utilization, University of North Dakota, 2020.
[41] M. van der Spek, S. Roussanaly, E.S. Rubin, Best practices and recent advances in CCS cost engineering and economic analysis, Int. J. Greenh. Gas Control 83 (2019) 91–104, https://doi.org/10.1016/j.ijggc.2019.02.006.
[42] S.J. Gerssen-Gondelach, D. Saygin, B. Wicke, M.K. Patel, A.P.C. Faaij, Competing uses of biomass: assessment and comparison of the performance of bio-based heat, power, fuels and materials, Renew. Sustain. Energy Rev. 40 (2014) 964–998, https://doi.org/10.1016/j.rser.2014.07.197.
[43] J.C. Meerman, M.M.J. Knoope, A. Ramírez, W.C. Turkenburg, A.P.C. Faaij, Technical and economic prospects of coal- and biomass-fired integrated gasification facilities equipped with CCS over time, Int. J. Greenh. Gas Control 16 (2013) 311–323, https://doi.org/10.1016/j.ijggc.2013.01.051.
[44] C.M. Alves, M. Valk, S. de Jong, A. Bonomi, L.A.M. van der Wielen, S.I. Mussatto, Techno-economic assessment of biorefinery technologies for aviation biofuels supply chains in Brazil, Biofuels, Bioprod Biorefining 11 (2017) 67–91, https://doi.org/10.1002/bbb.1711.
[45] O.P.R. van Vliet, A.P.C. Faaij, W.C. Turkenburg, Fischer–Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis, Energy Convers. Manag. 50 (2009) 855–876, https://doi.org/10.1016/j.enconman.2009.01.008.
[46] A. Bonomi, O. Cavalett, M.P. da Cunha, M.A.P. Lima, in: A. Bonomi, O. Cavalett, M. Pereira da Cunha, M.A.P. Lima (Eds.), The Virtual Sugarcane Biorefinery Concept, Springer International Publishing, Cham, 2016, pp. 5–11, https://doi.org/10.1007/978-3-319-26045-7_2.
[47] M.O.S. Dias, M. Modesto, A.V. Ensinas, S.A. Nebra, R.M. Filho, C.E.V. Rossell, Improving bioethanol production from sugarcane: evaluation of distillation, thermal integration and cogeneration systems, Energy 36 (2011) 3691–3703, https://doi.org/10.1016/j.energy.2010.09.024.
[48] M.O.S. Dias, T.L. Junqueira, O. Cavalett, M.P. Cunha, C.D.F. Jesus, C.E.V. Rossell, et al., Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash, Bioresour. Technol. 103 (2012) 152–161, https://doi.org/10.1016/j.biortech.2011.09.120.
[49] A. de Vita, I. Kielichowska, P. Mandatowa, P. Capros, E. Dimopoulou, S. Evangelopoulou, et al., ASSET Project: Technology Pathways in Decarbonisation Scenarios, 2018.
[50] P. Bolat, C. Thiel, Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: techno-economic inputs for hydrogen production pathways, Int. J. Hydrogen Energy 39 (2014) 8898–8925, https://doi.org/10.1016/j.ijhydene.2014.03.170.
[51] K. Riahi, D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, et al., The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Global Environ. Change 42 (2017) 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.
[52] S. Kc, W. Lutz, The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100, Global Environ. Change 42 (2017) 181–192, https://doi.org/10.1016/j.gloenvcha.2014.06.004.
[53] Gobierno de Colombia, Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC), 2020. Bogotá D.C., Colombia.
[54] F. Tayari, S. Blumsack, R.T. Johns, S. Tham, S. Ghosh, Techno-economic assessment of reservoir heterogeneity and permeability variation on economic value of enhanced oil recovery by gas and foam flooding, J. Pet. Sci. Eng. 166 (2018) 913–923, https://doi.org/10.1016/j.petrol.2018.03.053.
[55] Zep, The Costs of CO2 Storage: Post-demonstration CCS in the EU, 2011. Brussels, Belgium.
[56] A. Kanudia, N. Berghout, D. Boavida, M. van den Broek, H. Cabal, J. Carneiro, et al., CCS infrastructure development scenarios for the integrated iberian peninsula and Morocco energy system, Energy Proc. 37 (2013) 2645–2656, https://doi.org/10.1016/j.egypro.2013.06.149.
[57] I. Tsiropoulos, D. Tarvydas, A. Zucker, Cost Development of Low Carbon Energy Technologies - Scenario-Based Cost Trajectories to 2050. 2017 Editi, Publications Office of the European Union, Luxembourg, 2018, https://doi.org/10.2760/23266.
[58] R. Delgado, T.B. Wild, R. Arguello, L. Clarke, G. Romero, Options for Colombia's mid-century deep decarbonization strategy, Energy Strategy Rev. 32 (2020), 100525, https://doi.org/10.1016/j.esr.2020.100525.
[59] J.O. Asibor, P.T. Clough, S.A. Nabavi, V. Manovic, A country-level assessment of the deployment potential of greenhouse gas removal technologies, J. Environ. Manag. 323 (2022), 116211, https://doi.org/10.1016/j.jenvman.2022.116211.
[60] N.E. Ramírez-Contreras, D. Munar-Florez, F. van der Hilst, J.C. Espinosa, Ocampo-Duran Á, J. Ruíz-Delgado, et al., Ghg balance of agricultural intensification & bioenergy production in the orinoquia region, Colombia, Land 10 (2021) 289, https://doi.org/10.3390/land10030289.
[61] F. Yang, J.C. Meerman, A.P.C. Faaij, Carbon capture and biomass in industry: a techno-economic analysis and comparison of negative emission options, Renew. Sustain. Energy Rev. 144 (2021), 111028, https://doi.org/10.1016/j.rser.2021.111028.
[62] J.E. Mariño-Martínez, L.E. Moreno-Reyes, Posibilidades de captura y almacenamiento geológico de CO2 (CCS) en Colombia – caso Tauramena (Casanare), Bol. Geol. 40 (2018) 109–122, https://doi.org/10.18273/revbol.v40n1-2018007.
[63] G. Fischer, H. van Velthuizen, F.O. Nachtergaele, Global Agro-Ecological Zones Assessment: Methodology and Results, Interim Report. Laxenburg, Austria, 2000.
[64] UPRA. Zonificación de aptitud para los cultivos maíz, palma de aceite y plantaciones comerciales en Colombia, a escala 1:100.000 2019. https://sipra.upra.gov.co/(accessed May 23, 2019)..
[65] E.M.W. Smeets, I.M. Lewandowski, A.P.C. Faaij, The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting, Renew. Sustain. Energy Rev. 13 (2009) 1230–1245, https://doi.org/10.1016/j.rser.2008.09.006.
[66] O. Ricci, S. Selosse, Global and regional potential for bioelectricity with carbon capture and storage, Energy Pol. 52 (2013) 689–698, https://doi.org/10.1016/j.enpol.2012.10.027.
[67] Ecopetrol, Annual Report on Form 20-F 2016, 2017. Bogotá, Colombia.
[68] Ecopetrol, Material Information: 2021 Results, 2022. Bogotá D.C., Colombia.
[69] Ecopetrol, Annual Report on Form 20-F 2021, 2022. https://www.sec.gov/ix?doc=/Archives/edgar/data/0001444406/000141057822001007/ec-20211231x20f.htm#a371Refining_622776. (Accessed 12 August 2022).