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BECCS as climate mitigation option in a Brazilian low carbon energy system: Estimating potential and effect of gigatonne scale CO_2 storage

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ABSTRACT

Bioenergy with carbon capture and storage (BECCS) can lead to negative emissions, and is seen as an important option to decarbonize energy systems. Its potential decarbonization contribution depends on low-carbon resource availability, its ability to meet end-use demand and the geological storage potential to safely trap CO_2. Here an energy system model is used to assess the BECCS decarbonization potential in Brazil, considering uncertainty in low-carbon biomass resources, and storage potential, injection rates and costs of CO_2 storage, assessed in eight scenarios. A spatial explicit analysis is done to make improved estimates on the storage potential, injection rates, and costs for CO_2 storage in the Rio Bonito saline aquifer of the Paraná basin.

Although there are large differences in storage potential (12–117 Gt CO_2) and costs (on average 5–15 \$/t CO_2), the accumulated volume of CO_2 stored between 2010 and 2050 is 2.9 Gt CO_2 for all scenarios, with injection rates around 240 Mt CO_2 in 2050. This shows that BECCS is a cost-competitive option to decarbonize the Brazilian energy system, even under pessimistic estimates of CO_2 storage potential and costs, and low biomass availability. The cheapest sink locations are selected, in the high development scenario. When CCS development is low, injection rates are the limiting factor. Locations are selected with the highest injection rates, even though sometimes more expensive. When CO_2 storage is limited, total system costs increase, mainly because decarbonization of the industry and freight transport sector relies on more expensive decarbonization options such as green hydrogen.

1. Introduction

Carbon capture and storage from bioenergy (BECCS) is seen as an important option to reduce net atmospheric greenhouse gas emissions (GHG) and mitigate global warming (IPCC 2018). It is "likely necessary" that BECCS is needed to achieve net-zero energy systems, mainly because its potential for carbon dioxide removal (Clarke et al., 2022), but also for baseload power generation to stabilize power grids that need to deal with high shares of wind- and solar energy (Mac Dowell et al., 2017), and for low-carbon transport fuels and hydrogen production (Muratori et al., 2020). Brazil is seen as one of the most promising countries where BECCS can be deployed since it has large biomass potential (IRENA 2014; Welfle 2017), though, this potential is largely variable (Lap et al., 2022), and there are already pilot-scale BECCS projects in the sugarcane industry (Chum et al., 2011). Globally, Brazil is considered as one of the countries with the highest storage potential for CO_2 in the subsurface (CCS Institute 2016). In 2020 Brazil emitted approximately 2 Gt $CO_{2\text{-eq.}}$ of which approximately 75% is linked to land-use change (LUC) and agriculture (Potenza et al., 2021). GHG emissions in the energy sector mostly relate to the combustion of oil in the transport sector. The emission intensity of the electricity sector is relatively low, because renewables (most notably hydropower) produce 70% of all generated electricity (EPE 2020). Preventing LUC, and re- and/or afforestation in Brazil can contribute significantly to GHG mitigation. Nonetheless, providing low-carbon energy to an economy with growing needs for energy seems inevitable and BECCS can play a dominant role.

While global decarbonization pathways to limit global warming to (well-below) 2 °C show that subsurface storage of CO_2 should reach 6 Gt/y towards 2050 (International Energy Agency 2014b), the accumulated level of captured CO_2 in all running CCS projects until 2017 was estimated to be 30 Mt (IPCC 2018). This requires a substantial effort to

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upscale CCS projects (Minx et al., 2017), and Brazil does have the potential to store gigatonnes of CO_2 in the subsurface. This, combined with the large biomass potential, results in a large potential for BECCS as a negative emission technology within Brazil.

However, apart from (BE)CCS there are plenty of other technologies that can contribute to mitigating global warming, with the substitution of fossil fuels by renewable alternatives as the most apparent option. Biomass is also an option to substitute fossil fuels to meet the demand for energy services. The deployment of all GHG mitigation technologies is determined by its supply potential, the costs to reduce carbon dioxide from the atmosphere, and the ability to meet demand for energy service. This leads to the question: what is the role of bioenergy with CCS considering competition for biomass, and competition with other GHG mitigation technologies?

To assess the contribution of BECCS as GHG mitigation option in low-carbon trajectories, its complete chain should be considered: capture, transport and storage. There is abundant scientific literature available on the abatement potential from (BE)CCS (e.g. for power production (Woolf et al., 2016), for ethanol production (Moreira et al., 2016), or the negative emission potential (Sanchez et al., 2018)), but the majority analyzes the BECCS abatement potential on the costs to mitigate CO_2. However, the economic competition with other CDR technologies, and the competition for biomass to meet the demand for energy services is often not considered as it requires an energy system analysis with a detailed representation of a BECCS chain. Selosse and Ricci (2017) and Butnar et al. (2020) assess the deployment of CCS within an energy system model. However, they use global models that do not specifically use spatio-temporal biomass supply potential, including associated LUC related GHG emissions and costs which is essential for assessing the potential of BECCS in low-carbon energy systems (Hanssen et al., 2020). Other studies such as Hanssen et al. (2020) and Bauer et al. (2018) assess BECCS within integrated assessment models (IAMs). Those models show the BECCS potential in competition with other biomass end-uses and CDRs with different BECCS technologies. However, these IAMs operate on a global scale. This scale requires aggregation of data (van Vuuren et al. 2009) and can therefore lead to over- or underestimation of certain results. The potential for CCS in Brazil is for instance classified as the 'theoretical' potential (CCS Institute 2016).While this estimate is the most comprehensive review on geological storage potential in Brazil, this is likely to be used as input for integrated energy system assessments and consequently its global warming mitigation potential can be overestimated within global CCS assessments. Additionally, the above-mentioned global assessments do not specifically perform a source-sink matching analysis, which is recommended to make more accurate and realistic investment decisions (Bradshaw et al., 2007).

The Brazilian (BE)CCS chain is analyzed in the scientific literature. Rockett et al. (2011) performed a source-sink analysis on the current CCS potential in Brazil, but detailed data on storage potential and injection rates (a key parameter to assess CO_2 storage costs) are missing. Furthermore, da Silva et al. (2018) analyzed the potential for storing CO_2 from ethanol distilleries within the offshore Campos basin. However, both studies focus on the current situation and ignore the competition with other GHG mitigation options. (Lap et al. (2019) show that biomass sources, and deployment of BECCS conversion technologies may change over time, influencing the contribution of BECCS in low-carbon pathways. Furthermore, da Silva et al. (2018) focus on storage within empty gas and oil fields using enhanced oil recovery. However, the storage potential in empty gas and oil fields is limited to 2 Gt (Ketzer et al., 2015). To store large quantities of CO_2 for a longer time, as required for 'Paris' trajectories, as quantified by Lap et al. (2019), other basins with larger storage potential are required. The only basin within close range of substantial CO_2 emitting sources, with significant storage potential is the Paraná basin (Ketzer et al., 2015). However, the key underlying data to estimate both storage potential and injectivity is only marginally available. Especially the injectivity of CO_2 is considered as the most important parameter to estimate the storage costs (Lap et al., 2019). Here, a spatially explicit analysis is carried out on the CO_2 storage potential of the Paraná basin, including estimates on storage potential, injection rates and associated costs. This allows for a detailed source-sink analysis. While source-sink analyzes are studied for large scale BECCS (e.g. by Baik et al. (2018)), these are generally not linked to a complete energy system model. Doing so, allows to analyze the complete deployment trajectory over time and space of the BECCS supply chain.

As the biomass potential is variable over time and space, the storage potential is uncertain, and future CO_2 transport networks are still to be developed, the BECCS potential and its associated costs within Brazil are difficult to analyze. This paper aims to decrease that uncertainty by structurally analyzing the BECCS chain, from source to sink, and to assess its contribution as a climate mitigation option within low-carbon energy system trajectories. A literature study is performed to collect data, that is required to estimate CO_2 injectivity and storage potential. From this data so-called cost-storage curves are generated, showing the potential to store the CO_2 in the subsurface with the associated costs. A literature review is performed on the costs for different CO_2 transport networks. Analyzes on the availability of biomass for CCS are obtained from (Lap et al., 2022). While biomass availability and geological storage potential of CO_2 are shown to have a great impact on the modeling results (Lap et al., 2019), a set of eight scenarios is created to show the range in possible outcomes. The data on the CCS chain is incorporated within the TIMBRA (The Integrated Market allocation Energy flow optimization System-BRAzil) model. This model is used to minimize the costs of the complete Brazilian energy system for 2050. This methodological framework allows to assess the potential for BECCS within a low-carbon Brazilian energy system for 2050, including its deployment pathways and its impact on the energy system (total system costs and energy mix), considering uncertainty in biomass sources, CO_2 transport options, injection rates and storage potential of CO_2.

2. Methods

To analyze the potential for BECCS in a Brazilian low-carbon energy system, first the CO_2 storage potential is estimated, including its associated costs. This leads to CO_2 cost-storage curves, showing how much CO_2 can be stored per potential location, and at what costs (see Section 2.3 for details). These CO_2 cost-storage curves are used as input for the TIMBRA model (see Section 2.1 for details), which is the second part of the analysis. In TIMBRA the costs for the CO_2 capturing technologies is included, as well as the costs to transport the captured CO_2 from the industrial source to the sink location. Hence, the costs of the complete BECCS chain is represented as well as the storage potential, showing the levelized CO_2 abatement costs.

These costs are also calculated in TIMBRA for other GHG mitigation options (e.g. solar energy, hydropower, and electric vehicles). TIMBRA will eventually show the most cost-effective energy system to reduce GHG emissions, while fulfilling the demand for energy services in Brazil for 2050.

Estimating storage potential and associated costs is prone to uncertainty. Together with low-carbon biomass availability, these are the key factors that determine the potential for BECCS as climate mitigation measure (Lap et al., 2019). Eight scenarios are created to provide insight in the contribution of BECCS within the Brazilian low carbon energy system, and how these key factors affect this contribution. Furthermore, a sensitivity analysis is performed to analyze in depth the sensitivity of single parameters on CO_2 storage, injectivity and costs (see Appendix IV).

2.1. TIMBRA

TIMBRA is an energy system model developed especially for Brazil, which aims to fulfill energy demand for Brazil while minimizing total energy system costs (Nogueira 2016). The model consists of three main parts: 1) supply potential of energy carriers, 2) techno-economics of energy conversion technologies, and 3) energy demand for end-use sectors (industry, transport, residential & commercial, agriculture and non-energy). The model contains fossil and renewable energy options. A detailed description of the supply potential, energy conversion technologies and demand is found in Lap et al. (2019). Considered cost factors are: annualized technology costs (CAPEX and OPEX), and fuel costs. The objective function of the model is to minimize the net present value of the entire energy system (Loulou et al., 2005). The model runs from 2010 (reference year) until 2050, with time steps of 5 year and is calibrated for 2015 based on the Brazilian energy statistics (MME 2016). A carbon budget of 16 Gt CO_2 for the period 2010–2050 is incorporated in TIMBRA. This budget represents the allowable GHG emissions for the Brazilian energy sector to keep global warming below 2 °C (Rochedo et al., 2018).

2.1.1. Techno-economics CO_2 capture

A portfolio of CCS technologies is present in TIMES and consists of both BECCS and fossil CCS technologies. The individual techno-economic characteristics of the technologies determines the selection of the technology. Important characteristics are production costs (CAPEX, OPEX, fuel costs, CO_2 capture costs [part of the CAPEX and OPEX]), demand for end-products and CO_2 capture rates. The techno-economic characteristics of the CCS technologies is shown in Table 1. Future techno-economic characteristics are listed in Appendix III.

2.2. CO_2 transport costs

Transportation costs from source to sink depends on the volume of CO_2 that is transported and the distance (Knoope 2015). In this study the average costs per kilometer are used. Van der Spek et al. (2019) performed a thorough analysis on cost projections on CO_2 infrastructure. The range found in this study is used to represent the transport costs of CO_2 here. The study area (see Section 2.3 for details) is mapped in a grid cell matrix with grid cells of 100 by 100 km. The CO_2 transport costs are plotted per grid cells, assuming increasing costs from northeast (source location) towards southwest (sink location), following the range in costs (van der Spek et al. 2019). It is assumed that the biomass is produced within the northeast part of the Paraná basin in the state of Sao Paulo, where currently most sugarcane is cultivated (EPE 2016).The matrix of the transport costs is found in Appendix II.

2.2.1. Linking the CO_2 storage curves to TIMBRA

The geological storage potential and the associated costs of the Rio Bonito formation are calculated per grid cell (see Section 2.3 for details). By ordering the grid cells to their costs, and cumulating its storage potential, the CO_2 storage curves are created. The list of sink locations, with the associated data, is input data for TIMBRA. By linking the capture technologies, to the transport and eventually the storage locations, the full CCS supply chain is represented in TIMBRA (Fig. 1). The model selects the cheapest sink location, and the amount of injected CO_2, based on the potential storage capacity, transport- and storage costs.

The restrictions on CO_2 emissions by the carbon budget, apply to all forms of GHG mitigation, allowing for a uniform analysis on suitable GHG mitigation strategies. Hence, the deployment, scale and timing of (BE)CCS can be compared to other GHG mitigation technologies.

2.3. CO_2 cost-storage curves

A preselection is carried out to locate suitable locations for geological CO_2 storage. Per location, a spatially explicit analysis is done to estimate storage potential, injection rates and associated costs.

2.3.1. Storage potential: basin selection and data

A preselection from all suitable basins in Brazil is made to distinguish what basins are available for large-scale CO_2 storage with injection rates over 100 Mt/y (see Appendix I). From this preselection the Paraná basin is selected for this study, because the geology allows for safe trapping of CO_2, it can store enough CO_2, it is in close proximity to (future) CO_2 point-sources, and there is enough data available to calculate the operational storage capacity and costs. All other basins lack one or more of the abovementioned criteria and are therefore not studied here (see Appendix I for detailed information).

The Paraná basin is a saline aquifer and exists of different geological formations. All formations are ranked on their geological storage suitability, based on the acknowledged ranking mechanism developed by Bachu (2003), and applied to the Paraná basin by Diakakis (2019). From this analysis the Rio Bonito sandstone formation is selected as the target formation, mainly because of its favorable porosity and depth. Details on the ranking mechanism are found in Appendix I.

A literature research is performed to screen scientific and gray literature for geological characteristics of the Rio Bonito formation. The assessed parameters for storage potential estimation are: formation thickness [m], formation depth [m], temperature at storage depth [°C], average porosity over the thickness of the formation [-], permeability [mD], and density of CO_2 at target formation [kg/m^3]. The characteristics of the Rio Bonito formation are found in Appendix I, as well as characteristics of other present formations within the Paraná basin for

Table 1
Techno-economic characteristics of fossil- and biobased carbon capture technologies as used in TIMBRA.

Name[a]	Feed-stock[b]	Main end-product	Conversion efficiency (Gj_{out}/Gj_{in})	CAPEX ($/kW)	OPEX ($/MW/y)	Captured carbon (kg/GJ_{out})	Sources[d]
FBC	Coal	Electricity	0,34	3000	78	258	1
PC	Coal	Electricity	0,36	2500	90	158	2,3
IGCC	Coal	Electricity	0,42	2600	54	150	2,3
CCGT	NG	Electricity	0,43	3090	23	78	2,3
SMR	NG	Hydrogen	0,74	622	47	77	5
BIGCC	BM	Electricity	0,40	3200	68	150	5, 6
FT-syn.	BM	Biofuels	0,49	2450	107	96	7, 8
BG	BM	Hydrogen	0,66	1700	58	135	8
Ann-EOH	SC	EOH/sugar	0,47	747	75	11[c]	9
Aut-EOH	SC	Ethanol	0,47	981	98	28[c]	10
Imp-EOH	SC	Ethanol	0,58	1300	130	26[c]	11

[a] Fluidized bed combustion (FBC), Pulverized coal (PC), Integrated gasification combined cycle (IGCC), Combined cycle gas turbine (CCGT), Steam methane reforming (SMR), Biomass integrated gasification combined cycle (BIGCC), Fischer-Tropsch synthesis (FT-syn.), Biomass gasification (BG), Annexed Ethanol distillery (Ann-EOH), Autonomous Ethanol distillery (Aut-EOH), Improved Ethanol distillery (Imp-EOH).

[b] Natural gas (NG), biomass (BM), Sugarcane (SC).

[c] Per GJ of produced ethanol. The conversion rate is calculated based on (Möllersten et al., 2003).

[d] 1 = (Portugal-Pereira et al., 2016), 2 = (Simoes et al., 2013; Brouwer et al., 2015), 3 = (Simoes et al., 2013; Brouwer et al., 2015), 4 = (P. Rochedo 2016), 5 = (Gerssen-Gondelach et al., 2014; Meerman et al., 2013), 6 = (Gerssen-Gondelach et al., 2014; Meerman et al., 2013), 7 = (van Vliet, Faaij, and Turkenburg 2009; Alves et al., 2017), 8 = (van Vliet, Faaij, and Turkenburg 2009; Alves et al., 2017), 9 = (Bonomi et al., 2016), 10 = (Dias et al., 2011). 11 = (Dias et al., 2012).

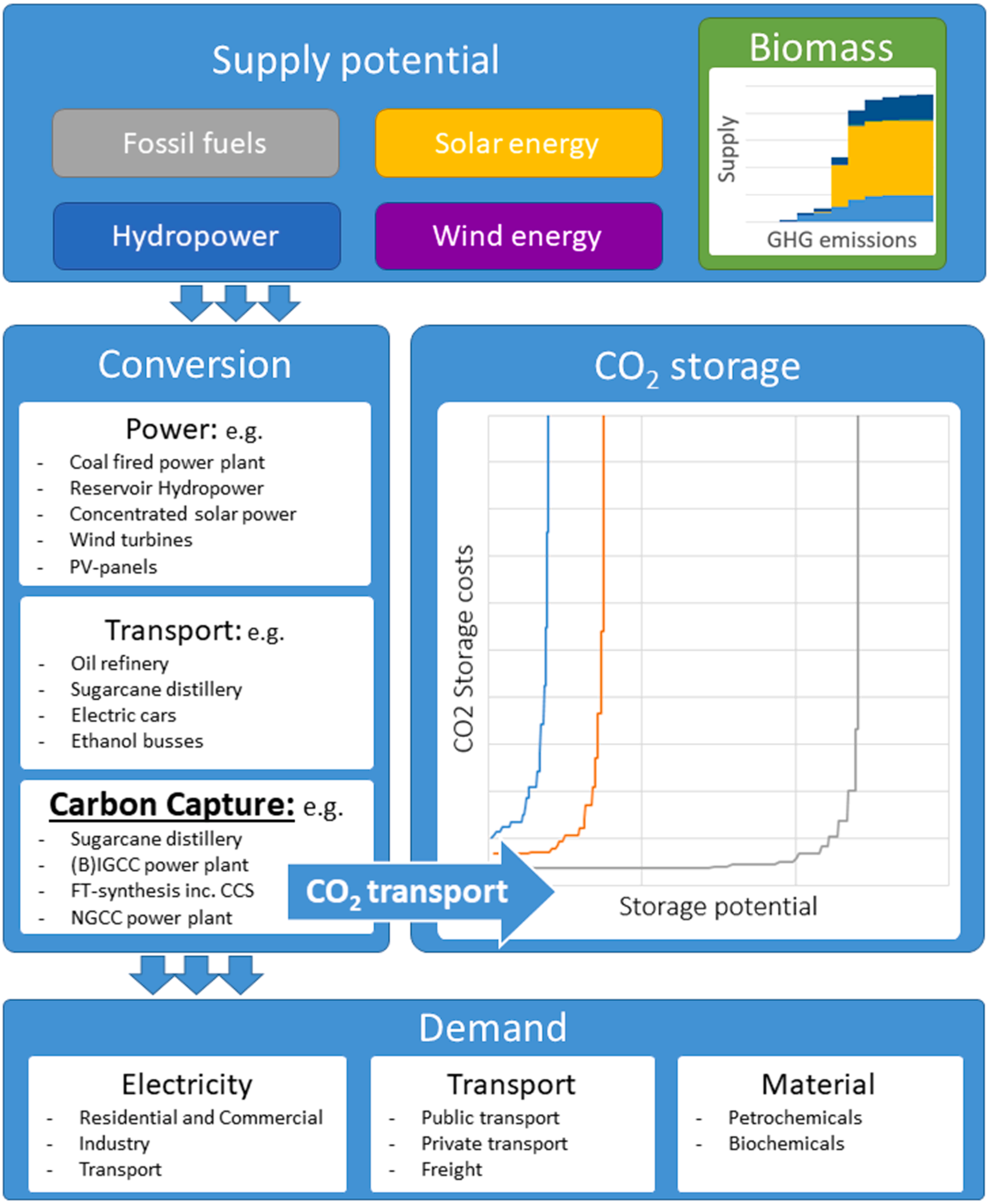

Fig. 1. Overview of the TIMBRA model, including the integration of the CO_2 storage curves.

comparison reasons. Quantification of the storage potential is done using a volumetric equation (Eq. (5)).

$$G_{CO2} = A * h_g * \varphi * \rho * E \quad (5)$$

- G_{CO2}: storage potential (Gt CO_2)
- A: Area being assessed (km2)
- h_g: Gross thickness of the formation (m)
- φ: Average porosity of the formation (-)
- ρ: Density of CO_2 at pressure & temperature of the target formation (kg/m^3)
- E: efficiency factor (%)

The depth of the Rio Bonito formation is studied by Bocardi et al. (2009), based on analysis of data from exploratory wells and scientific literature. The map presented by Bocardi et al. is divided in grid cells of 100 by 100 km, with in total 100 cells and an area of 1 million square kilometers covering the northern and middle part of the Paraná basin. This location is selected because it has close overlap with the states Sao Paulo, Paraná and Mato Grosso. Sao Paulo state is the largest sugarcane producing state in Brazil (UNICA 2016), showing large bioenergy potential for BECCS. Paraná is selected because of the geological CO_2 storage potential, and Mato Grosso has potential of new bioenergy plantations when livestock pastures can be transformed into bioenergy plantations, given agricultural intensification. Eventually the storage potential is calculated for each grid cell (using Eq. (1)). For each cell the average depth of the Rio Bonito is determined using data from Bocardi et al. (2009). Data on a geographical cross-section of the basin

(Machado et al., 2013), and data on thickness of the formation from other scientific literature (see Appendix I) is combined to estimate the thickness per grid cell, using the ratio between depth and thickness. By using a lithostatic pressure gradient of 10 kPa/m, based on Baik et al. (2018) and in line with data found for the Paraná basin, the pressure at target formation can be estimated. This gradient corresponds well to pressure gradients used for other CO_2 storage potential assessments (McCoy 2008). The temperature at target formation is estimated using a temperature-depth gradient of 30 °C/km, based on (Kolster et al., 2017), which is in line with the data found for the formations in the Paraná basin (Appendix 1). The phase-density diagram (Bachu 2003) is used to estimate the density of the injected CO_2 in the target formation. The porosity of the formation is based on the bore samples from the Rio Bonito formation, as found in scientific literature (see Appendix 1). The efficiency factor is chosen based on research from Van Der Meer and Yavuz (2008), and Bachu (2015).

2.3.2. Injectivity

Apart from the storage potential, the injectivity of CO_2 is a key factor that determines the costs for geological CO_2 storage (Baik et al., 2018). The injectivity is the maximum amount of CO_2 that can be injected in the target formation per injection well per year. While cost of geological storage of CO_2 is closely linked to the number of wells that is required to reach a target injection rate, injectivity is an important parameter from financial perspective.

The injection rate per well is calculated using Darcy's law for single-phase flow.

$$Q_{max} = \frac{k * A * \Delta P}{\mu * L} \tag{1}$$

Q_{max} = maximum flow of CO_2 (m_3/s)
k = average permeability of the reservoir (m^2)
A = well surface (in contact with the target formation, m^2)
μ = the viscosity of CO_2 (Pa s)
ΔP = pressure differential (Pa)
L = distance between wellhead and wellbore (m)

The injection rate (Q_{max}) is calculated for each grid cell (see Section 2.3.1). The permeability is based on data for the Rio Bonito formation (see Appendix 1). For the well surface area (within the target formation), a 7-inch liner is assumed. The length of the wellbore is assumed to be equal to the thickness of the formation. The viscosity is determined using phase-density diagram (Bachu 2003), in combination with depth and pressure. The pressure differential is assumed to be 1 MPa over a length (L) of 10 meter, and the amount of CO_2 that is injected per well over one year, is calculated by using the CO_2 density at target formation.

2.3.3. CO_2 storage costs

The levelized costs for CO_2 storage are calculated per well. Included cost parameters are:

- Capital expenditures injection wells (including drilling costs and injection equipment)
- Site characterization (monitoring geological trapping over the set time horizon, based on areal footprint)
- Operation & Maintenance costs
- Site closure costs

Levelized costs calculations are based on methods from McCoy (2008). All cost parameters are converted to US$$_{2015}$ using the CEPCI index (CEPCI 2020). Injection well CAPEX costs data is taken from Tayari et al. (2018). Site characterization are obtained from McCoy (2008), as well as site closure costs, backed up with data from ZEP (IEAGHG and ZEP 2010). O&M costs are assumed to be 5% of the total capital expenditures, following Kanudia et al. (2013).

The number of injection wells that is required to meet the target injection rate is calculated by dividing the CO_2 storage potential (see Section 2.3.1) by the annual injection rate times the assumed economical lifetime of 25 years. The total storage costs per grid cell are calculated by multiplying the annualized storage costs with the number of injection wells.

Estimating CO_2 storage costs is prone to uncertainty. A list of all considered cost factors is shown in Appendix II. This list shows the assumptions made for the scenarios (see Section 2.4). Furthermore, a sensitivity analysis is done to identify the most critical parameters influencing CO_2 storage costs (Appendix IV).

2.4. Scenarios

Estimating the potential for (BE)CCS in the Paraná basin comes with a range of assumptions, as described in Section 2.3. To analyze the impact of CCS as GHG mitigation option, three CCS development pathways are distinguished to express the uncertainty in technology availability and costs: high, medium and low development. Next to CCS potential, biomass availability is the most sensitive factor within the TIMBRA model with regard to its cost-competitive contribution to fulfill low-carbon energy demand (Lap et al., 2019). This shows that both CCS and biomass are key options that can ensure the transition towards a low-carbon energy system in Brazil, while minimizing the total system costs. However, the development of both factors is very uncertain and therefore it is important to explore several potential development pathways.

2.4.1. Biomass availability

There is ample research on the potential available biomass within Brazil. However, the amount of biomass that is available with a low GHG emission profile is limited and subject to debate (van der Hilst et al. 2018; Lossau et al., 2015; Lapola et al., 2010; Follador et al., 2019). The availability of biomass within Brazil with a low GHG emission profile is studied by Lap et al. (2022), based on methods developed by Daioglou et al. (2017). Three types of biomass sources are included, biomass from: 1) existing bioenergy plantations (mainly sugarcane), 2) agricultural residues, and 3) new bioenergy plantations.

Three key parameters influence the potential for low-carbon biomass: agricultural productivity, time horizon selection and accounting for natural succession. Low-carbon biomass is classified as biomass with an emission factor (EF) lower than 15 kg CO_2-eq./$GJ_{primary\ biomass}$ (Lap et al., 2022). In the most optimistic circumstances (high agricultural productivity, long time horizon and no accounting for natural succession), the total low-carbon biomass potential is 41 EJ/y, while in less optimistic circumstances (low agricultural productivity, short time horizon, and including accounting for natural succession) it is 11 EJ/y. These two sides of the spectrum are selected within this study for the biomass availability. In Section 2.4.1, the selection of the scenarios from Lap et al. (2022) is discussed.

2.4.2. CCS development

The development of CCS has three main elements: geology, techno-economics, and technological development. The geological element determines the storage potential and injectivity per well of geological CO_2 storage. Techno-economics is related to the costs of storing and transporting the CO_2 from the capture site to the geological sink, and technological development relates to the cost development and introduction year of technologies in relation to the technological readiness level of technologies capable of capturing CO_2. The parameters per element are quantified per development stage in Table 2 and Table 3.

An explanation of the each geological parameter is found in Section 2.3.1. The sensitivity of each individual parameter is assessed in Appendix IV, to analyze the individual contribution of each parameter to the storage potential.

Details about the costs of CO_2 storage and transport are found in Section 2.3.3. The sensitivity of each parameter with respect to the

Table 2
Geological data per as used in the CCS development scenarios.

Geological parameters	CCS-High	CCS-Medium	CCS-Low
Thickness gradient (%)	3.5	3.0	2.5
Depth-density gradient (%)	30	25	20
Porosity (%)	20	15	10
Efficiency (%)	2	1	1
Permeability (mD)	1500	1200	900
Maximum injectivity (Mt CO_2/well/y)	1.4	1.2	1.0

Table 3
Cost data per parameter as used in the CCS development scenarios.

Cost parameters	CCS-High	CCS-Medium	CCS-Low
CAPEX injection wells (%)	80	100	120
Monitoring plume radius (%)	175	250	300
O&M costs (%)	3	5	7
Site closure costs ($/t CO_2 injected)	0.8	1	1.2
CO_2 transport costs ($/t CO_2 transp.)	1.5–3	3–5.5	4.5–7

annualized storage cost is found in Appendix IV. The parameterization of both CAPEX and introduction year for CO_2 capture technologies is found in Lap et al. (2019), where SSP1 relates to high development, and SSP3 to low development.

2.4.3. Scenario set

Based on the uncertainty in the development of both CCS (see Section 2.4.2) and biomass availability (see Section 2.4.1), six different scenarios are studied. Two additional scenarios are explored to show the effect when CCS is no option. The total set of eight scenarios is shown in Table 4.

3. Results

The results are split into two parts. The first part shows the results of the CO_2 storage costs curves. These curves are linked to the TIMBRA model, showing the results of the integration of the CCS module within a low-carbon energy system for Brazil.

3.1. CO_2 storage curves

The CO_2 storage curves show the potential to store CO_2 in the Rio Bonito sandstone formation of the Paraná basin, and the accompanying costs (see Fig. 2). The storage potential varies between 20 Gt CO_2 for the lower estimate, to 120 Gt CO_2 for the highest estimate. The large difference between these estimates is caused by the lack of data, and the large uncertainty within the scarce data that is available. The sensitivity of individual parameters on the storage potential is shown in Appendix IV. From the sensitivity analysis it can be concluded that storage efficiency and porosity are the most influential factors. A high storage efficiency can double the storage potential, in comparison to the mean estimate. For porosity, the storage efficiency is doubled from 25 (low: 10% porosity) to 50 Gt CO_2 (high: 20% porosity). The accumulated effect of all parameters leads eventually to the large difference between the three estimates for the storage potential.

The trends between the three estimates for costs for CO_2 storage in the Rio Bonito formation are similar to those of the storage potential, basically because storage potential determines the costs to a large extent.[1] This has to do with the injection rate per well. When the geological conditions are less favorable (e.g., a dense and thin formation) the injection rate per well is relatively low, in comparison to more favorable conditions. To store the same amount of CO_2, more wells are required in less favorable conditions, compared to favorable conditions, and more wells means higher costs. For the low CCS development scenario, approximately 12 Gt CO_2 can be stored at costs below $15 per tonne CO_2, compared to 32 and 117 Gt CO_2 for respectively the medium- and high CCS development scenario. The largest share of the costs is related to site characteristics with on average 85% of the total costs. The costs for the injection wells is relatively low, with just under 5% of the total costs.

3.2. TIMBRA results

3.2.1. Total stored CO_2

The maximum amount of CO_2 stored in the Paraná basin reaches to approximately 245 Mt CO_2 in 2050 (Fig. 3). The total amount of stored CO_2 between 2010 and 2050 ranges between 2.84–2.95 Gt CO_2, which is approximately 18% of the entire Brazilian carbon budget for that period (see Section 2.1 for details on the carbon budget). The stored CO_2 originates from biomass in all scenarios. When comparing the six scenarios, two things stand out. At first, there is no difference between CCS development in terms of captured CO_2. This shows that CCS is seen as a robust technology to mitigate CO_2 emissions and that lower estimates of CO_2 storage potential are sufficient to meet the goals for decarbonization of the energy system. If the levels of CO_2 storage in the Paraná basin are assumed to stay the same, these injection rates can be maintained for approximately 75 years for the lower estimated storage potential.

Second, biomass availability is limiting the storage rate towards 2050 (Fig. 4). When the availability of low-carbon biomass is below 11 EJ/y, the annual injection rate drops to 220 Gt CO_2/y, compared to nearly 250 Gt CO_2/y for the scenarios with high potential of low-carbon biomass. On the contrary, the annual injection rate in 2040 increases under low biomass availability, compared to high biomass availability. This can be explained by looking at the carbon budget. When less low-carbon biomass is available, the potential of this source can be used earlier to mitigate CO_2 emissions earlier. The reason why earlier adoption is not happening when more low-carbon biomass is available is costs: earlier deployment of CCS technologies is more expensive. There is also a difference in the CCS technology mix. Under high biomass availability, CO_2 is captured in FT-synthesis plants, while under low biomass availability this mix exists of FT-synthesis and BIGCC power plants, with respectively 60- and 40% of the capture CO_2. BIGCC power plants are not necessarily the second best cost-competitive technology to capture CO_2. The main reason why BIGCC is part of the CCS capture mix is because there is more demand for electricity since the demand for low-carbon transportation is partly switching from biomass to electric transportation.

The estimated time before the Rio Bonito formation is theoretically saturated with CO_2 can be quantified based on the storage capacity and the maximum annual injection rates. Even in the scenario where the CO_2 storage capacity is at its lowest, still CO_2 can be injected for just over 80 years. At maximum, CO_2 can be injected for over 550 years.

3.2.2. Injection rate and site

The injection rates and sites are shown in Fig. 5 for three CCS development stages. The sum of the injection sites corresponds to the total injection rate as shown in Fig. 3. Although the differences between the CCS development stages does not differ in terms of total stored CO_2 per scenario (Fig. 3), there are clear differences in location and injection rate per location for the different scenarios.

For the scenario with high CCS development, the maximum injection rate is much higher (122 Mt/y) in comparison to e.g. the low CCS development scenario (max 34 Mt/y). For the high CCS development scenario, the geological conditions allow more CO_2 injection with limited number of wells, leading to low injection costs. These injection

[1] The costs do usually increase with depth which can influence drilling costs substantially. However, in the case of the Paraná basin the thickness, and thus the wellbore area, increases (see Appendix I) and relative more CO_2 can be injected.

Table 4
Overview of the scenarios as used in this study.

Scenarios[a]	BH—CH	BH—CM	BH—CL	BL-CH	BL-CM	BL-CL	No CCS Low	No CCS High
Biomass availability	High			Low			High	Low
CCS development	High	Medium	Low	High	Medium	Low	High	Low

[a] The first part in the scenario abbreviations relates to biomass availability (B), with the high (H) and low (L) range. The second part relates to the CCS development (C), ranging from high (H), to medium (M) to low (L).

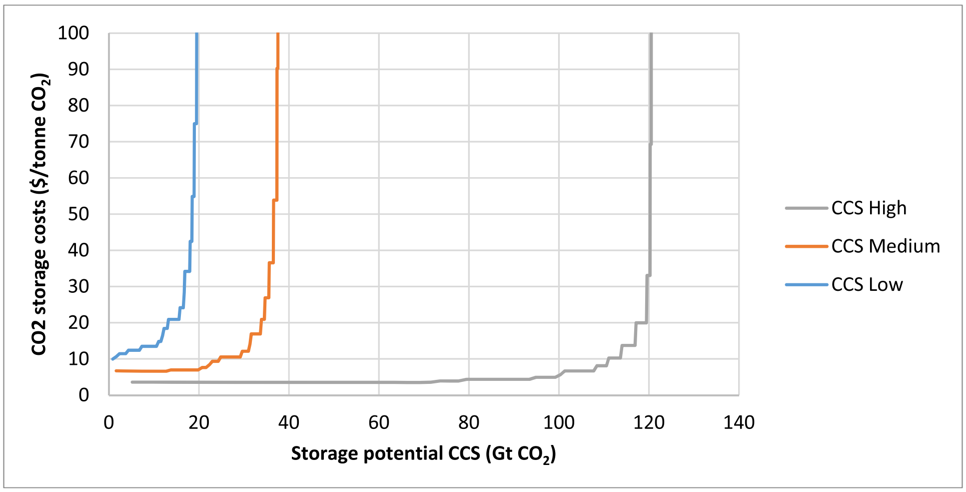

Fig. 2. CO_2 storage curves per scenario for the Rio Bonito formation in the Paraná basin, as described in Section 2.3.

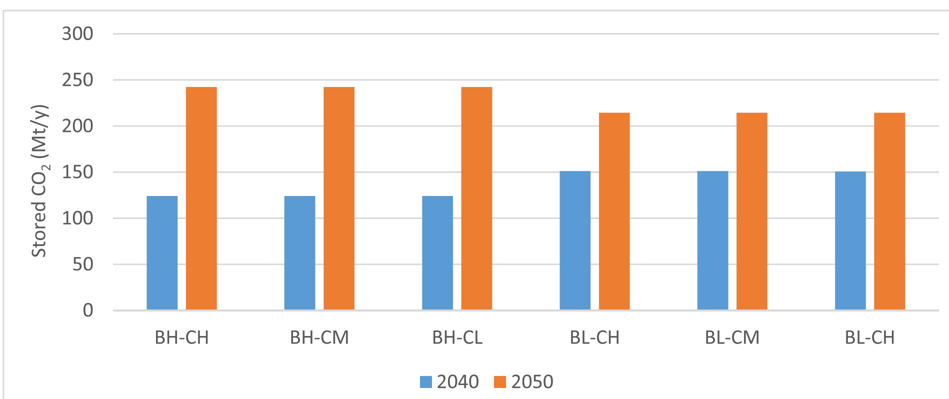

Fig. 3. Annual stored CO_2 per year per scenario in the Rio Bonito formation for 2040 and 2050.

sites are found around the north part of the deepest areas of the Rio Bonito formation. The optimal location in this case, is a trade-off between depth, storage potential and transport costs. Deeper is more expensive because of increasing drilling costs, but deeper also leads to more storage potential because the thickness of the formation increases and more CO_2 can be injected per cubic meter of pore volume (because of increasing pressure). Furthermore, transport costs increase from northeast (biomass source location) to southwest. For the low CCS development scenario, the location is focusing less on costs, and more on maximum injection rate. To reach the demanded injection target, more sites are required because geological conditions allow much less CO_2 to be injected per well and subsequently per site. Since injection rate is the limiting factor, sites with higher injection costs are selected, in comparison to the SSP1 scenario where levelized storage costs is the determining factor for site selection. Transport costs reveal also that is the injection rate is the determining factor for the selection of the sink location, as the selected locations B9 and C10 (see Fig. 5) have the highest transport costs of all locations.

3.2.3. *Energy mix*

The total final energy consumption ranges between 14 and 17 EJ in 2050, for the studied scenarios (Fig. 6). The impact of the CCS development is not present in the energy mix, as also observed in the CO_2 storage per scenario. Biomass is seen as a cost-effective option for climate-change mitigation, when the availability is higher, it represents 54% of the final energy consumption, compared to 36% when biomass availability is low. In the high biomass scenarios other GHG mitigation options are less visible. When the potential for low-carbon biomass is low, electricity and hydrogen are used as low-carbon alternatives for biomass. Especially in the transport sector a switch is observed from biomass towards electricity and hydrogen.

Production of liquid biofuels by the Fischer-Tropsch process is the main BECCS technology. In the high BM scenario, all CO_2 is captured within the FT process, meeting demand for fuels in the freight transport sector in particular. In the low BM scenario, around one third of the CO_2 is captured from BIGCC power plants. Although this seems counterintuitive (less biomass is available for the transport sector), it makes sense

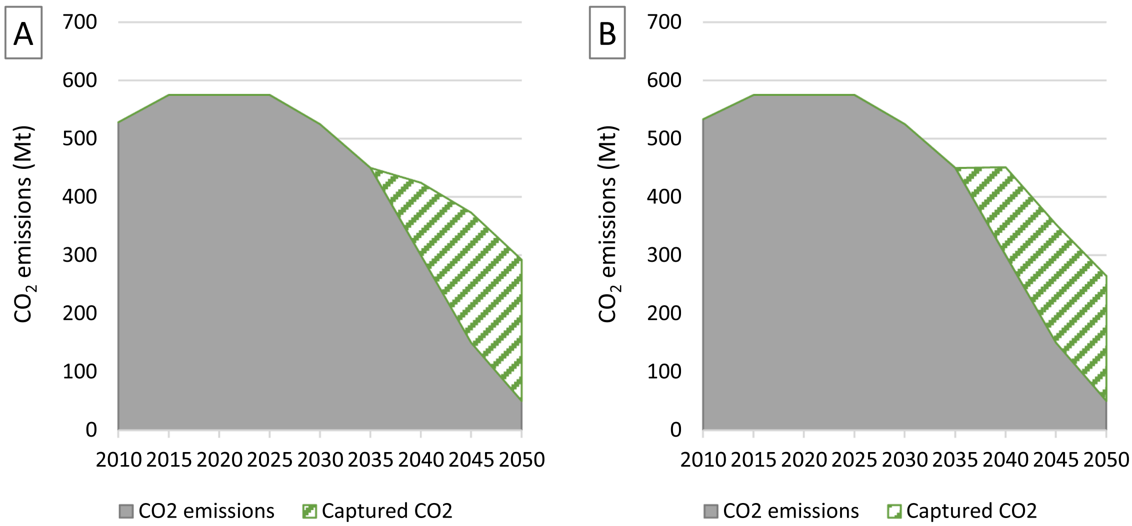

Fig. 4. CO_2 emissions and the volume of captured and stored CO_2 over time, for A) the BH—CH scenario, and B) the BL-CL scenario.

from a system-perspective because there is a larger need to decarbonize the industry by converting electricity to hydrogen using electrolyzers. Battery Electric Vehicles (BEVs) compete with ethanol cars in general. While BEVs require additional power generation technology and infrastructure, ethanol cars are more cost-competitive in the high BM scenario. When biomass is less available, relative more biomass is used in other sectors leading to higher adoption of BEVs.

In both scenarios without CCS, differences occur within the industry sector mainly in comparison to the other scenarios. When CCS is allowed, the negative emissions from BECCS provide some room for other sectors that are cost-effectively more difficult to decarbonize, to remain partly dependent on fossil fuels. When CCS is not present, the major share of the industry uses biomass as low-carbon alternative to fulfill energy demand. This biomass can't be used in other sectors, resulting in increasing electrification, mainly in the transport sector, and growing use of hydrogen in the transport sector. Another change is observed in the technology mix. When CCS is not present, more expensive conversion technologies are used, and they are also deployed earlier, in comparison to the other scenarios.

3.2.4. *Total system costs*

The total system costs range from 475 to 530 bn$ in 2050, depending on the scenario (Fig. 7). The differences in costs between the CCS development stages is marginally, while the difference for high or low biomass availability has a larger impact. This is mainly because a switch from biomass towards electricity is observed, due to lower availability of biomass. This reflects in the cost categories: when biomass availability is high, supply costs (including biomass) are higher, and when biomass is less available supply costs decrease, but power generation costs increase. The accumulated effect of lower biomass leads to higher costs. Also because more electrolyzers are required to produce hydrogen for freight transportation and industrial processes.

Although the costs for CCS seems relatively even for all scenarios, there are small changes. The CCS share of the total costs ranges from 3.4% (BH—CH) to 4,1% (BL-CL). Although the costs for CCS transport and storage are substantially different per development stage (see cost-storage curves Fig. 2), the share of CCS costs within the total system costs, and the differences between the CCS development stages, are rather small. Even when the lower estimate is considered with higher costs, still CCS is selected within the energy mix without compromising the total stored CO_2 (as observed within Fig. 3).

The highest CO_2 injection rates are nearly 250 Mt in 2050. To analyze the impact of CCS on the total system costs, a Pareto analysis is performed (Fig. 8). The annual injection rate in TIMBRA is limited from 250 back to 0, with steps of 25 Mt CO_2. For each run the total system costs are plotted against the maximum CO_2 injection rate. The costs range from just over bn$ 530 to nearly bn$ 565 in 2050. Three different stages can be found in the Pareto analysis. When CCS injection is limited between 200 and 250 Mt CO_2 per year the costs range between differ with bn$ 2 (between bn$ 531 and 533). Note that costs remain the same above an injection rate of 250 Mt CO_2 per year, as the cost-competitive limit of CCS is reached and other GHG mitigation options are proven to be more costs competitive. When the injection rate is limited between 100 and 175 Mt CO_2 per year relative small differences occur and the total system is around bn$ 540. When the CO_2 injection rate is increasingly limited below 100 Mt/y, the costs increase with on average bn$ 0.3 per Mt of CO_2 decrease.

4. Discussion

4.1. *Sensitivity CO_2 storage potential and costs*

Estimating the storage potential and injectivity of storing CO_2 in the subsurface is prone to uncertainty. For the storage potential, storage effectivity is the most sensitive parameter. When the storage efficiency is 2%, the total storage efficiency will double in comparison to the reference scenario (1%). In the scientific literature, the sensitivity of the storage efficiency is recognized. A review written by Bachu (2015) explores the use of storage efficiency in the literature and concludes that the efficiency usually ranges between 1 and 10%. Furthermore, they come up with a list of factors that need to be considered on how to interpret a certain value. In general, it can be concluded that the storage efficiency increases along with increasing level of detail on geological data. Since the level of detail in our analysis in low, the conservative approach in this study seems justified.

Porosity is the second most sensitive parameter concerning the storage potential. In the literature review for geological data of the Paraná basin, all sandstone formations are reviewed giving a porosity range of 0.1–0.2. This seems to be in line with scientific literature from different places around the world (Burnside and Naylor 2014). In general, porosity decreases with depth. So the results in the CH scenarios (see Section 2.4) can be slightly overestimated since deeper locations are preferred (see Section 3.2.2). Permeability and porosity are closely associated, as shown in porosity-permeability plots.

Just like porosity influences the storage capacity, permeability influences the storage costs. The difference between high (1500 mD) and

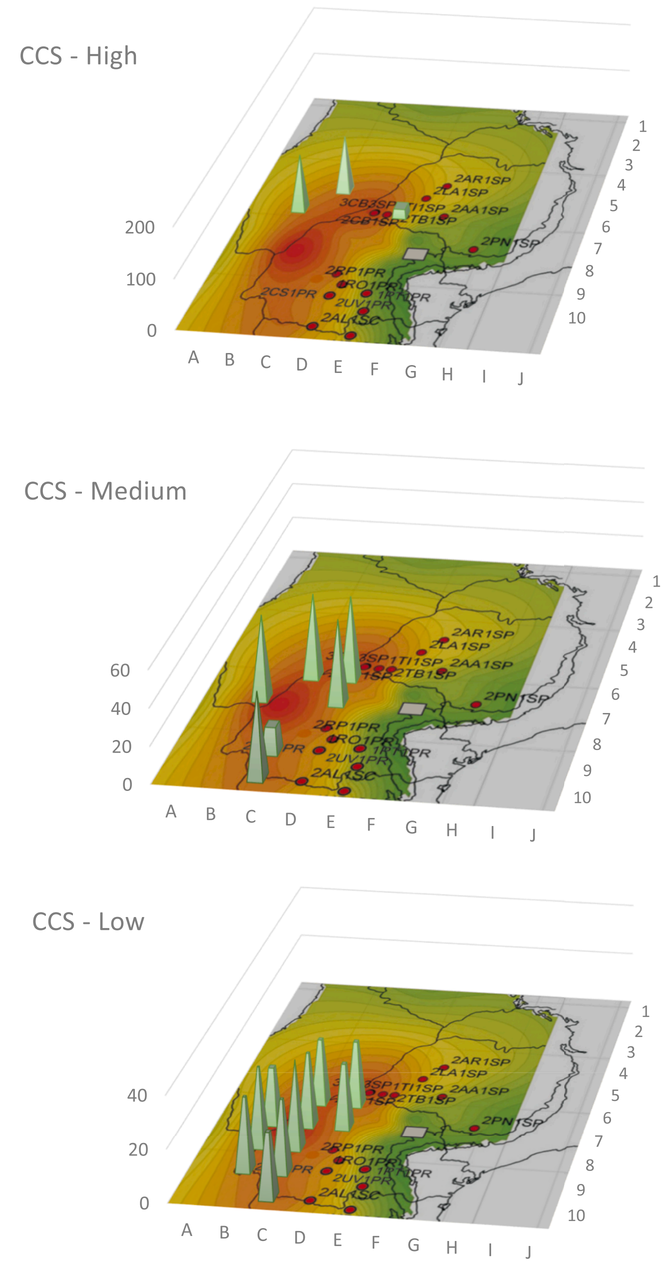

Fig. 5. Injection rates (Mt CO_2/y) and site for 2050 for the three CCS development stages (map obtained from (Bocardi et al., 2009)). Note that the scaling of the y-axis (injection rate) differs per scenario.

low (900 mD) estimates on permeability result in annualized storage costs of respectively \$13 and \$20/t CO_2, compared to \$15.5 for the medium estimate (1200 mD). The permeability levels used here are based on actual core samples from the Rio Bonito formation (Queiroz 2002) and show similar geological properties with other well-studied formations such as the Berea Formation (Costa 2016). The found permeability ranges of the bore samples may not occur throughout the entire formation and can be lower in reality. With permeability levels of 500 mD, the storage costs will increase to over \$30/t CO_2. In a new model run (based on the BL-CL scenario) using a permeability level of 500 mD we see (nearly) no changes in the total volume of stored CO_2 and in injection rates. However, the costs of CCS increase. In the initial BL-CL scenario, CCS is accountable for 4.2% of the total system costs (see Fig. 7), while this share increases to 5.8%. Although the costs increase significantly, it is not affecting the deployment rates of CCS and the merit order of CDR technologies.From all 10 parameters that are selected for the sensitivity analysis on storage costs, two are directly linked to the monitoring of the injection: site characteristics and the plume radius. Both substantially influence storage costs, mainly because of the drilling of monitoring wells, which is closely related to the area under investigation. The estimated values for both parameters are obtained by reviewing CO_2 storage cost models (i.e. in McCoy (2008) and the FE/NETL CO_2 cost storage model (Grant and Morgan 2017)), and scientific literature. Assuming a monitoring radius of 300% of the expected CO_2 plume leads to increasing costs of \$0.5, while a plume radius of 175% decrease of \$4.5, compared to the medium value of \$15.5/t stored CO_2. Differences (±20%) of the CAPEX for site characterization compared the medium \$15/t CO_2, is ±\$2.8 for low and high estimates.

Two other parameters that show high sensitivity to the storage costs are the density-depth gradient, and the thickness-depth gradient. Both parameters relate to the amount of CO_2 that can be injected per injection well. The estimates are based on relation between depth and density, and depth and thickness in the literature review on data on the Rio Bonito formation (see Appendix I). For both parameters the lower estimate leads to approximately \$2 lower in comparison to the medium value of \$15/t CO_2, and approximately \$3 higher for the higher estimate.

Other factors (i.e. injection well costs, O&M costs, site closure costs, maximum injectivity and storage effectivity) influence the costs only marginally (± \$0.3/t CO_2), mainly because they are smaller cost fractions in comparison to site closure costs.

4.2. Suitability for CO_2 storage

The ranking mechanism for assessing the potential for geological CO_2 storage of the different formations can range from 0 to 1 (see Appendix I), where value 1 means that the preconditions for geological CO_2 storage are good, given the selected set of weighed parameters. From all present formations in the Paraná basin, the highest score for the Rio Bonito formation is just below 0.7. While it seems that the Paraná basin is less suitable for CO_2 storage, this gap of 0.3 is caused by lack of data. Two geological parameters: fault intensity and trapping mechanism, score low because of lack of data. Both parameters are important for keeping the CO_2 in the targeted formation. When the trapping mechanism is poor, CO_2 can potentially escape upwards, and when there is faults in the sealing formation, the CO_2 can leak to upper formations. In the case of the Rio Bonito formation, the CO_2 can be trapped in the saline water (chemical trapping). Lack of information on the vault intensity is more important. On top of the Rio Bonito formation, clay- and siltstones from the Palermo formation form a natural seal. However, the vault intensity of this caprock is unknown, infiltration into the siltstone is possible (Iglesias et al., 2012), and the increasing pH due to injected CO_2 might affect the claystones (De Lima et al. 2011). More information is required to ensure successful trapping of the CO_2 in the target formation. Another factor which is negatively influencing the ranking score, is the geothermal condition, which determines the density of the injected CO_2. This depends, among others, on the surface temperature which is relatively high in the south of Brazil. In comparison to colder locations in the world, this important factor scores low in the ranking mechanism.

The Paraná basin is selected as a prime location for CCS in Brazil, because it has the ability for long-term Gt-storage and it is near large point-emitting CO_2 sources. However, there are other locations of interest. Two potential candidates are the saline aquifers of the Campos and Santos basin. While the petroleum fields of those locations show limited storage capacity, the saline aquifers have over 150 Gt CO_2 storage capacity, locate near the shores of the states Rio de Janeiro and Sao Paulo with large CO_2 emitting sources. However, data availability of these aquifers is even more sparse than for the Paraná basin (Diakakis 2019; Ketzer et al., 2015). Furthermore, storage costs for offshore CCS are higher than onshore CCS (van der Spek et al. 2019). On the other hand, onshore CCS can attract protest and social unrest because of safety concerns, e.g. in the case of the Barendrecht project (Feenstra et al.,

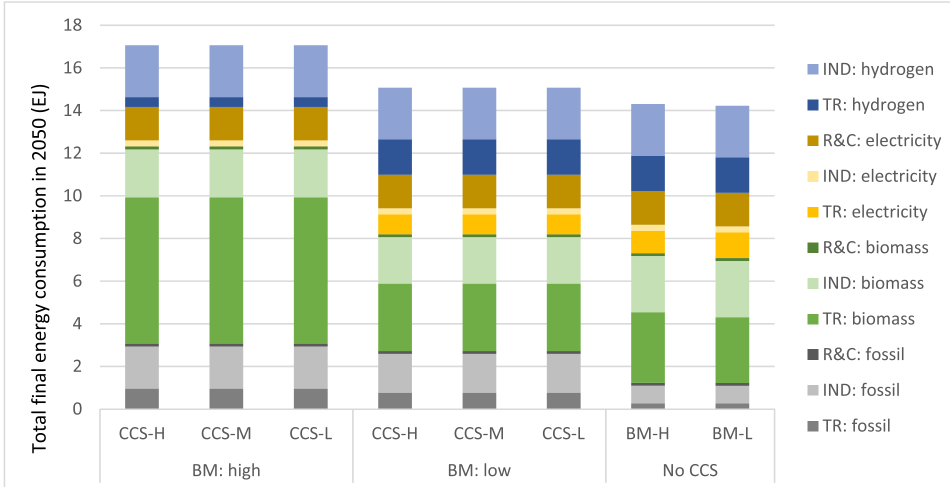

Fig. 6. Final energy consumption per energy carrier and sector in 2050, for all scenarios. Scenario acronyms are: *H* = high, *M* = medium, *L* = low, and sector: IND = industry, TR = transport, R&C = residential and commerical.

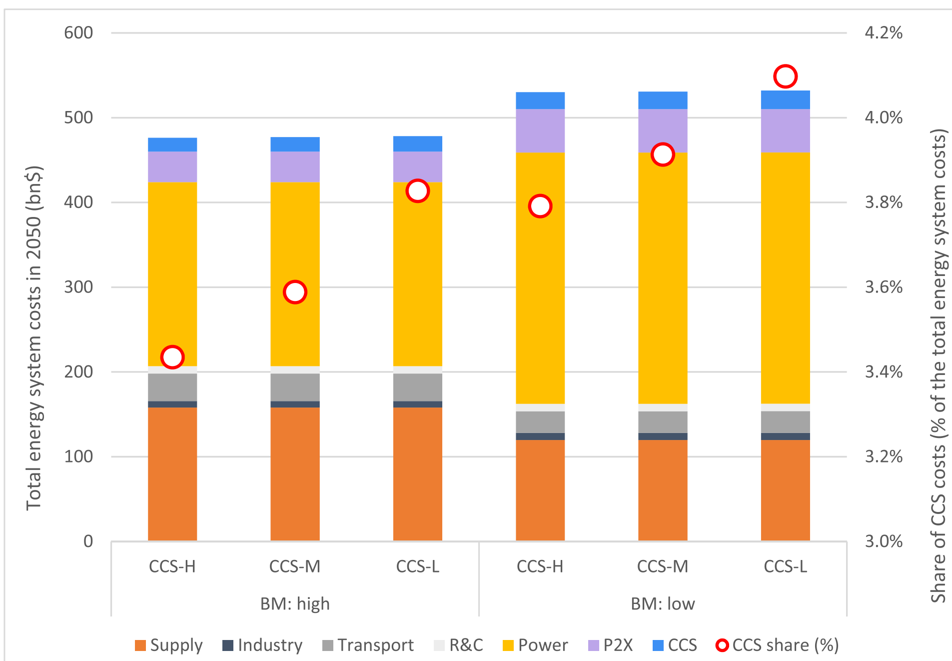

Fig. 7. Total energy system costs per sector, and the relative share of CCS costs for the modelled scenarios in 2050.

2010), causing a shift from onshore to offshore CCS (McCulloch et al., 2016).

From storage potential point-of-view, the is no direct comparison of another estimate for the Rio Bonito formation. The storage capacity of the whole Paraná basin is estimated at 462 Gt CO_2 (Ketzer et al., 2007), which is nearly four times higher than the maximum storage potential of 120 Gt CO_2 in the Rio Bonito formation found in this study. The presence of more suitable formations of the Paraná basin (as also observed in Appendix I) can lead to higher estimates.

4.3. TIMBRA

Capture technologies that are assessed in this study are related to the power- and transport sector. However, there are interesting options for (BE)CCS in the industry as well. Rochedo et al. (2016) show that in Brazil, production facilities for ammonia, cement and steel have potential for CCS. However, the modeling structure of the industrial sector of TIMBRA only assesses the total final energy consumption. To integrate CCS from industrial plants, the demand should be expressed in useful energy, i.e. in tons of produced products. The level of detail of industrial processes in Brazil, and its availability is currently insufficient to transit from final energy to useful energy. Nonetheless, this could create more insight in the required CO_2 infrastructure and the potential benefits of creating hubs and clusters of multiple CO_2 capturing sources (and sinks). The rollout of CO_2 infrastructure is expensive and creating a network to combine different sources might lead to mutual benefits for different sectors, accelerating BECCS deployment.

The annual CO_2 injection rate is determined as a critical parameter that can have large influence on the modeling results of the Brazilian low-carbon energy system (Lap et al., 2019). Rockett et al. (2011) showed that the matched capacity for the Paraná basin is 135 Mt CO_2 per year. However, this injection rate is limited because it is limited by the

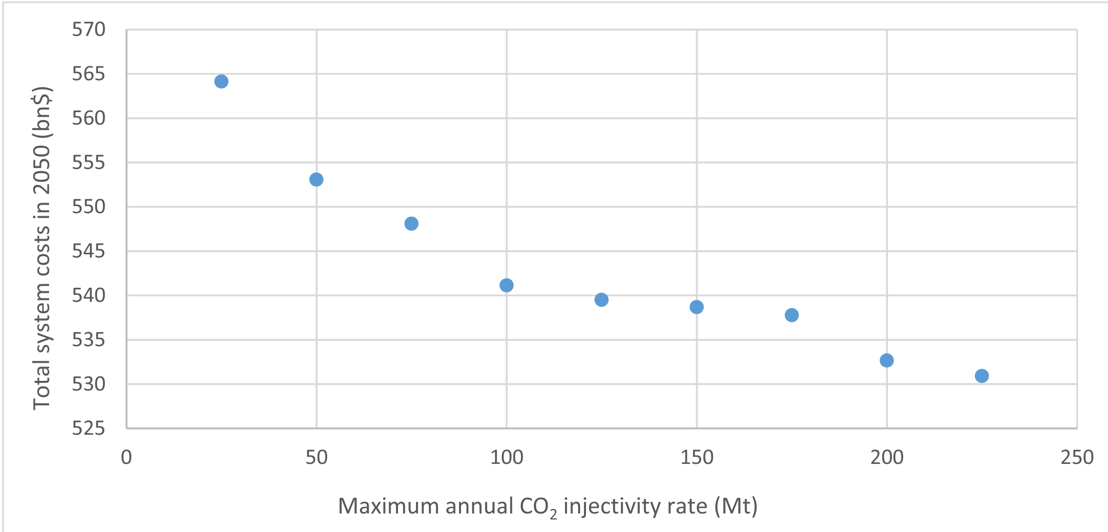

Fig. 8. Pareto analysis showing the relation between the maximum annual injection rate of CO_2 and the total system costs. This analysis is based on the BL-CH scenario.

source side, as this rate is related to the sum of all large CO_2 emitting sources. Rochedo et al. (2018) show that the injection rate in 2050 in Brazil can reach up to 245 Mt CO_2, which is in line with the results in this study. However, they give no details on geological data and storage locations. (Köberle et al., 2020) measured the potential of BECCS in competition to CCS and carbon sequestration by afforestation. They find an accumulated sequestration of CO_2 by BECCS of 2.2 Gt within the period 2010–2050, compared to 2.9 Gt in our study. While their study does not focus specifically on the storage part of BECCS, they show that reforestation or afforestation might reduce the deployment of BECCS, even though atmospheric carbon removal by BECCS remains the most important option.

For a complete source-sink assessment, data on other basins is needed. When this data is available, storage potential and levelized costs can be included in TIMBRA for a thorough assessment. Other basins might be interesting sink locations, as new CO_2 point-sources might be placed closely to other point-sources. Current domestic energy consumption is centralized on the southeast part of Brazil, and consequently the point-sources are concentrated there. International trade of low-carbon energy can for instance result in new point-sources. Other basins that are currently not interesting because there are no large point-sources, can become interesting, as shown for example by Fajardy et al. (Fajardy et al., 2018), investigating the BECCS potential in Brazil to fulfill UK energy demand.

The costs of CO_2 capture technologies are prone to uncertainty. Previously, the sensitivity of costs is studied showing limited effects on the deployment of BECCS technologies (Lap et al., 2019). The costs of ethanol refineries equipped with CCS are based on financial-, mass- and energy flows mentioned in (Bonomi et al., 2016). BECCS costs are extensively studied in Daioglou et al. (2020). The cost ranges shown there are within the explored range of this study. While costs are an important trademark in energy system models, there are more factors that determine deployment trajectories (Daioglou et al., 2020). In this study, the ability for large-scale capture of biogenic CO_2, its potential to deliver low-carbon energy for specific sectors (e.g. the aviation- and freight transport sector) and the ability to store CO_2 in the deep subsurface, are important factors in comparison to alternative strategies (e.g. [in]direct electrification of the industry and the transport sector). The same accounts for CO_2 transport costs, being a share of the total CCS chain. While actual costs for CO_2 transportation may be higher (e.g. to bypass urban areas, or nature conservation areas), it is likely not to influences total injection costs substantially and/or the merit order of CDR technologies.

Conclusion

The total storage capacity of the Rio Bonito aquifer of the Paraná basin is estimated to range between 12 and 117 Gt CO_2, with levelized costs below \$15/t CO_2. The large differences mainly occur because data sources are scarce and data uncertainty is large. Though, the conservative estimates still allow for approximately 50 years of storage capacity under annual injection rates of 250 Mt CO_2/y. Site characterization is responsible for more than 80% of the total costs for geological storage.

Geological storage ranges up to 245 Mt CO_2 in 2050 at maximum, while the total stored CO_2 covers nearly 18% of the Brazilian carbon budget for the period 2010–2050. Biomass is the only source for the stored CO_2, showing that BECCS is preferred above fossil CCS. Although storage potential and associated costs vary widely with respect to the CCS development scenarios, this does only marginally impact the accumulated volume of stored CO_2 as they are approximately the same for all scenarios. The availability of biomass does affect the demand for CCS. When less low-carbon biomass is available, CCS deployment starts earlier, but peaks less towards the end of the modeling horizon. Yet, the total stored CO_2 is nearly the same for all scenarios. Injection locations however, differs per scenario. Under high CCS development, the cheapest locations are selected since there is enough capacity to meet CCS demand. When CCS development is low, injection rate is the major limiting factor which results in the selection of locations with the highest injection rate, although these are sometimes more expensive locations.

Biomass and BECCS play a prominent role in the final energy mix in 2050. The negative emissions from BECCS allow some space to use fossil fuels in those sectors. Approximately 3 EJ of the total final energy consumption in 2050 is met with fossil fuels. This is mainly related to decarbonization of freight transport and industrial processes, which are from cost-competitive point-of-view difficult to decarbonize. The total final energy consumption ranges from 17.1 to 15.1 EJ in 2050, with biomass shares of 54% and 46% for respectively the high- and low biomass scenarios. Energy demand and CO_2 goals are still met when CCS is not used. However, costs increase substantially in that case with bn\$ 33 (+6%), in comparison to the high biomass scenario. This is due to electrification of the transport sector, and the use of hydrogen in both the transport sector and the industry.

BECCS is key option for GHG mitigation in the Brazilian energy mix, but many factors need to be considered to guarantee successful deployment. It is recommended to have more precise geological data for the Paraná basin, and other potential locations. This is needed for precise identification of sink locations, make business cases, but it is also required to make detailed risk assessments to communicate about possible risks such as leakage.

CRediT authorship contribution statement

Tjerk Lap: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **René Benders:** Software, Writing – review & editing, Supervision. **Floor van der Hilst:** Writing – review & editing, Supervision. **André Faaij:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

None

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2023.103945.

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