International Journal of Greenhouse Gas Control 112 (2021) 103503

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

What is the future potential of CCS in Brazil? An expert elicitation study on the role of CCS in the country

Pedro Gerber Machado [a,*], Adam Hawkes [b], Celma de Oliveira Ribeiro [c]

[a] *Department of Chemical Engineering, Imperial College London, London SW7 2AZ, the United Kingdom/Institute for Energy and Environment, University of São Paulo, São Paulo, SP, Brazil*

[b] *Department of Chemical Engineering, Imperial College London, London SW7 2AZ, the United Kingdom*

[c] *Production Engineering Department, University of São Paulo, São Paulo, SP, Brazil*

A R T I C L E I N F O

Keywords:
Carbon Capture and Storage
Net-zero emissions
Expert elicitation
public policies
Brazil

A B S T R A C T

This article presents the results of an expert elicitation about the role of carbon capture and storage (CCS) in Brazil as a measure to reduce greenhouse gases emissions, its costs, and the most appropriate policies to develop this technology at a commercial scale. Experts were elicited based on a scenario oriented towards net-zero emissions in Brazil by 2050. Five parameters were elicited, and all present great uncertainty. Results show that experts believe CCS has the potential to reduce CO_2 emissions in Brazil. Still, with the current lack of supporting market, policy and regulatory frameworks in place, it could take another five years to begin implementation, reaching commercial scale not earlier than 12 years from the time of writing. Experts say that the chance of Brazil reaching the elicited value of 190 million tons of CO_2 per year is very low. This indicates that though CCS can play a role in achieving net-zero emissions in the country, many other measures will be necessary. Policy-wise, the experts bet on a carbon market as the most probable policy instrument to help CCS development in Brazil. The experts also estimated the total investment necessary to reach 190 million tons of CO_2 per year captured at USD 58 billion. When it comes to public expenditures, experts believe the role of the government in funding CCS in the country would be approximately 25% of total investments coming from different sources of public investment.

1. Introduction

Since the publication of the IPCC Assessment Report 5 (IPCC, 2014), which emphatically demonstrates the role of Carbon Capture and Storage (CCS) in reducing Greenhouse gases (GHG) emission and the cost of its mitigation, Negative Emissions Technologies (NET) have been recognised as extremely important, with CCS being a key underpinning technology.

However, it has been noted that CCS knowledge and experience built mainly in North America, Western Europe and Australia, have not yet been deployed at scale to explore CCS technologies (van Alphen, Hekkert and Turkenburg, 2010). The movement of CCS innovation towards a more advanced concept at a larger scale will require direct policy initiatives to foster entrepreneurial activity, market formation, strengthening the innovation system and, in many countries, regulatory guidance (van Alphen, Hekkert and Turkenburg, 2010).

Many uncertainties surround the deployment of CCS at a large scale as a GHG emission mitigation technology. Its development towards a mature business is one example of a technological innovation system (TIS) (Pickard and Foxon, 2013), a "dynamic network of agents interacting in a specific economic/industrial area under particular institutional infrastructure and involved in the generation, diffusion and utilisation of technology" (Carlsson and Stankiewicz, 1991). Developing a TIS such as CCS requires the complex integration between market creation while considering the learning-by-doing effect, and all set up within a stable underpinning legal and political environment (Pickard and Foxon, 2013). Nonetheless, the lack of political support, policy continuity, a clear funding mechanism, and market signals have been identified as the main barriers for CCS (Xenias and Whitmarsh, 2018).

The uncertainties surrounding CCS are even steeper when it comes to Brazil. Despite the Brazilian geological potential for carbon dioxide injection (Netto *et al.*, 2020) of 2035 Gt of CO_2 (Rockett *et al.*, 2011), the current activities in Enhanced Oil Recovery (EOR) for the extraction of crude oil using CO_2 have stored 14 Mt of CO_2 by 2019 (Global CCS

* Corresponding Author.
E-mail address: ppgerber@gmail.com (P.G. Machado).

https://doi.org/10.1016/j.ijggc.2021.103503
Received 12 May 2021; Received in revised form 24 August 2021; Accepted 17 October 2021
Available online 30 October 2021

Institute, 2020a), far from the country`s potential. Furthermore, at the time of writing this article, Brazil scores very low (9 out of 100) in the CCS Policy Indicator created by the Global CCS Institute. The Indicator tracks policies from direct support for CCS to broader implicit climate change and emission reduction policies (Global CCS Institute, 2020b). The absence of a concrete policy structure to promote net-zero emissions technologies is a barrier to CCS deployment (Mascarenhas et al., 2019) and increases the uncertainties against the geological storage of CO_2 in the country.

Based on the above, this study aims to estimate the uncertainties surrounding the future of CCS in Brazil based on an expert elicitation process. The experts are elicited based on their field to contrast CCS potential in Brazil versus the reality regarding storage capacity, mandate policies, taxes, investment demands and the governmental role in financial incentives. Some of the expert responses were then compared to energy and integrated assessment models results for further analysis.

2. Literature review

Expert elicitations are a valuable tool to support policy decision-making, based on structured discussions with experts to obtain estimates for uncertain parameters (O Schmidt *et al.*, 2017). In conditions of uncertainty and limited data availability, expert elicitation encodes the beliefs of experts about uncertain values through a formal interview process to translate those judgments into probabilities that can be used in further analyses. The use of expert elicitations in energy, environmental and carbon capture and storage research is not new (Nemet, Baker and Jenni, 2013), and applications range from risk assessment in CO_2 injection (Gerstenberger and Christophersen, 2016), energy penalties of carbon capture (Jenni, Baker and Nemet, 2013), public engagement with CCS (Xenias and Whitmarsh, 2018), future costs of a variety of technologies, such as carbon capture (Chan *et al.*, 2011; Nemet, Baker and Jenni, 2013), natural gas turbines (Bistline, 2014), water electrolysis (O. *Schmidt et al., 2017*), and the projection of macroeconomic and energy-related variables and their uncertainties (Usher and Strachan, 2013; Zhou *et al.*, 2019). Moreover, results from an elicitation can serve as input for the application of models as in (Gerstenberger and Christophersen, 2016), or compared to model results, as done by Van Sluisveld et al., who compare their elicitation results to integrated assessment model results for solar, wind, biomass, nuclear, and carbon capture and storage under 2°C scenarios (van Sluisveld *et al.*, 2018).

These elicitations generally do not focus on a particular country, and its application to CCS in Brazil is a novelty. The literature on CCS in Brazil presents several technical developments for geological storage (Rockett *et al.*, 2012; Barbero *et al.*, 2020; Costa *et al.*, 2020), studies using assessment models and cost estimation, which will serve as the basis for comparison in the results session (Rockett *et al.*, 2012; Lucena *et al.*, 2014; Nogueira *et al.*, 2014; Rochedo *et al.*, 2016; Köberle *et al.*, 2020; Fragkos *et al.*, 2021), estimation of geological potential (Rockett *et al.*, 2011; Machado, Rockett and Ketzer, 2013; Iglesias *et al.*, 2015) and the social challenges for the development of CCS in the country (Mascarenhas *et al.*, 2019; Netto *et al.*, 2020). However, this elicitation process for the future of CCS in Brazil is a first of its kind.

The following section will discuss the methodology applied in this study, including a short overview of the elicitation process, the parameters elicited, the experts chosen, and the models used for comparison.

3. Methodology

This study aims to understand what measures are necessary to make capture and geological storage of CO_2 a reality in Brazil. To this end, the methodology chosen was the expert elicitation process, which serves to ascertain from the specialists the uncertainty related to a particular problem.

Elicitation is a quantitative analysis developed to construct probability curves for an event to happen; that is, it represents the uncertainties inherent to some event or magnitude (O'Hagan *et al.*, 2006). For example, eliciting experts could find out how long it takes to get from London to Paris. Precisely because it depends on several other variables (travel mode, accidents on the track, and rain, for example), experts are consulted to know the minimum possible time, the maximum possible time and the chance of each travel time occurring.

In the case of CCS in Brazil, we consider the "Scenario oriented towards net-zero emissions." It assumes that private companies are interested in developing the CCS industry in the country and that the government is inclined to use various policies, financial measures, and not financial constraints to coerce (GHG)-emitting industries to deploy CCS to help achieve net zero emissions by 2050.

To quantify the problem, first, a literature review was performed to determine which measures are the most suitable for the development of CCS. Then these measures were converted into variables that can be elicited and have intrinsic uncertainty in them.

The following subsections will detain the elicitation process and its application to the future of CCS in Brazil.

3.1. Brazilian GHG emissions profile

Brazilian GHG emissions profile is shown in Fig. 1. CO_2 emissions represent 65% of total emissions, CH_4 follows with 26% and N_2O, 9%. CO_2 Emissions from the energy and industry sectors account for 21% of total GHG emissions, or 462 $MtCO_{2e}$.

Emissions from land use and land use change in Brazil have been historically the most significant for CO_2, while agriculture emits most CH_4 and N_2O.

Moreover, the country had 600 $MtCO_2$ removed from the atmosphere in 2019 in the land use and forestry sectors, which, when abated from the total GHG emissions shown in Fig. 1, leads to a net total of 1.57 $GtCO_{2e}$.

3.2. Expert Elicitation

O'Hagen et al. (O'Hagan *et al.*, 2006) present a 5-stage protocol to perform an elicitation. The first two steps refer to identifying the variables to be elicited and the choice of experts. The choice of variables intrinsically depends on the problem at hand and will vary according to each objective.

The choice of experts, according to O'Hagen et al. (O'Hagan *et al.*, 2006), should be based on the following:

a) Tangible evidence of expertise (publications, projects participated);
b) Reputation;
c) Availability and willingness to participate;
d) Understanding of the general problem area;
e) Impartiality;
f) Lack of an economic or personal stake in the potential findings.

The other three steps comprehend the interview portion of the elicitation process:

1) Motivate the expert by explaining why their judgments are required and how what they say can be used. Explain the variables that are being elicited and bring out some of the issues that bias the assessment.
2) Structure the elicitation by specifying the quantities analysed, including a specification of their measurement units.
3) Applying one of the elicitation methods (Morris, Oakley and Crowe, 2014):
   a The roulette method: The expert is provided with a grid of m equally sized bins covering the range of X and is asked to allocate n chips between the bins.

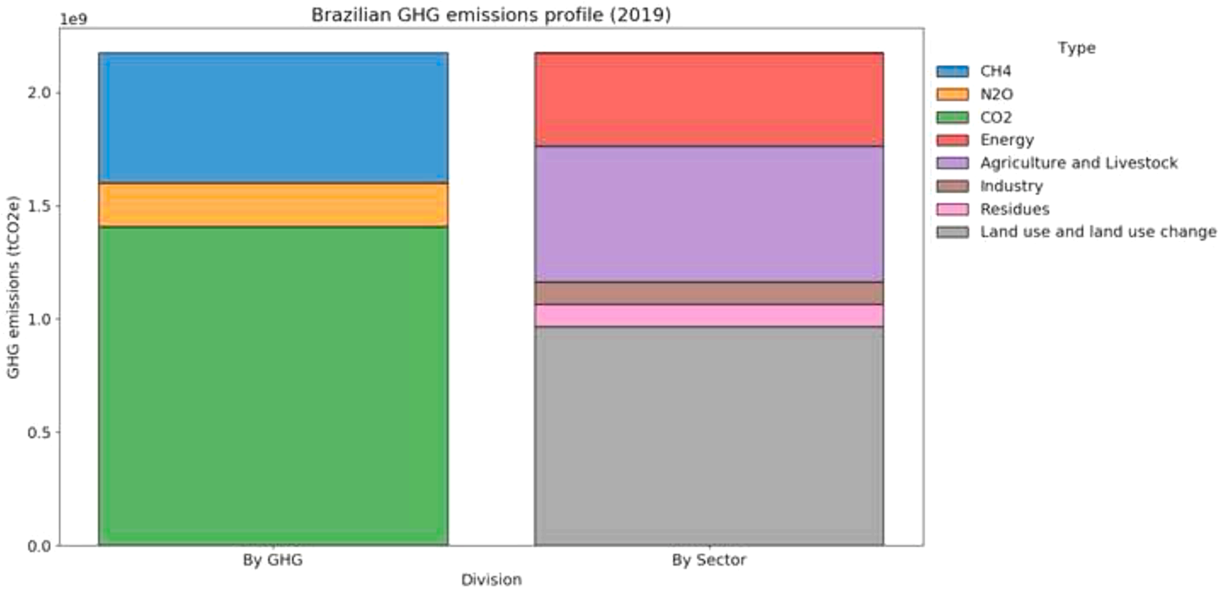

Fig. 1. – Brazilian GHG emissions profiles by major GHG and sectors of the economy in 2019.
Source: (SEEG, 2020).

b The quartile method: The expert specifies the median, lower quartile, and upper quartile of X.
c The tertile method: The expert specifies the median, the 33rd percentile, and the 66th percentile.
d The probability method: The expert specifies three probabilities. If the range of X is [0, 1], then the default probabilities asked for are $P(0 < X < 0.25)$, $P(0.75 < X < 1)$ and $P(0 < X < 0.5)$, but the numbers in these inequalities can be changed.

Since this elicitation is focused on nonexistent events so far, the roulette method has been chosen for all parameters analysed due to its association with bets, giving the expert a more tangible framework to estimate uncertainties. The other methods require real-life experience that the experts lack due to the nature of CCS in Brazil. Knowing statistical parameters such as median average and quartiles in events that have not occurred is a more difficult task than providing a guess. After each expert is elicited, their responses are aggregated to provide insights into the problem, most notably on the uncertainties of the elicited issue.

3.3. Selection of uncertain parameters

Since the objective of this study is to determine the uncertainties in the future of CCS in Brazil, the uncertain parameters selected are related to the central metric of the problem (Verdolini *et al.*, 2018), i.e., storage capacity and to the measures and policies needed to impel the use of CCS in the country. The first two parameters (a) and (b) elicited, shown in Table 1, were designed to capture the timely evolution of carbon capture and storage in Brazil. Instead of eliciting the absolute amount stored in the country, the problem was divided into two parameters with different volumes and the unit was adapted to "year of amount reached." A literature review of the potential for CCS in the country was undertaken to establish the parameter thresholds. The values of 40 million tons of CO_2 per year (parameter (a)) and 190 million tons of CO_2 per year (parameter (b)) were based on Rochedo et al. (Rochedo *et al.*, 2016), who calculated the potential of CCS for 2030. The lowest value in parameter (a) was based only on the electricity generation potential for carbon capture, while the highest volume in parameter (b) considers the full potential calculated, including emissions from oil and gas production, oil refineries, coal and natural gas use in the power sector, and the production of cement, steel and ammonia.

The measures elicited in parameter (c) (CCS mandate, CO_2 tax, CO_2 cap and trade, CCS tax breaks, CCS Subsidies, and Operational support (tariffs)) were also based on the literature. Several measures and policies have been named in the literature and include CO_2 taxes or tax breaks (Araújo and de Medeiros, 2017; Jessica F. Green, 2017; Romasheva and Ilinova, 2019), CCS mandate (von Stechow, Watson and Praetorius, 2011), subsidies (Romasheva and Ilinova, 2019), cap and trade (von Stechow, Watson and Praetorius, 2011; Jessica F. Green, 2017) and direct financial support (Cox, Edwards and Robert Edwards, 2019; Romasheva and Ilinova, 2019). Finally, the financial and economic parameters (d) and (e) were elicited to demonstrate the necessary investments.

Table 1
- Elicited uncertain parameters

Key parameter(x)	Variable description	Unit
a)Capture and storage 1	Year in which Brazil will reach 40 million tons of CO_2 captured and stored in geological sites per year.	year
b) Captureand storage 2	Year in which Brazil will reach 190 million tons of CO_2 captured and stored in geological sites per year.	year
c)CCS policy	The probability associated with each of these policies having a role in developing CCS in Brazil.	Probability (%)
d) CCSinvestment	Present value of the accumulated capital investment needed to achieve the storage in key parameter (b).	Million USD
e)Government share	Government share of the investment in key parameter (d).	Share (%)

Experts were asked to evaluate the parameter uncertainties based on a "scenario oriented towards net-zero emissions." Table 1 shows a description of each parameter elicited. Based on previous studies (Usher and Strachan, 2013), the elicitation was restricted to six parameters to avoid extended interviews. Based on Usher et al. (Usher and Strachan, 2013), this number of parameters is compatible with two-hour interviews.

3.4. Selection of experts

The choice of experts was based on the parameters proposed by O'Hagen et al. (O'Hagan *et al.*, 2006). Brazil is yet in its infancy regarding CCS deployment, and only Enhanced Oil Recovery is performed. For that reason, the existence of experts in the field is limited. However, the increase in attention to CCS globally has led to a rise in professionals in energy, energy policy, climate change policy, and technology involved in CCS activities in Brazil.

The sample size in elicitations has been of interest to scholars, but there is little consensus (Clemen and Winkler, 1999; O'Hagan *et al.*, 2006; Usher and Strachan, 2013). In energy literature, for example, elicitations range from 4 (Bistline, 2014), 7 (Chan *et al.*, 2011), 10 (O Schmidt *et al.*, 2017), to a higher number as 39 (van Sluisveld *et al.*, 2018) and 73 experts interviewed (Zhou *et al.*, 2019). Clemen and Winkler (Clemen and Winkler, 1999) advise using three to five experts due to the little marginal returns of adding experts. Moreover, access to similar evidence by the experts from the same field or area tends to lead to redundant information, then heterogeneity of specialities is preferred over large samples. In total, 19 experts were contacted to be part of the elicitation, and 12 accepted the invitation. The experts were then divided into the areas of affiliation policy, technology or industry. Table 2 shows the number of experts contacted and interviewed per area of affiliation.

3.5. Overview of the elicitation process

After selecting parameters and experts, the interviews were scheduled and performed between October 26th, 2020 and January 18th, 2021. Each interview lasted between 40 minutes and one hour and forty minutes. All of the experts were free to abstain from responding to any of the questions. Table 3 shows each key parameter each expert was able to respond to.

At the start of the interview, experts were introduced to the objective of the study, and a first exemplary round was performed to familiarise the interviewees with the process. The key parameters were explained and detailed, and any further questions from the experts were answered.

For parameters (a), (b), (d) and (e), the elicitation method was used as the roulette method (Morris, Oakley and Crowe, 2014) with a total of five bins available and ten chips available per bin for bets. In the roulette method, experts were asked about a minimum and a maximum value for each parameter. Then, the range between these values was divided into five bins. The expert was allowed to bet up to ten chips for each bin, with ten chips being most certain about that parameter and 0 chips having no confidence that that value would occur. The MATCH tool (Morris, Oakley and Crowe, 2014) for performing elicitations was used to generate the probability curves associated with the bets done by each expert.

After betting their chips, the MATCH tool draws six probability functions (normal, student-t, scaled beta, gamma, Log-Normal, and Log student-t) based on the chips in each bin in Fig. 2. The tool then calculates the least squared error of each probability function and gives the best fit.

For parameter (c), the experts were not asked to draw probability curves but associate a percentage probability of each measure having a role in developing CCS in Brazil. For example, the chance of Brazil establishing a CO_2 tax is "30%", and so on. The measures are not mutually exclusive, meaning the sum of probabilities across measures will not be 100%.

At the end of the elicitation process, the experts were asked of any institution or source of data (reports, studies, scientific papers) they use to stay informed about CCS globally and in Brazil. Table 3 shows the sources of data listed by each expert.

GCCSI: Global CCS Institute, IEA: International Energy Agency, IEAGHG: IEA Greenhouse Gas R&D Programme, SciPa: Scientific Papers, IRENA: International Renewable Energy Agency, DOE: Department of Energy (USA), EPE: Brazilian Energy Research Company, IndAss: Industry associations, OilCom: Oil Companies, IPCC: Intergovernmental Panel on Climate Change, UNICA: Brazilian Sugarcane Industry Association, IBGE: Brazilian Geography and Statistics Institute, EPA: Environmental Protection Agency (USA), Leg: Legislation (BR), SEEG: System for Estimating Greenhouse Gas Emissions and Removals (online), 45Q: American tax credit for carbon sequestration, CM Brazil: Brazilian carbon geological sequestration map (CarbMap project), NPC: National Petroleum Council (USA), OGCI: Oil and Gas Climate Initiative, PetroBr: Petrobrás (Brazilian oil company), COPPE: Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (BR), CSLF: Carbon Sequestration Leadership Forum, UNIDO: United Nations Industrial Development Organization, MCTI: Ministry of Science, Technology and Innovations (BR), IAMC: Integrated Assessment Modelling Consortium. Table 4

The most mentioned institution by experts was the Global CCS Institute, an international CCS think tank and the International Energy Agency. The Ministry of Science, Technology and Innovation and the Brazilian Energy Research Company are the most cited Brazilian institution. Half of the experts have mentioned scientific papers as their source of data.

After the end of the interview round, the probability curves generated by the MATCH tool for parameters (a), (b), (d) and (e) were processed into kernel density functions to simplify visualisation. Kernel density estimation (KDE) is a non-parametric way to estimate the probability density function. It is a technique that allows for creating a smooth curve given a set of data (Rosenblatt, 1956; Parzen, 1962). It is important to highlight that the KDE does not change the initial probability curves and was applied for graphical purposes to depict the results more stylistically. Each expert answer was then plotted individually and aggregated into the field of expertise and for the entire group of experts. For parameter (c), a box plot will show the distribution of answers for each measure (6 measures in total).

3.6. Aggregation of expert beliefs

Usher and Strachan discuss how expert beliefs can be aggregated either by behavioural or mathematical aggregation. (Usher and Strachan, 2013) On the one hand, behavioural aggregation implies simply bringing the experts together and eliciting the parameters for the group as a whole. However, group expert interviews require careful management and were not feasible for this study. The mathematical aggregation was therefore chosen for the aggregation, using an equally weighted linear pool to represent the aggregated belief of experts as shown in Equation 1 (Usher and Strachan, 2013):

$$p(\theta) = \frac{1}{n}\cdot\sum_{i=1}^{n} p_i(\theta) \qquad \text{(Equation 1)}$$

Where n is the number of experts that answered each question, $p_i(\theta)$ represents i's probability of parameter θ, and $p(\theta)$ represents the aggregated probability of parameter θ.

3.7. Selection of assessment studies for comparison

As mentioned in the literature review, the elicitation process results will be compared to other studies to improve the analysis and provide coherent suggestions for future policies. The selection of the proper

Table 2
– Experts affiliation

Expert affiliation	Description	Experts Contacted	Experts interviewed
Policy	Academics of law and policies, energy and environment-related government employees	7	4
Industry	Coal, oil and gas, and infrastructure employees	6	4
Technology	Geologists, engineers, energy systems academics	6	4
Total		19	12

Table 3
– Experts affiliation, elicited inputs and data sources listed by experts

ID	Affiliation	Key param. elicited	Sources of data and information on CCS listed by the expert									
I1	Industry	(a)(b)(c)(d)(e)	GCCSI	IEA	IEAGHG							
I2	Policy	(a)(b)(c)(e)	SciPa	IRENA	IEA	DOE	EPE	IndAss				
I3	Industry	(a)(b)(c)(d)(e)	GCCSI	IEA	OilCom	CCS projects	Thesis	SciPa				
I4	Technology	(a)(b)(c)(e)	SciPa	IPCC	IEA	DOE	GCCSI	UNICA	IBGE	EPA		
I5	Policy	(a)(b)(c)(d)(e)	GCCSI	SciPa	IEA	Leg						
I6	Policy	(a)(b)(c)(d)(e)	GCCSI	IEA	Northern Lights project	SEEG						
I7	Policy	(a)(b)(c)(d)(e)	45Q	CM Brazil	GCCSI							
I8	Industry	(a)(b)(c)(d)(e)	NPC	OGCI	IEA	GCCSI	PetroBr	COPPE				
I9	Technology	(a)(b)(c)(e)	IEA	GCCSI	CSLF	IEAGHG	DOE	UNIDO	PetroBr	OGCI	MCTI	EPE
I10	Technology	(a)(b)(c)(d)(e)	MCTI	SciPa								
I11	Industry	(a)(b)(c)(d)(e)	GCCSI	IEA	SciPa							
I12	Technology	(a)(b)(c)(d)(e)	SciPa	IAMC	GCCSI							

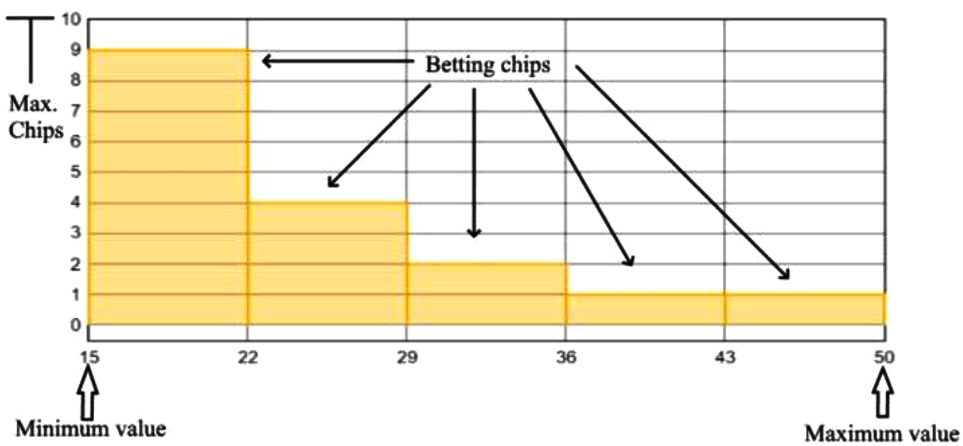

Fig. 2. – Exemplifying overview of the MATCH elicitation tool.
Source: (Morris, Oakley and Crowe, 2014).

Table 4
– Key studies used for comparison

Source	Method	Variables available	Time horizon
(Rockett *et al.*, 2012)	Data review and analysis	Potential capture and storage, costs	2025
(Rochedo *et al.*, 2016)	Data review and analysis	Potential capture and storage, costs	2030
(Köberle *et al.*, 2020)	BLUES model	Carbon sequestration for 1.5°C scenario	2050

studies was a matter of finding papers highlighting the role of CCS in Brazil to reduce emissions. Moreover, the results of the study must be disaggregated enough to allow for direct comparison. A few studies have analysed the potential and the costs of CCS in the country, but not all provide correct information for comparison. For example, (Lucena *et al.*, 2014) compare several energy models applied to Brazilian energy systems and analyse the role of CCS. Still, their results do not specify the amount of CO_2 captured and stored. Most of their results are shown in energy produced and total emissions from the system. The same goes for (Nogueira *et al.*, 2014) and (Fragkos *et al.*, 2017), who consider CCS an option for CO_2 emissions reduction in Brazil, but how they depict their results hinders the comparison with this elicitation, in particular.

Due to these barriers, three studies have been chosen, which explicitly estimate the potential capture and storage and, in 2 cases, calculate CCS costs in the country. To compare costs, the answers from experts for parameter (d) were translated into total costs based on the share of capital costs in total CCS costs published by the Global CCS Institute (Irlam, 2017), which vary from 59 to 67% depending on the rate of return. The capital cost elicited in question (d) has been annualised based on a range of return rates from 8 to 12 %- and a 30-years project lifetime. The annualised cost was then divided by the 190 million tons of CO_2 captured and stored to generate the cost per ton of CO_2 captured. Outliers have been removed from the plotted results in Fig. 8.

Since this study brings novel information such as the one obtained from parameters (c) and (e), they cannot be compared to any literature on CCS in Brazil.

4. Results

4.1. Capture and storage potential

Although CCS in Brazil is restricted to EOR and has not been used for emissions reductions, experts have mentioned that the experience acquired from this activity in the last decade indicates that the country can develop this technology. Moreover, experts also point out that the geological storage potential of Brazil is enough to support thousands of years of CO_2 emissions from stationary sources, including bioenergy.

However, experts highlight the priority in emissions reductions when it comes to the Brazilian profile. While in many high-income countries, emissions mainly come from electricity, transport and industry sectors, in Brazil, GHG emissions are mostly associated with land-use change and agriculture, responsible for approximately 70% of Brazilians gross emissions (SEEG, 2020).

Experts have mentioned that CCS becomes secondary with this particular GHG emissions profile, requiring more short-term efforts to contain deforestation and increase reforestation. Nonetheless, most of the experts still see room for CCS in the country, considering the scenario studied in this elicitation in which "the government is inclined to use various policies, financial measures and not financial constraints to coerce (GHG)-emitting industries to deploy CCS to help achieve net zero emissions by 2050". In general, the experts were more confident that the first level of capture elicited of 40 million tons of CO_2 per year would be reachable. In contrast, the 190 million ton of CO_2 level was considered highly unlikely.

Fig. 3 shows parameter (a) results for individual responses (left) of the experts, their responses aggregated by area of expertise (centre), and the total aggregated responses (right). Only one did not believe the amount of CO_2 capture and storage in the country would ever reach 40 million tons per year from twelve experts. From the remaining eleven, responses vary from 2025 up to 2100 to reach the potential mentioned.

In the first level of grouping, considering their areas of expertise, the industry sector experts seem to be less optimistic regarding CCS development in the country. In contrast, experts involved in technology development tend to have a more positive response regarding 40 million tons of storage. Finally, the aggregated response shows a 50% chance that Brazil will reach 40 million tons of CO_2 captured and stored in 2048.

The response was less optimistic for 190 million tons of CO2 captured and stored per year, as shown in Fig. 4. Out of 12 experts, only six believed there is any chance of reaching this volume. Of the non-believers, half were from the industry, two from policy and one from technology sectors. From the six "believers", the responses varied from the year 2040 up to 2180. Again, the reactions of the industry sector showed the longest time to reach such volume of CO_2 stored. In this case, experts from the policy sector were the most optimistic. When it comes to the overall aggregation based on the experts that believe 90 million tons of CO_2 per year is possible, there is a 50% that Brazil will reach 190 million tons of CO_2 by 2060, which surpasses the 2050 limit to net-zero considered in this study.

On the other hand, considering that half of the experts believe 190 million tons of CO_2 stored will never happen, the 2060 threshold becomes the 25% quantile (half of the experts said they did not think this amount would ever be reached). Mathematically speaking, this makes the median undefined since saying something will never happen is equivalent to saying it will happen in the infinite. Therefore, considering all experts responses, reaching this storage level has a 25% chance of happening in 2060. In Fig. 4, the straight line on the chart on the right represents the median when the group called "Believers" is considered, or the 25% quartile if all experts' responses are considered.

Some of the barriers mentioned to reach 40 or 190 million tons per year in Brazil were the lack of regulation, the lack of governmental support and the lack of infrastructure. Experts mentioned the lack of natural gas or ethanol pipeline development to substantiate their pessimism towards developing and disseminating robust CO_2 pipelines to connect CO_2 emitters and the geological storage sites available. The size of the country and storage location distance have also been mentioned as barriers to CCS. Moreover, the most cost-effective storage options in the country, reported by one of the experts, are associated with shale formations. CCS in these formations would increase revenues from shale gas and decrease overall costs. However, there is considerable resistance from oil and gas companies due to the environmental problems linked to shale gas and the opposition of society towards its exploitation. Moreover, the exploitation of shale gas in the country is not yet regulated.

One of the experts mentioned that new research projects have recently started on deeper layers of geological formations, which would take approximately four years. From then, demonstration plants could start being built in the country. With 6-8 years, the country would finally reach the commercial stage of large-scale CCS. This would mean that commercial-scale CCS in Brazil would not happen before 2033.

Bioenergy with CCS (BECCS) has been mentioned as the most interesting CCS application in the country due to the proximity of existing mills to storage sites and the possibility of converting ethanol sugarcane and bagasse electricity into negative-emissions energy carriers. However, in general, experts` beliefs in CCS were not affected by the potential of BECCS in the country, nor does it indicate that CCS will happen sooner.

4.2. Measures and policies to develop CCS in Brazil

The lack of CCS applications in the country as a CO_2 emissions-reduction technology in the short to mid-term is not a matter of lacking storage capacity, but the late start on infrastructure development and the late start of research on geological formations.

In general, the lack of policies to unlock commercial-level CCS creates a snowball effect on other barriers. Therefore, the experts were asked to estimate the probability of a set of policies to develop CCS in

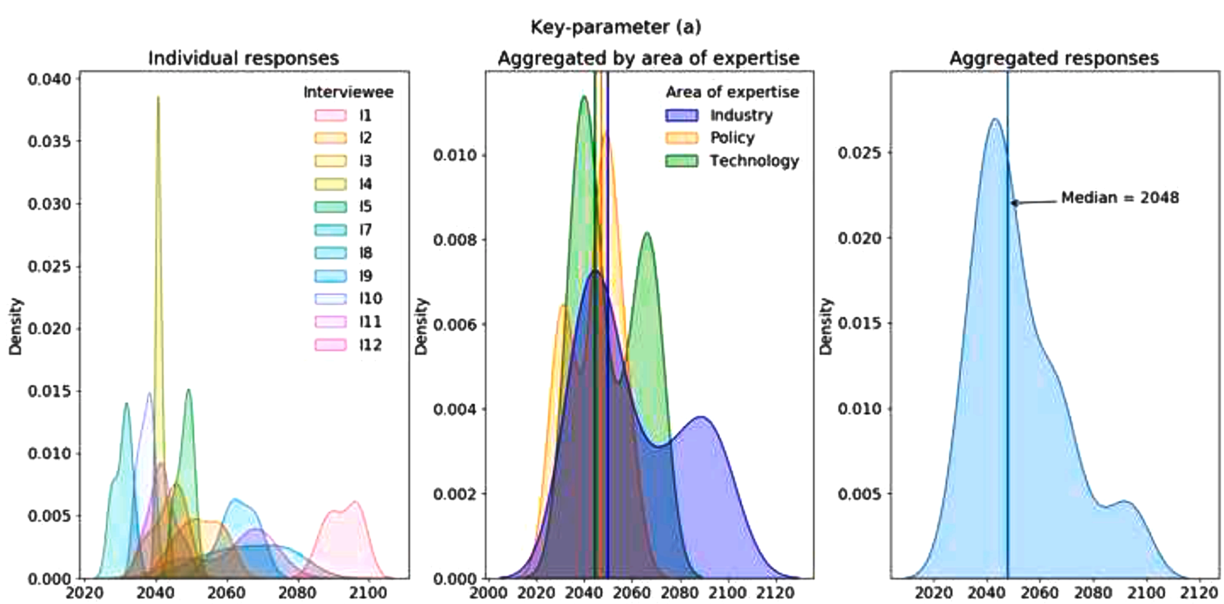

Fig. 3. – Results for key parameter (a) - Year in which Brazil will reach 40 million tons of CO_2 captured and stored in geological sites per year, for individual experts (left), aggregated by area of expertise (centre) and total aggregation (right). The vertical lines in the figures in the centre and on the right represent the median of the variable for each group. Note that vertical scales differ between sub-plots for legibility.

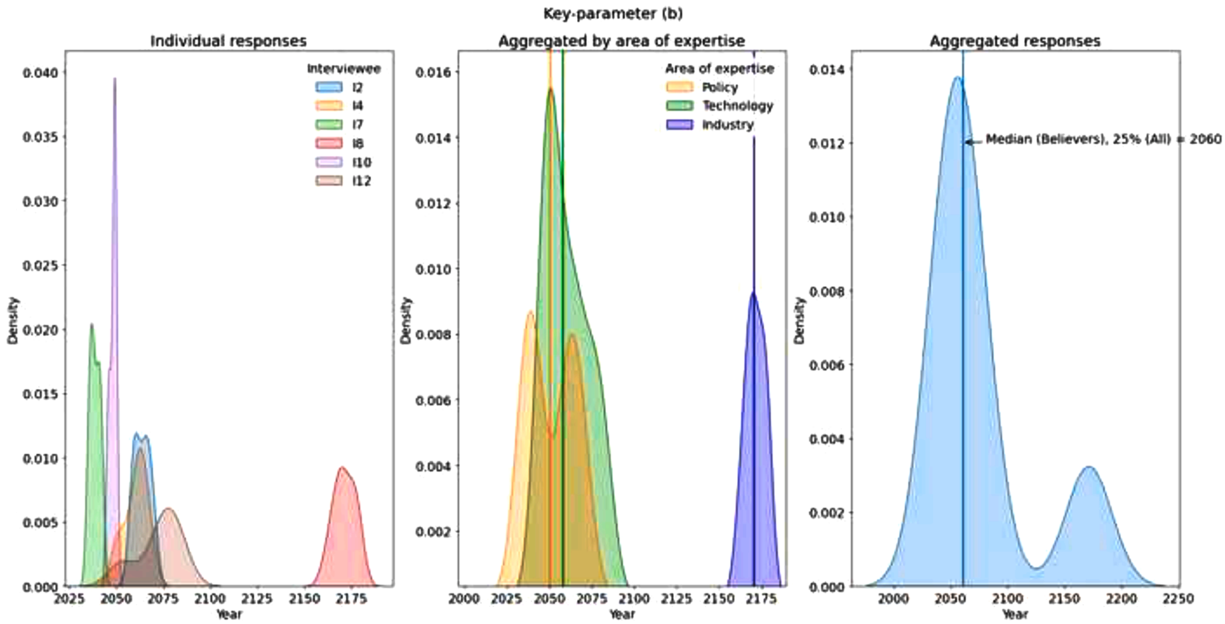

Fig. 4. – Results for key parameter (b) - Year in which Brazil will reach 190 million tons of CO_2 captured and stored in geological sites per year, for individual experts (left), aggregated by area of expertise (centre) and total aggregation (right). The vertical lines in the figures in the centre and on the right represent the median of the variable.

Brazil.

Fig. 5 shows the box plot of each policy and the beliefs of experts. The policies are not mutually exclusive and would probably take place as a package of policies. Nonetheless, the experts believe establishing a carbon market would be the most probable policy to develop CCS, with an average chance of 65% of happening.

Most experts mentioned the development of the Biofuel Decarbonisation Credit (CBIO), a financial instrument to attract investments focusing on expanding biofuel production established in 2017. BECCS could already be boosted with CBIO since negative emissions in the ethanol industry would mean more credits sold. However, experts mentioned that the current low price of 10 USD per credit is too low for CCS applications, including BECCS. The experts also mentioned a global preference for measures that help monetise the efforts to reduce emissions, as is the Low Carbon Fuel Standard case in California.

Followed by the carbon market, tax exemptions are the most probable policy to be in place. Experts mentioned that this already happens in the country in the infrastructure and energy sectors. One of the experts noted the Special Incentive Scheme for Infrastructure Development (REIDI), instituted in 2007, which suspends two federal taxes levied on goods and services projects aimed at the implementation of infrastructure: the Contribution to the Social Integration and Training Program for the Property of Civil Servants (PIS/PASEP) and the Contribution to the Financing of Social Security (COFINS) in the sectors of transport, ports, energy, basic sanitation and irrigation. These federal taxes represent aliquots of 1.65 and 7.6% over gross income, respectively.

Experts are most divided when it comes to taxation of CO_2 emissions, with a 50% chance of having a role in developing CCS in Brazil. While

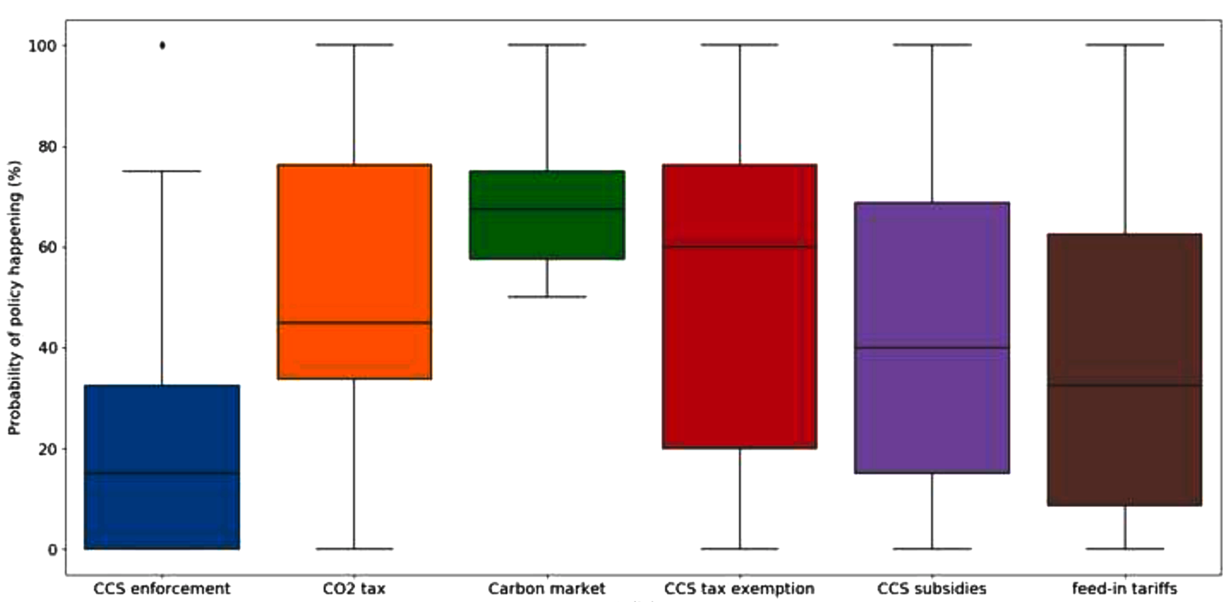

Fig. 5. – Results for key parameter (c) - Probability associated with each policy of having a role in developing CCS in Brazil.

some experts mention the interest of politicians to increase government income, others point out that the current political environment of the country is to cut down taxes, not create new ones. Experts did mention the ongoing project in the country, which aims to discuss the convenience of including emissions pricing (via tax and carbon market) in the package of instruments aimed at implementing the National Policy on Climate Change.

There is also disagreement towards CCS subsidies in the country, with a 42% chance of happening. However, there are examples of subsidies such as the Energy Development Account (CDI), Light for All Program, and direct subsidies for the coal, oil and gas industries of the country. Approximately USD 20 billion have been directed towards these industries in direct payments or tax exemptions in 2019 (INESC, 2020).

Finally, the least probable policies to develop CCS in the country are feed-in tariffs and CCS enforcement. Feed-in tariffs have a higher probability of happening than CCS enforcement, but some experts say there is a low chance of occurring because of the impact on final prices for consumers. On the other hand, the experts said enforcing a particular technology was not common in Brazil. Nonetheless, one expert mentioned a 100% chance that CCS would be enforced on coal-based thermopower plants.

Experts also roughly estimate a timeline for policy implementation in Brazil. Without any regulation or specific law for CCS before 2021, experts expect the first legislation to start its approval process in 2022. With an average time of two years for processing, this law would have to be regulated, which could take approximately one year. After law approval and regulation, there is still the bestowal for CCS operations, which could take another year.

4.3. Investments

The total capital investment to reach 190 million tons of CO_2 captured per year was the least answered parameter due to its difficulty to be estimated. Three experts chose not to answer this question because there is great variability in CCS costs and most of the data comes from international experiences rather than Brazilian applications. The individual answers are shown in Fig. 6 (left) and indicate the uncertainty surrounding the topic of costs. Experts estimated a total accumulated capital cost ranging from USD 10 billion to USD 1 trillion. On average, Fig. 6 (centre) shows that policy experts believe CCS will have higher costs than those experts in the technology field.

Fig. 6 (right) shows a 50% chance that the accumulated capital cost of CCS in the country will reach USD 58 billion in the aggregated response.

Experts mentioned that the capital cost is uncertain, but not only because there is little knowledge on the actual costs of CCS but also because there is a different type of technology for each industry or sector. The costs also depend on the quality of CO_2 and the characteristics of storage systems.

This total capital cost to reach 190 million tons of CO_2 captured and stored per year is equivalent to 32 USD/ton (30 years, 10% return). Two experts mentioned that total costs (i.e., capital cost plus operational costs) could range from USD 70 to USD 400 per ton of CO2 captured and stored during the elicitation (capital and operating costs).

4.4. Government share of investment

The government share of investment is an important parameter, especially for developing countries like Brazil. With high government expenditures and a lack of public services, Brazil has little room to fund large-scale infrastructure projects, let alone CCS. Public expenses towards CCS are not uncommon globally, but such variable is overseen in most research and modelling exercises. In this elicitation, this parameter is innovatively estimated and is presented in Fig. 7.

Experts, in general, have a low expectation regarding the participation of public funding in CCS development. The industry sector has lower expectations with approximately 15% of the government share, while the policy experts believe in a higher median share of 40% of the government share (Fig. 7, centre). Overall, a median of 24.7% participation on overall government investments was estimated, which would reach USD 14.3 billion of investments to capture and store 190 million tons of CO_2 per year.

The experts were asked to estimate this value based not only on direct investment but also on tax exemptions, subsidies, and loans by development banks (which lend money with a lower rate of return, reducing the overall capital cost of the project). The value estimated is comparable to the amount of government support the oil and gas industry received in 2019 of USD 20 billion (INESC, 2020).

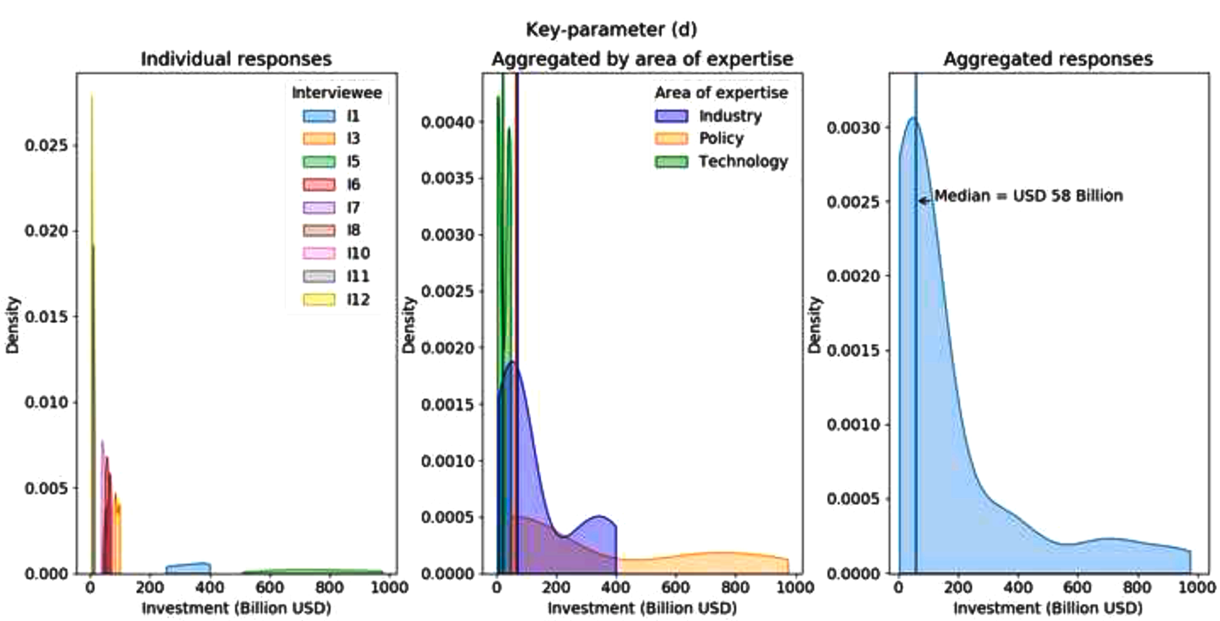

Fig. 6. – Results for the key parameter (d) - Present value of the accumulated capital investment needed to achieve 190 million tons of CO_2 per year.

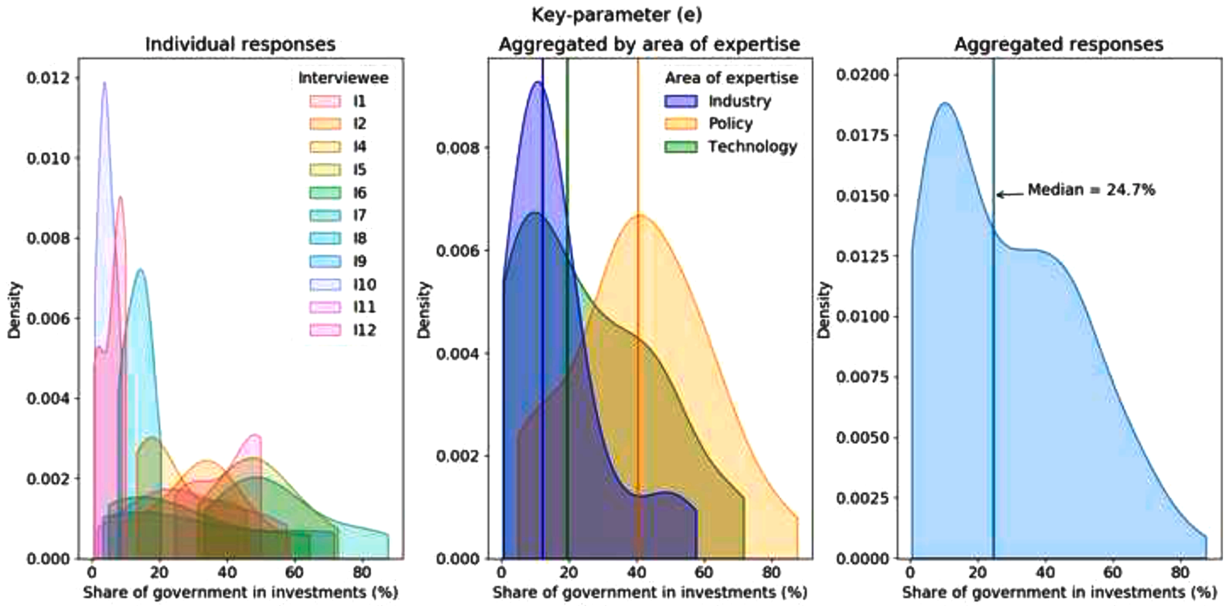

Fig. 7. - Results for the key parameter (e) - Government share of CCS investment (for 190 million tons of CO_2 per year).

4.5. Literature comparison

The elicited parameters (a), (b) and (d) have been compared to other results in the literature to broaden the discussion. Fig. 8 (left) shows the CCS potential found in (Rockett *et al.*, 2012), (Rochedo *et al.*, 2016), (Köberle *et al.*, 2020) and the results for parameters (a) and (b) of this elicitation. On the right, the costs in USD/ton calculated from parameter (d) are compared to the cost estimation published in (Rockett *et al.*, 2012) and (Rochedo *et al.*, 2016).

In terms of volume potential of capture and storage, (Rockett *et al.*, 2012) estimate a potential of 36 million tons of CO_2 stored per year by 2025. The authors calculate the costs per ton of capture and storage based on the technology needed to reach this volume and present costs associated with capturing 10 million tons of CO_2 per year. (Rochedo *et al.*, 2016) estimated 190 million tons of CO_2 captured yearly by 2030, while in this elicitation, experts estimated this volume to be reached in 2060. (Köberle *et al.*, 2020) in their recent study shed new light on the role of CCS in Brazilian GHG emissions reductions. The authors estimated, based on their BLUES model (Brazil Land Use and Energy System model), the necessary amount of CO_2 to be captured and stored by 2050 in different scenarios. Fig. 8 (left) shows their scenario compatible with a 1.5°C global average temperature increase, which considers net-zero emissions by the country. The authors estimate that 50 million tons of CO_2 will have to be stored by the oil and gas industry and 737 million tons of CO_2 from BECCS by 2050. However, the authors state that reaching this volume in the country is complex and that policies supporting and regulating CCS in Brazil are lacking.

This scenario is not shared with other regions of the world. The global CCS institute state that in 2020 17 new commercial facilities have entered their database in different stages of development compared to 2019, representing a 33% increase in capacity in a year, despite the COVID-19 pandemic. The recent advancements in CCS facilities

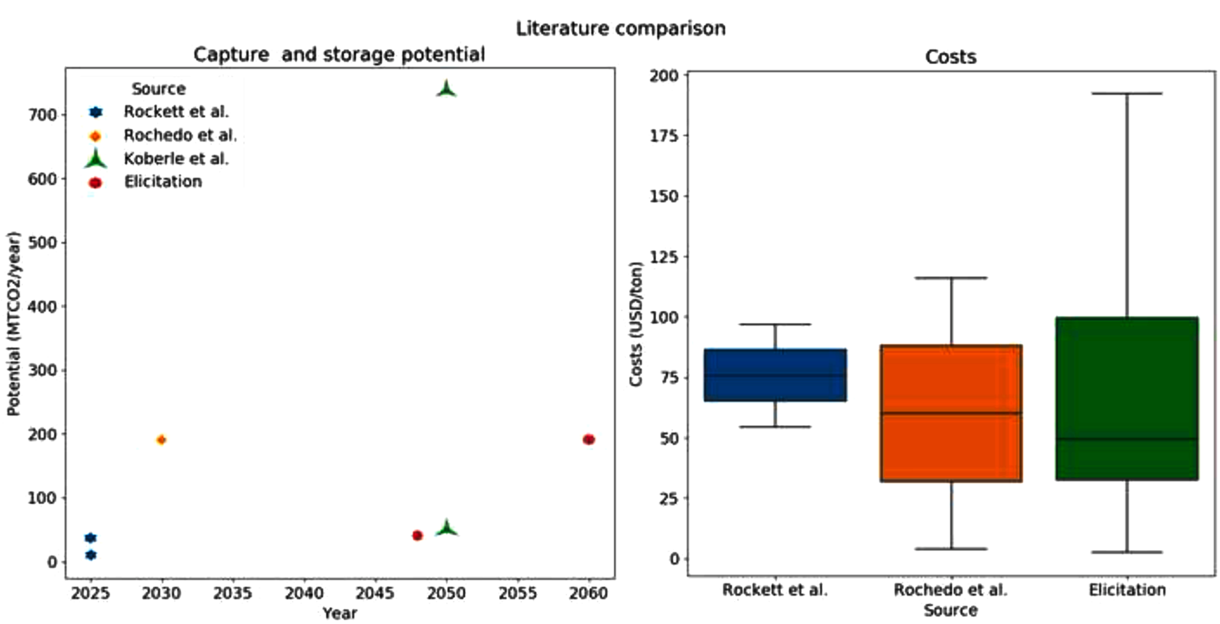

Fig. 8. – Comparison of elicitation results to the existing literature on capture and storage potential (left) and CCS costs (right).

reported by the Institute are due to the technological progress in the field and strong policy support. Some examples worldwide are the 45Q tax credit and the California Low Carbon Fuel Standard (LCFS) that incentivised new CCS projects in the USA. The US Department of Energy commitment to award more than $270 million in co-funding agreements in 2020 has also boosted the implementation of CCS projects in the country. In Canada, the Government of Alberta launched the $80 million (CAD) Industrial Energy Efficiency and CCUS grant program, providing up to 75 per cent of project expenses up to $20 million. In Europe, The European Green Deal and Climate law converting the political commitment to climate neutrality into a legal obligation has led to the development of additional EU policy supportive of CCS, leading to the launch of the first call for projects under the EU's €10 billion Innovation fund. In Australia, An AUD50 million CCUS development fund and regulatory CCS frameworks federally and in several state jurisdictions have been established. Other countries like Saudi Arabia, the United Arab Emirates and Iran, Iraq and other seven explicitly mention the role of CCS in their NDC as a strategy to decarbonise their economies.

Currently, there are no investments in Brazil, and CCS has not yet been included in Brazilian NDC as a measure to fight climate change. While there is research investment in regulatory practices and to determine storage potential in the country, no companies have financed the construction of storage sites. On the capture side, Brazil lacks examples of private or public companies besides Petrobras in its application in EOR. This example is the only CCS application in the country since 2011 when the Miranga CO_2 injection demonstration project was terminated.

For costs, parameter (d) results were converted into total costs per ton of CO_2 captured and stored to compare with other studies. The estimated range of total cost per ton of CO_2 stored for Brazilian CCS in this elicitation encompasses the country-specific studies found in the literature, i.e., (Rockett *et al.*, 2012) and (Rochedo *et al.*, 2016), with a median of 49 USD/tonCO_2, the first quartile of 32 and the third quartile of 99 USD/tonCO_2. The range of values capture the choice of the rate of return (between 8 and 12%) and also reflect the uncertainty of CCS activities in the country, according to the experts participating in this elicitation.

Additionally, the global CCS institute provides information on costs for a range of applications. Although not country-specific as the publications used in Fig. 8, their values vary from 20 USD/tonCO_2 in gas processing and ethanol facilities to 130 USD/tonCO_2 in cement plants. Again, the values found in this elicitation encompass the range presented by the Institute (Irlam, 2017).

5. Conclusions

In this study, an expert elicitation was performed on the CCS industry in Brazil. Potential, total and public costs and the possible measures to develop CCS in the country have been estimated based on 12 interviews with experts from different fields of expertise. The assessments presented in this study suggest that CCS can become an important tool to reduce CO_2 emissions in Brazil. However, other GHG emission reduction measures in the land-use change and agriculture sectors are most needed. With the current lack of regulations and laws, the CCS kick-start should take another five years, reaching commercial scale in at least 12 years. This indicates that Brazil is falling behind compared to other regions in the world, which already have governmental incentives and regulations in place, such as the USA, Australia and Canada. While these countries will see commercial-scale facilities still in this decade, despite the COVID-19 pandemic, Brazilian slow pace to regulate CCS activities will push its advent to almost mid-century.

Expert beliefs regarding potential vary greatly, but Brazil has a chance to reach 40 million tons of CO2 per year before 2050. 190 million tons of CO_2 per year, on the other hand, appears very improbable, as half of the experts believe there is a 0% chance of Brazil reaching this volume of stored CO_2, with a 25% chance of achieving this value in 2060, considering all experts responses. Other authors estimate a necessary capture and storage of four times this value to match the emission profile compatible with a 1.5ºC global temperature increase, indicating that CCS shall be in place to reach net-zero emissions.

Policy-wise, the experts bet on establishing a carbon market to help CCS development in Brazil. Tax exemptions for building the necessary infrastructure and taxation on CO_2 emissions follow the carbon market as the most probable policies to be in place.

The experts also estimated the total investment necessary to reach 190 million tons of CO_2 per year, at a capital cost of USD 58 billion, translating into approximately 32 USD/ton of CO_2 captured and stored based on a 10% return rate. The total cost calculated based on this capital cost ranges from 45 to 56 USD/ton, which is on the lower end of the values are presented in the literature.

When it comes to public expenditures, experts believe the role of the government in funding CCS in the country would be 24.7% of total investments coming from subsidies, direct investments through development banks and tax exemptions. Experts are most influenced by the current political environment of the country, which is seeking to reduce government public services and investments.

Finally, future research could use the results in this elicitation in modelling exercises (general equilibrium models, agent-based models, energy models), testing the policies elicited to understand the most efficient to deploy CCS in Brazil. Other elicitations could also be performed to include other capture and storage options for the country, such as direct-air CO_2 removal and reforestation.

CRediT authorship contribution statement

Pedro Gerber Machado: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Adam Hawkes:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Celma de Oliveira Ribeiro:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the Institute of Energy and Environment, University of São Paulo and support from SHELL Brazil and FAPESP through the "Research Centre for Gas Innovation (RCGI) hosted by the University of São Paulo" (FAPESP Grant Proc. 2014/50279-4). PGM would like to thank CNPq (Brazilian National Research Council), process number 205987/2018-4, for the financial support. COR received support from CNPq grant number 307126/2018-8.

References

van Alphen, K., Hekkert, M.P., Turkenburg, W.C., 2010. Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. International Journal of Greenhouse Gas Control 4 (2), 396–409. https://doi.org/10.1016/j.ijggc.2009.09.019.

Araújo, O., de, Q.F., de Medeiros, J.L., 2017. Carbon capture and storage technologies: present scenario and drivers of innovation. Current Opinion in Chemical Engineering 22–34. https://doi.org/10.1016/j.coche.2017.05.004.

Barbero, M., et al., 2020. Technology readiness assessment of ultra-deep salt caverns for carbon capture and storage in Brazil. International Journal of Greenhouse Gas Control 99 (June), 103083. https://doi.org/10.1016/j.ijggc.2020.103083.

Bistline, J.E., 2014. Energy technology expert elicitations: An application to natural gas turbine efficiencies. Technological Forecasting and Social Change 86, 177–187. https://doi.org/10.1016/j.techfore.2013.11.003.

Carlsson, B., Stankiewicz, R., 1991. Evolutionary Economics On the nature, function and composition of technological systems. J Evol Econ.

Chan, G., et al., 2011. Expert elicitation of cost, performance, and RD&D budgets for coal power with CCS. Energy Procedia 2685–2692. https://doi.org/10.1016/j.egypro.2011.02.169.

Clemen, R.T., Winkler, R.L., 1999. Combining Probability Distributions From Experts in Risk Analysis. Risk Analysis.

Costa, P.V.M.da, et al., 2020. Parametric study and geomechanical design of Ultra-deep-water Offshore Salt Caverns for Carbon Capture and Storage in Brazil. International Journal of Rock Mechanics and Mining Sciences 131, 104354. https://doi.org/10.1016/j.ijrmms.2020.104354.

Cox, E., Edwards, N. R. and Robert Edwards, N. (2019) 'Climate Policy Beyond carbon pricing: policy levers for negative emissions technologies Beyond carbon pricing: policy levers for negative emissions technologies'. doi: 10.1080/14693062.2019.1634509.

Fragkos, P., et al., 2017. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy 100, 216–226. https://doi.org/10.1016/j.enpol.2016.10.023.

Fragkos, P., et al., 2021. Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States'. Energy 216. https://doi.org/10.1016/j.energy.2020.119385.

Gerstenberger, M.C., Christophersen, A., 2016. A Bayesian network and structured expert elicitation for Otway Stage 2C: Detection of injected CO2 in a saline aquifer. International Journal of Greenhouse Gas Control 51, 317–329. https://doi.org/10.1016/j.ijggc.2016.05.011.

Global CCS Institute (2020a) *Facilities - Global CCS Institute*.

Global CCS Institute (2020b) *Policies - Global CCS Institute*.

Iglesias, R.S., et al., 2015. Carbon capture and geological storage in Brazil: an overview. Greenhouse Gases: Science and Technology 5 (2), 119–130. https://doi.org/10.1002/ghg.1476.

INESC (2020) *Subsídios ao combustíveis fósseis no Brasil: conhecer, avaliar e reformar*. Available at: https://www.inesc.org.br/wp-content/uploads/2020/12/EstudosFosseisPT_Errata.pdf?x13944 (Accessed: 8 March 2021).

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Z., T., Edenhofer, J.C.M., Pichs-Madruga, O., R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C. (Eds.), Cambridge, United Kingdom. Cambridge University Press, New York, NY, USA.

Irlam, L., 2017. Global Costs of Carbon Capture and Storage. Global CCS Institute. Available at: https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf (Accessed: 9 March 2021).

Jenni, K.E., Baker, E.D., Nemet, G.F., 2013. Expert elicitations of energy penalties for carbon capture technologies. International Journal of Greenhouse Gas Control 12, 136–145. https://doi.org/10.1016/j.ijggc.2012.11.022.

Jessica F. Green (2017) 'Don't link carbon markets', *Nature*. Available at: https://ssrn.com/abstract=1086242 (Accessed: 31 March 2020).

Köberle, A. C. et al. (2020) 'Brazil's emission trajectories in a well-below 2°C world: the role of disruptive technologies versus land-based mitigation in an already low-emission energy system', *Climatic Change*. Climatic Change, 162(4), pp. 1823–1842. doi: 10.1007/s10584-020-02856-6.

Lucena, A. F. P. et al. (2014) 'Climate policy scenarios in Brazil: A multi-model comparison for energy', *Energy Economics*. Elsevier B.V., 56, pp. 564–574. doi: 10.1016/j.eneco.2015.02.005.

Machado, C.X., Rockett, G.C., Ketzer, J.M.M., 2013. Brazilian renewable carbon capture and geological storage map: Possibilities for the paraná basin. Energy Procedia 6105–6111. https://doi.org/10.1016/j.egypro.2013.06.539.

Mascarenhas, K. L. et al. (2019) 'Challenges for the Implementation of Carbon Capture and Storage (Ccs) in Brazil: a Socio-Technical Approach', *Polytechnica*. Springer Science and Business Media LLC, 2(1–2), pp. 1–8. doi: 10.1007/s41050-019-00016-z.

Morris, D.E., Oakley, J.E., Crowe, J.A., 2014. A web-based tool for eliciting probability distributions from experts. Environmental Modelling and Software 52, 1–4. https://doi.org/10.1016/j.envsoft.2013.10.010.

Nemet, G. F., Baker, E. and Jenni, K. E. (2013) 'Modeling the future costs of carbon capture using experts' elicited probabilities under policy scenarios', *Energy*. Elsevier Ltd, 56, pp. 218–228. doi: 10.1016/j.energy.2013.04.047.

Netto, A.L.A., et al., 2020. A first look at social factors driving CCS perception in Brazil: A case study in the Recôncavo Basin. International Journal of Greenhouse Gas Control 98. https://doi.org/10.1016/j.ijggc.2020.103053.

Nogueira, L. P. P. et al. (2014) 'Will thermal power plants with CCS play a role in Brazil's future electric power generation?', *International Journal of Greenhouse Gas Control*. Elsevier, 24, pp. 115–123. doi: 10.1016/j.ijggc.2014.03.002.

O'Hagan, A., et al., 2006. Uncertain judgements: Eliciting experts' probabilities. Uncertain Judgements: Eliciting Experts' Probabilities. https://doi.org/10.1002/0470033312.

Parzen, E., 1962. On Estimation of a Probability Density Function and Mode. The Annals of Mathematical Statistics 33 (3), 1065–1076. https://doi.org/10.1214/aoms/1177704472.

Pickard, S., Foxon, T.J., 2013. The state of development of the UK CCS industry: An expert questionnaire and systems-based approach. Energy Procedia. Elsevier Ltd, pp. 7613–7621. https://doi.org/10.1016/j.egypro.2013.06.707.

Rochedo, P.R.R., et al., 2016. Carbon capture potential and costs in Brazil. Journal of Cleaner Production 131, 280–295. https://doi.org/10.1016/j.jclepro.2016.05.033.

Rockett, G.C., et al., 2011. The CARBMAP project: Matching CO2 sources and geological sinks in Brazil using geographic information system. Energy Procedia. Elsevier Ltd, pp. 2764–2771. https://doi.org/10.1016/j.egypro.2011.02.179.

Rockett, G.C., et al., 2012. large scale carbon capture and storage in Brazil: A preliminary cost modeling for campos basin's oil field. Geociências 2, 485–503.

Romasheva, N., Ilinova, A., 2019. CCS projects: How regulatory framework influences their deployment. Resources 8 (4). https://doi.org/10.3390/RESOURCES8040181.

Rosenblatt, M., 1956. Remarks on Some Nonparametric Estimates of a Density Function. The Annals of Mathematical Statistics 27 (3), 832–837. https://doi.org/10.1214/aoms/1177728190.

Schmidt, O, et al., 2017. Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy 42, 30470–30492. https://doi.org/10.1016/j.ijhydene.2017.10.045.

Schmidt, O., et al., 2017. The future cost of electrical energy storage based on experience rates. Nature Energy 2 (8), 17110. https://doi.org/10.1038/nenergy.2017.110.

SEEG (2020) *Brazilian Total Emissions 2019*. Available at: http://plataforma.seeg.eco.br/total_emission# (Accessed: 19 January 2021).

van Sluisveld, M.A.E., et al., 2018. Comparing future patterns of energy system change in 2 °C scenarios to expert projections. Global Environmental Change 50, 201–211. https://doi.org/10.1016/j.gloenvcha.2018.03.009.

von Stechow, C., Watson, J., Praetorius, B., 2011. Policy incentives for carbon capture and storage technologies in Europe: A qualitative multi-criteria analysis. Global Environmental Change 21 (2), 346–357. https://doi.org/10.1016/j.gloenvcha.2011.01.011.

Usher, W., Strachan, N., 2013. An expert elicitation of climate, energy and economic uncertainties. Energy Policy 61, 811–821. https://doi.org/10.1016/j.enpol.2013.06.110.

Verdolini, E., et al., 2018. Future prospects for energy technologies: Insights from expert elicitations. Review of Environmental Economics and Policy 12 (1), 133–153. https://doi.org/10.1093/reep/rex028.

Xenias, D., Whitmarsh, L., 2018. Carbon capture and storage (CCS) experts' attitudes to and experience with public engagement. International Journal of Greenhouse Gas Control 78, 103–116. https://doi.org/10.1016/j.ijggc.2018.07.030. September 2017.

Zhou, F., et al., 2019. Long-term forecasts for energy commodities price: What the experts think. Energy Economics 84, 104484. https://doi.org/10.1016/j.eneco.2019.104484.