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DOI
10.1016/j.ijhydene.2023.08.209

Publication date
2023

Document Version
Final published version

Published in
International Journal of Hydrogen Energy

Citation for published version (APA):
Ciotta, M., Tassinari, C., Larizatti Zacharias, L. G., van der Zwaan, B., & Peyerl, D. (2023). Hydrogen storage in depleted offshore gas fields in Brazil: Potential and implications for energy security. *International Journal of Hydrogen Energy*, *48*(100), 39967-39980. https://doi.org/10.1016/j.ijhydene.2023.08.209

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 48 (2023) 39967–39980

Available online at www.sciencedirect.com

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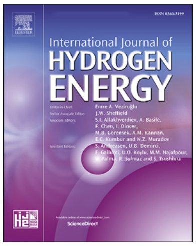
journal homepage: www.elsevier.com/locate/he



Hydrogen storage in depleted offshore gas fields in Brazil: Potential and implications for energy security

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HIGHLIGHTS

- Offshore natural gas fields in Brazil are suitable for hydrogen storage.
- Depleted offshore gas fields can store around 5483 TWh worth of hydrogen.
- Two main offshore storage clusters exist in the Southeast and Northeast of Brazil.
- Fossil fuel dependence in Brazil can be reduced through hydrogen use and storage.
- Large-scale hydrogen storage can contribute to Brazil's energy security.

ARTICLE INFO

Article history:
Received 11 March 2023
Received in revised form
29 July 2023
Accepted 17 August 2023
Available online 02 September 2023

Keywords:
Geological hydrogen storage
Offshore wind energy
Green hydrogen
Depleted gas fields
Energy security

ABSTRACT

This article estimates the potential of using depleted offshore gas fields in Brazil for hydrogen storage and the effects this may have in terms of energy security. Brazil is starting to invest in producing green hydrogen associated with offshore wind energy generation. This initiative has stimulated the search for suitable locations to store hydrogen, including in depleted offshore gas reservoirs. The methodology used in this paper allows for identifying which of the 85 assessed depleted offshore gas fields are the most suitable for hydrogen storage and evaluating the storage capacity of the selected fields. In addition, a wind speed analysis is made to investigate possible locations for prospective wind energy generation projects that can accommodate green hydrogen production. As our main result, we find that the selected depleted offshore gas fields have the potential to store around 5483 TWh worth of hydrogen. This amount is equivalent to about 10 times the total annual electricity consumption in Brazil. Hence, Brazil can comfortably leverage its offshore wind potential in connection with hydrogen production to enhance the energy security of its electricity supply. Considering that to date primarily natural gas has been used as the main source of energy security in Brazil and that its share in the electricity sector has significantly increased over the last decade, the combination of hydrogen storage and renewable energy such as offshore wind power has the potential to provide a resilient and decarbonised electricity system in the country. Furthermore,

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https://doi.org/10.1016/j.ijhydene.2023.08.209

hydrogen stored in offshore reservoirs in Brazil can become an important resource in the international energy market and constitute a possible key to energy security for countries to which Brazil may export hydrogen. We end our paper by providing comments on the challenges, opportunities, and prospects of offshore hydrogen storage in Brazil.

1. Introduction

Hydrogen is recognised as an important energy carrier in international decarbonisation strategies [1,2]. Given the increasing demand for cleaner energy sources, hydrogen is assuming multiple roles in the global energy transition, particularly in decarbonising hard-to-abate sectors [3–7]. On the other hand, the use of hydrogen also brings forth new questions and challenges, including developing secure hydrogen-based energy systems that have low environmental impact, yield high energy efficiency, and involve cost-competitive technologies [6,8–10]. Among all production types, green hydrogen stands out as ultimately the most desirable option [11]. While produced from renewable energy through electrolysis of water, it has the potential to provide power systems much-needed flexibility and serve as buffer for the intermittent renewable energy sources from which it is generated [12–14].

Yet, even though green hydrogen is positioned as an essential stake in the future of energy, such as in the case of Brazil, the form and pace at which this energy carrier will develop remain uncertain [15–17]. To foster the growth of an hydrogen market in Brazil, it is crucial to establish a long-term policy framework, create market demand, and provide adequate support for research and development (R&D) [17]. Considering the specific context of the country, it is remarkable that Brazil's electricity sector, historically characterised predominantly by the use of renewable energy, is becoming increasingly dependent on the use of natural gas, which serves as a crucial component of guaranteeing national energy security [18]. In the year 2000, hydroelectric power accounted for 89% of electricity generation, while natural gas contributed only 1% [18,19]. However, by 2021 these figures had changed significantly, with hydroelectric power representing only 57% of electricity generation and natural gas contributing 13% [18,19]. The explanation for this change is that hydroelectric plants, which earlier had ensured much of the country's energy security, faced drought-related challenges and consequently gradually lost their prominent role. Thus, part of the ensuing gap was subsequently filled by solar and wind energy [18,20–22].

As a result of reduced water availability, the persistent critical situation in the affected basins implies that hydroelectric power production operates well below capacity [23]. Under these conditions, the use of natural gas in thermoelectric plants has become an increasing reality to guarantee electricity supply in Brazil [24]. Given the contradictory position of this perspective in the face of the world's need for decarbonisation, it is necessary to think of alternatives that ensure the country's energy security but do not compromise the clean energy transition.

In this sense, the production of green hydrogen in Brazil associated with offshore wind energy generation, appears as an increasingly relevant possibility [25–27]. The Brazilian government is presently developing strategies to integrate hydrogen into the national energy system, with particular attention being given to green hydrogen [15]. Parallel to this, specialists involved in current national energy planning project a rapid advance of offshore wind energy generation [18,28]. Thus, the use of wind electricity to produce green hydrogen and the export of this hydrogen to the international market may become an important element in hydrogen becoming an economical energy carrier for the country [2]. However, for hydrogen to address the intermittency of renewables and become available in sufficient quantities for both export purposes and the enhancement of security of the Brazilian electricity sector, measures need to be taken such as the realisation of hydrogen storage, for instance in geological reservoirs [29,30].

Geological hydrogen storage is a relatively new topic, but its development is believed to play a key role in establishing it as an energy carrier in the long-term [29]. A significant part of the effort to select appropriate geological reservoirs for storage consists of searching for geological features that favor safe containment in large quantities [27,29,31,32]. In the selection process, physical-chemical properties, reservoir tightness and geochemical interactions should be considered [27]. The desirable characteristics for hydrogen reservoirs tend to be the same as those already extensively explored for CO_2 storage. However, there are differences such as the expected storage time (hydrogen storage is thought to be mostly needed only for the short-term, while CO_2 storage is usually meant for the long-term) as well as in terms of the characteristics of the gases that suggest different physical-chemical requirements [27,29,33]. In the present work, we investigate using depleted gas fields for hydrogen storage, given the large technical expertise accumulated for these fields in Brazil and elsewhere, as well as the already available presence of infrastructure that can be adapted for hydrogen storage purposes at relatively low costs [34–36].

Against the background of a transition of Brazil's traditionally clean energy system towards, unfortunately, a more fossil fuel-based supply, the importance of studying hydrogen storage in the country becomes particularly evident. Given the possibility that hydrogen (storage) becomes part of the national strategic energy plans, and the potential to hereby address the intermittency of renewable energy sources, it is crucial to explore the feasibility of utilising the Brazilian depleted offshore gas fields for storage purposes. This article aims to determine the potential of depleted offshore gas fields in Brazil for hydrogen storage and the effects that this may have on the country's energy security. We present an inventory of the storage capacity of depleted offshore gas fields in Brazil and discuss the implications of this potential for Brazil's energy planning. Moreover, based on favorability criteria and capacity numbers, we formulate the prospects for implementing geological hydrogen storage in the country. Even though the eventual use of hydrogen in Brazil is still under discussion and national strategies have not considered which buildings and end uses will be prioritised, understanding the prospects for hydrogen storage is one of the steps that must be considered in the overall planning process.

The methodology applied in this work encompasses a layered approach, enabling the integration of diverse analyses, such as of the potential for hydrogen generation, the available infrastructure, the proximity to consumption centers, and the required hydrogen storage capacity. We identify contexts under which a hydrogen storage project would become feasible by a favorable overlapping of these factors. Such contexts could include proximity to future hydrogen generation projects, proximity to consumption centers, secure reservoir locations with good storage potential, and the availability of infrastructure for injection and transportation of hydrogen, even if some adaptations might be needed. Our main results show two clusters of greatest interest: one in Southeastern Brazil and another one in the Northeast. These fields have the joint potential to store around 5483 TWh worth of hydrogen produced by offshore wind energy. This level of green hydrogen production represents around 10 times the total annual amount of Brazilian electricity consumption (based on the year 2021) [19]. Considering the possibility of competition with the use of these depleted gas fields for CO_2 storage, it is important to note that the simultaneous utilisation of CO_2 storage and hydrogen storage projects is also a possibility. Moreover, the Northeast region stands out as the primary cluster of interest, in line with Brazil's offshore wind energy generation plans. A careful selection of regions characterised by distinct favorability criteria is important for planning possible hydrogen storage regions on the Brazilian offshore territory. Our inventory of storage capacities and selection of preferred zones is innovative, since no such analysis has yet been reported in the literature, while it also provides information relevant for national energy planning and security provisions. The present study represents the first evaluation of the potential of depleted gas fields for hydrogen storage in the offshore areas of Brazil. In addition, our study provides data regarding the local potential for establishing clusters that integrate offshore wind energy generation and hydrogen production.

2. Methodology

The methodology applied in this work consists of calculating the hydrogen storage capacity in the offshore Brazilian territory and assessing all satellite issues related to this subject. It can be divided into four distinct topics (see Fig. 1).

i.Data Collection: The first stage of this work consisted of extensive data collection from the Brazilian offshore fields and coastal sedimentary basins. The underground hydrogen storage (UHS) potential depends especially on geological conditions (e.g. the mineralogy of the rocks of the chosen formation and their structural stability) and physical-chemical conditions of the fluid-rock interaction. The analysis of the overall viability of the fields was based on criteria already established in the literature [27,37–39]. Data was also collected regarding the wind power generation potential of the Brazilian offshore areas [40]. This information was used to have a geospatial notion of where future green hydrogen generation projects associated with wind generation can be located, allowing comparison with the selected fields. Finally, data on the location of Brazilian gas pipelines were used to analyse the distance relationship and connection of the studied regions [41].

ii.Data Processing: The collected data served a dual purpose: to quantitatively assess the basins and qualitatively evaluate the characteristics of the studied fields, determining their viability for hydrogen storage. Thus, only fields that met the mineralogical and structural requirements for the desired application were considered in this study [33,42–46].

iii.Data Analysis: Estimating the hydrogen storage capacity in gas reservoirs follows the fundamental assumption that the volume previously occupied by the produced hydrocarbons becomes available for hydrogen storage [39]. The methodology applied for calculation consists of a few steps drawn from the available literature on the subject [27,32,39,47,48], depending on prior geological site selection. The analysis of the hydrogen storage capacity of gas fields was based on initial estimates of recoverable gas and is expressed by:

$$CR_{H_{2,Max}} = ERG \times \frac{\rho_{CH_{4,STP}}}{\rho_{CH_{4,R}}} \times \rho_{H_{2,R}} \times HHV_{H_2}$$

in which ERG is the estimated recoverable natural gas of the reservoir, $\boldsymbol{\rho}$ the gas density (STP denotes the standard condition while R is used for specific reservoir pressure and temperature conditions), and HHV the higher heating value of hydrogen. H2CapEs, an open-source software, was used in the calculation process [31,49]. The software uses the Noble-Abel equation [50] of state for calculating hydrogen density, and methane has been treated as an ideal gas. We also considered the cushion gas volume of 45% as an average value for depleted fields, which refers to the minimum amount of gas that must be held in the reservoir to maintain adequate pressure for gas extraction [51,52]. The estimated recoverable natural gas of the reservoir, pressure and temperature applied derived from the information available on the National Petroleum Agency's (ANP) website, where the average depth of the reservoirs can be found [53]. The density of the gases was calculated using the GERG-2008 equations of the state through the H2Thermobank software, which predicts the thermophysical properties of hydrogen-containing mixtures [54].

iv. Outcome: The main result obtained was the calculation of the hydrogen storage capacity of the 85 Brazilian depleted offshore gas fields, presented in the form of maps that also include the offshore wind generation potential and the pipeline transportation infrastructure.

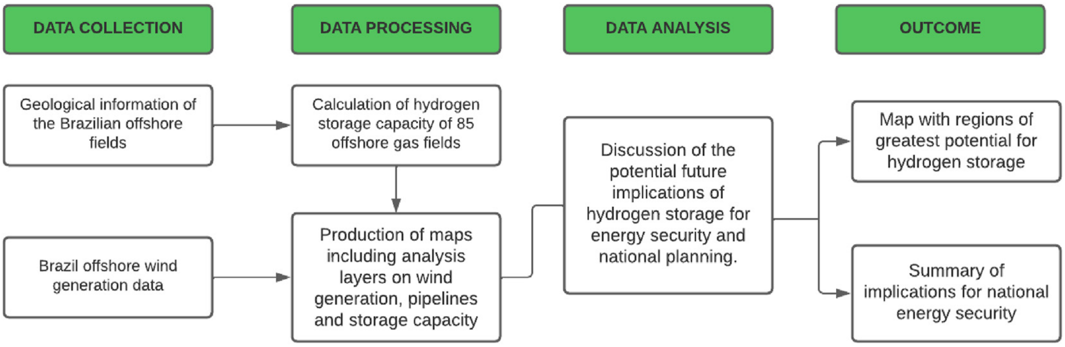


Fig. 1 – Methodological framework.

3. Literature survey

In this section, we present a literature review that provides a comprehensive overview and analysis of existing research and academic papers related to the geological storage of hydrogen in different aspects that are linked to this work. We also aim to highlight gaps in the literature that reinforce the relevance of the present study.

3.1. *Geological hydrogen storage and the brazilian context*

With this subsection, we seek to understand the state-of-the-art of geological hydrogen storage and how this knowledge applies to the study of Brazilian offshore reservoirs and the feasibility of its use. One of the primary motivations for utilising underground reservoirs lies in the inherent

limitation of storage and discharge capacity in surface hydrogen storage systems, such as pipes or tanks (MWh; hours-days), while storage of hydrogen in geological reservoirs may deliver energy in the GWh/TWh range over weeks to months [29,55–57]. As with CO_2 storage, there are several possible reservoirs for storing hydrogen: saline aquifers, depleted oil and gas fields, and salt caverns are the most recognisable possibilities [39]. Each potential reservoir has its advantages and challenges, and it is essential to thoroughly assess each situation to make an informed decision and select the best reservoir for each studied case.

Salt cavern storage is a good option for short to medium-term changes in energy demand since it allows for numerous injection and reproduction cycles per year, but it can only be used in areas with evaporitic rock formations of the right thickness and extent [55,58]. The potential movement of hydrogen in aquifers raises risks, such as the leaking via unnoticed fractures, biological processes, or interactions between hydrogen and minerals in the reservoir rock. Since the tightness of an aquifer is initially unknown, in contrast to the depleted oil and gas resources, and it must be determined by extensive, time-consuming, and expensive tests, which is why aquifers call for the drilling of wells, following in more expensive results [38,39].

The use of depleted gas fields to store hydrogen provides some advantages over other possibilities, such as greater knowledge of the local geology (from the previous exploration process) and the availability of a transport network and local infrastructure. The use of depleted gas fields also provides some challenges: even though all fields are representative of some kind of petroleum system, it is necessary to determine the conditions of each reservoir individually, classifying the local reservoir rocks, trap mechanisms, fault systems, and gathering mineralogical data to understand if the local geology is compatible with the desired storing process [36].

One challenge of using geological reservoirs comes from the knowledge that the same reservoirs can perform many purposes. Conflicts of interest may arise, for example, when competing reservoirs are used to store CO_2 or hydrogen [48,59]. The likelihood is quite low, though, as all initiatives of this sort are still very young, and competition difficulties may be handled right away [59]. In addition, some projects suggest using CO_2 and hydrogen storage simultaneously, which may become a common practice, reducing the problem of competitiveness of use. Understanding the storage capability of Brazil's offshore gas fields assets requires an in-depth geological description. Although the initial geological storage options for several gases and uses are the same, it is important to comprehend how each gas responds when in touch with various mineralogies, permeabilities, and porosities [48]. There are already records of the natural occurrence of hydrogen in geological reservoirs, a factor that may be important for the future understanding of the gas retention mechanisms in question [60].

Even though the study of this work is conducted on a field scale, it is crucial to comprehend the structural and lithological foundation of the investigated basins to understand the general fitness of the storing perspectives in the area. We investigated 8 sedimentary basins from offshore Brazil because of the presence of gas resources. Over 12,000 km of South America's divergent margin is covered by a continuous network of sedimentary basins that were created by processes for the distension of the atmosphere [61]. The definitive separation of the African and South American plates throughout the Mesozoic is strongly related to the Brazilian continental margin's geology and the Gondwana rupture processes [41,61,62].

Currently, no studies are available that specifically estimate the potential hydrogen storage capacity of Brazilian basins. However, given that similar conditions are required for CO_2 storage, one can leverage existing knowledge on this matter as an initial approach [36,63,64]. Ketzer et al. (2015) published the first Brazilian offshore's feasibility analysis at the basin level in the first Brazilian CO_2 storage Atlas. The basins are divided into low, medium, and high prospectivity [64]. The Atlas categorised the study basins as having low prospectivity (Campos, Santos, Potiguar, and Recôncavo), medium prospectivity (Sergipe-Alagoas, Espírito Santo), and high prospectivity (Camamu-Almada, Ceará) [64].

Considering the use of depleted gas fields for H_2 storage, key basin information was analysed (see Table 1), focusing especially on the characteristics of the local petroleum systems. Brazil has roughly 302 active fields, but some of these are in the onshore area, and many more either lack information or are not accessible for our kind of research. The Brazilian offshore research involved 85 gas fields in the 8 offshore sedimentary basins that were at various project maturity levels (see Fig. 2). These fields were selected given the data available for analysis [53]. A detailed assessment of the literature in ANP official papers and academic articles on Brazilian geology served as the starting point for the data collection for individual fields and basins [53,61,62]. Specific information regarding the depleted gas fields, including longitude and latitude, can be accessed as public information through the ANP website [65]. This process led to creating a sizable database of Brazilian offshore fields. Data on the lithology of the reservoir rock, the lithology of the sealing rock, and their physical characteristics were gathered for all the analysed reservoirs [53]. The stages of production for the fields this study takes into account vary. The fields have lithological and structural specificities that must be considered in case-by-case studies, but for the scale of this study, we apply a general feasibility assessment based on geological characteristics, production data and pre-established capacity calculation methodology.

3.2. Hydrogen-rock interaction

It is highlighted that the same geological formation can be used for different storage purposes [27]. At first, CH_4, H_2, and CO_2 can all be stored in the same formation. Still, it is necessary to understand the different physical-chemical properties of rock-fluid interaction that arise from the distinct characteristics of these gases [32,47,48]. Thus, for hydrogen storage to take place effectively and safely, it is necessary to ensure geological conditions that consider field-scale safety. It is also relevant knowing the subtleties of fluid-rock interactions to accurately predict the behavior of the gas in the reservoir [27,33,39]. At last, it is crucial to understand both the properties of hydrogen and the interactions at the mineralogical level, because rock chemistry can influence the expected results of storage effectiveness [66–68].

Depending on the temperature and pressure, hydrogen can exist in a variety of states [27,39,69]. Hydrogen is a solid at low temperatures, with a density of 70.6 kg/m^3 at 262 °C and it is a gas with a density of 0.089 kg/m^3 at 0 °C and a pressure of 1 bar at higher temperatures. The narrow region between the triple and critical points, with a density of 70.8 kg/m^3 at 253 °C, illustrates the breadth of hydrogen's liquid state [39,45]. Gaseous hydrogen has a high penetrability since its molecules are small, and it diffuses in solids quicker than methane, for example [39]. A possible issue when hydrogen interacts with

Table 1 – Key information on the studied basins according to the considered fields. The data were obtained from ANP (2020).

Basin	Depth of studied reservoirs (m)	Potential reservoir	Potential confining layer	Types of traps	Initial recoverable natural gas (BCF)
Camamu-Almada	4560	sandstones	shales	structural	86
Campos	1100–4700	turbiditic sandstones, carbonates, sandstones	shales, evaporites	hybrid, stratigraphic, structural	47,061
Ceará	1900	sandstones	shales	stratigraphic	300
Espírito Santo	3200	sandstones	shales	hybrid	2422
Potiguar	884–3850	sandstones, siltstones	shales, basalts	hybrid, stratigraphic, structural	1530
Recôncavo	376	sandstones	shales	stratigraphic, structural	78
Santos	2100–5560	sandstones, calcarenites	shales, evaporites	hybrid, stratigraphic, structural	72,435
Sergipe-Alagoas	1000–5000	sandstones	shales	hybrid, stratigraphic, structural	224

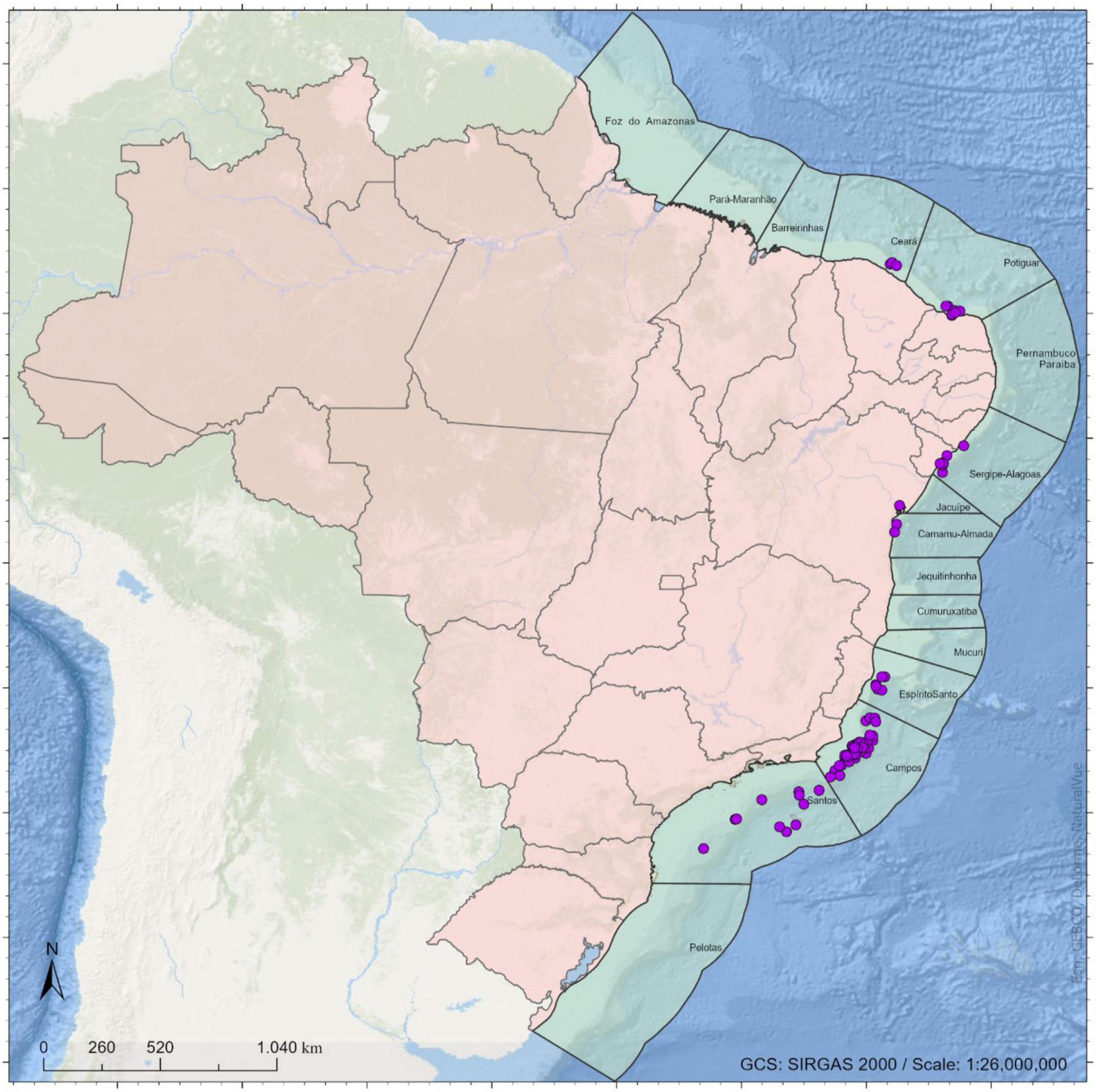


Fig. 2 – Distribution of the 85 fields selected and studied in this paper.

surrounding rocks is chemical reactions [39]. In the absence of catalysts and at temperatures below 100 °C, reactions in the mineral matrix appear very slowly. A significantly accelerated rate of the reactions may result from increased pressure (such as at higher depths), which suggests the search for reservoirs under precise conditions. Ensuring safe storage is a major concern for hydrogen, requiring the application of risk assessment methodologies [46]. Hence, any reservoir chosen as a potential hydrogen storage site must be studied extensively at both the mineralogical and reservoir scales.

It is critical to gauge the number of minerals that dissolve due to fluid-rock contact when considering geological hydrogen storage since the integrity of the formation and the amount of hydrogen that can be stored are determined by this measurement [70]. It is also worth mentioning that investigations regarding the high-pressure adsorption of hydrogen onto clay minerals and rocks are currently scarce in conditions of geological contexts. However, the mineral reactivity of hydrogen has been reasonably thoroughly documented [43]. When analysing the reaction of hydrogen with for instance sandstones, the main reservoir rock present in Brazilian offshore gas fields, there is conclusive evidence that abiotic geochemical reactions in these reservoirs do not pose a threat to hydrogen loss or reservoir integrity degradation [42].

3.3. *Hydrogen in Brazil*

The opportunities for hydrogen are now being defined, and the country's energy research company (EPE) has a key role in future decisions and planning. EPE is a public company linked to the Ministry of Mines and Energy (MME), and its purpose is to develop studies to subsidise national energy planning [15]. Brazil has distinguished itself as one of the potential contenders for leadership in the global hydrogen market due to its favorable climatic conditions, a competitive industrial sector with flexible possibilities, and mostly renewable power grid [71].

The Brazilian government also released the National Hydrogen Program (PNH2) guidelines in July 2021 to outline the nation's plans to advance the hydrogen market [72]. To support and promote hydrogen as an energy vector and fuel in the Brazilian energy matrix, PNH2 also tried to map out the current laws and regulations [72]. Research, development, and government support for international cooperation and project efforts targeted at accelerating the formalisation of the national hydrogen strategy are now one of the priorities of the National Energy Policy Council (CNPE) [72]. In this context, green hydrogen stands out as one of the most prominent alternatives in the country [17,71,73,74].

Although the prospects for national production are high, Brazil shows itself as a novice in the process compared to countries like Chile, which face similar challenges as emerging Latin American nations [74]. One of the challenges for implementing green hydrogen in the country is production logistics, whereas the national plans leave open where and how hydrogen generation projects will be in the country [15]. Thus, defining areas of interest for generation and storage is fundamental, going hand in hand with the purpose of more explicit national policies and, based on this, the production of norms and regulations that do not cause legal insecurity [75–78]. It is significant to remark that the use of hydrogen storage technology in multi-carrier power systems has proven to be an effective solution to reduce operating costs and increase the penetration of wind energy, but it is necessary to understand better what the role of geological storage would be [79].

4. Results

First and foremost, we identified a gap in the existing literature and set out to address it through our research. We noticed that no evaluation had been undertaken regarding the storage capacity of depleted Brazilian offshore gas fields specifically for hydrogen storage. Based on this, we did an extensive data survey and obtained their storage capacity as well as their geological evaluation. In addition, we applied a methodology including the availability of infrastructure for transportation and future green hydrogen generation sites (related to the offshore wind energy generation potential). Therefore, our evaluation of the best potential sites for storage considers diverse factors that culminate in regions of interest with higher feasibility for future projects.

The main results are divided into: (i) the estimated hydrogen storage capacity of the fields in terms of available energy (see Table 2) and; (ii) the production of maps that present the storage capacity layer along with offshore wind production capacity and pipeline availability for transportation.

The wind potential in the Brazilian offshore region was estimated by EPE using the ERA5 database. Table 3 presents the results of this study. However, it should be noted that restrictions were not considered in exploitable areas, such as environmental protection areas, trade routes, bird migration routes, oil exploration areas or other areas with conflicting uses. The results of this study show that for areas with speeds above 7 m/s, several areas can be considered attractive. This indicates that, at a height of 100 m, Brazil's potential would be 697 GW in places with a depth of up to 50 m, emphasising the Northeast region with the greatest potential, representing 51% of this potential.

Fig. 3 presents the whole perspective on Brazilian offshore wind generation and the fields with calculated hydrogen storage capacities. Considering the sum of the basins, the fields can store up to 5483 TWh worth of hydrogen. Fig. 4 shows the Northeast region, where it is possible to see that the storage potentials are smaller when compared to the Southeast region, and there are also fewer fields in that area. It is important to note that the Northeast region is less supplied by infrastructure, which clearly can become a problem when it is necessary to dispute the use of H_2 offloading gas pipelines with the gas production from the fields. However, the Northeast fields are located closest to the following wind generation projects to be executed in the Brazilian offshore. This means that even though the storage capacity may not be the highest, these fields may play an important role in the hydrogen generation implementation in the country. For example, the first pilot projects of a complete offshore wind generation and H_2 production/storage/distribution might be located in this region.

Table 2 – Results of H_2 storage capacity estimation in TWh by basin.

Basin	Number of fields studied	Total H_2 storage capacity estimation in TWh	Field with the highest storage capacity
Camamu-Almada	3	90	Manati (86 TWh)
Campos	46	2070	Jubarte (404 TWh)
Ceará	4	14	Xaréu (4 TWh)
Espírito Santo	6	107	Peroá (32 TWh)
Potiguar	8	69	Ubarana (24 TWh)
Recôncavo	1	4	Dom João Mar (4 TWh)
Santos	10	3023	Búzios (1613 TWh)
Sergipe-Alagoas	7	107	Caioba (31,22 TWh)

Table 3 – Accumulated Offshore Wind Potential in Brazil. The data were obtained from EPE (2020).

Speed/ Bathymetric	Useable areas (km^2)				Potential (GW)				Potential (TWh)			
	0–20	20–50	50–100	>100	0–20	20–50	50–100	>100	0–20	20–50	50–100	>100
≥6,0	175.754	186.188	171.923	2.784.706	628	641	531	9.100	1.789	2.048	1.576	30.140
≥6,5	147.234	171.441	147.519	2.602.599	522	591	467	8.420	1.582	1.949	1.450	28.793
≥7,0	79.869	123.078	79.907	1.765.981	276	421	237	5.833	1.008	1.528	902	21.872
≥7,5	38.637	64.276	57.360	1.237.126	129	209	159	4.014	566	890	667	16.101
≥8,0	29.017	46.109	50.429	674.730	100	147	137	2.056	456	664	587	8.934
≥8,5	16.835	22.227	31.507	333.324	63	81	87	993	308	398	383	4.612
≥9,0	3.996	7.337	1.852	143.039	15	28	7	399	82	149	38	1.929
≥9,5	729	560	154	2.971	3	2	1	11	16	12	3	63
≥10,0	–	–	–	–	–	–	–	–	–	–	–	–

Fig. 5 shows the storing potential of the Southeast region. Even though the potential itself is greater than those seen in the Northeast region, there is no short time plan indicating that there will be wind generation in the area. Also, this region could be of greater interest for CO_2 storage, given its proximity to emitting centers onshore and also the oil and gas facilities that emit as well.

5. Discussion

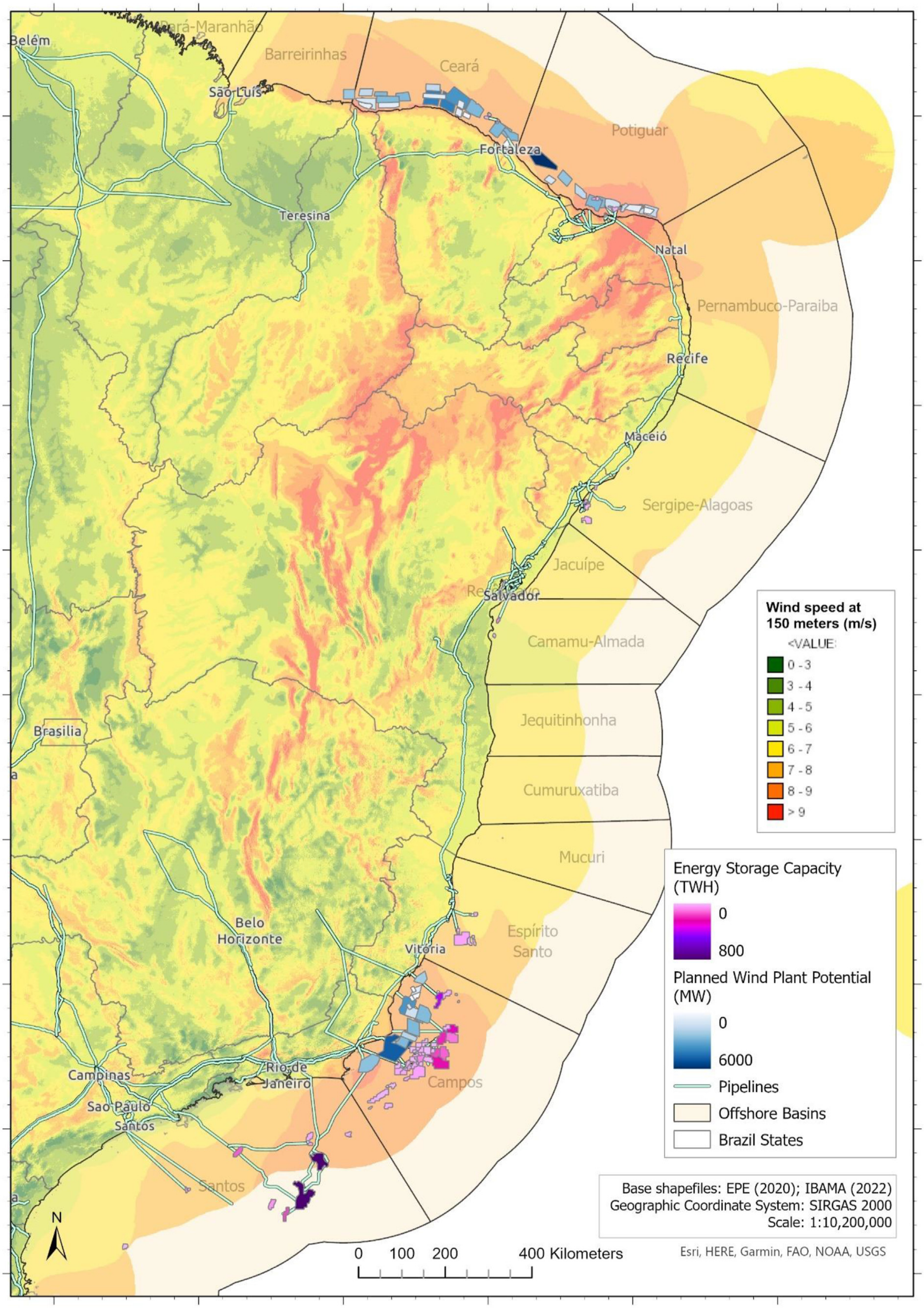
Geological hydrogen storage is a promising solution for addressing the intermittent nature of renewable energy sources, such as wind and solar power. One of the main challenges with renewable energy is that it is not always available due to weather conditions and other factors. This can make it difficult to consistently meet energy demand, particularly in locations with high levels of renewable energy penetration. In the case of Brazil, with the reduced presence of hydropower in the electricity sector due to droughts, and the associated increase in the use of natural gas, it is even more relevant to seek solutions that maintain the country's energy security while keeping up with the pace of international decarbonisation. Moreover, the relevance of seeking solutions is accentuated as natural gas is considered an additional source due to the increased consumption, backup of non-conventional renewables, droughts and energy crises.

The use of geologic storage of hydrogen is a key to both national energy security and the possible export of hydrogen or its derivatives to the international market, as it allows the availability of a large amount of stored energy. Thus, hydrogen can be stored in selected geological formations until it is needed. At this stage, it can be extracted and utilised to generate electricity through fuel cells or other technologies. It allows excess renewable energy to be stored and used to meet demand when renewable resources are unavailable. This scenario is particularly fertile from the perspective of offshore Brazil since the planning for wind power generation in this region is accompanied by the incentive to create the first green hydrogen generation projects in the country.

The MME published, in October 2022, Decree No. 52/GM/MME and the MME/MMA Interministerial Decree No. 03/2022, which define, respectively, the complementary rules and guidelines for the assignment of the use of offshore areas, to generate electricity and the guidelines for the creation of a Single Portal for Management of the Use of Offshore Areas [80,81]. The regulations contribute to the establishment of a safe and adequate legal framework for offshore power generation in Brazil. At the same time, the Brazilian Institute for the Environment and Renewable Natural Resources (Ibama) has already made available a map of the offshore projects in progress in Brazil, data that were used in this work [40]. The interpolation of these data, with information about available infrastructure (if not for immediate use, for future adaptation) and storage capacities, delimit the places of possible interest for a hydrogen generation project because choosing the scenario in which the factors are more favorable also results in the greater economy perspectives.

One of the main results of this article is that the calculated amount of hydrogen storage capacity in the country is about ten times the national electricity consumption for the whole year of 2021, which was 497 TWh [19]. Not all selected fields will be used for storage, but it is crucial to understand the dimension of geological storage and how it could help the country to achieve ultimate independence from fossil fuels in the mid-to long-term. Moreover, considering the large storage capacity of these offshore reservoirs and their strategic position for Brazil, these fields may become important future locations for the trading of hydrogen in the international market. In this regard, Brazilian hydrogen can help decarbonise the energy systems of other countries, such as those in Latin America. The country has a well-established energy sector and infrastructure, including a network of pipelines and storage facilities that could be used to transport and store hydrogen, be it for intern consumers or not. Moreover, Brazil's strategic location and strong trade relationships with other countries in the region could make it an attractive source of green hydrogen for neighboring countries.

Another crucial aspect to consider is the potential risk associated with hydrogen storage. Because it is lighter than CO_2 and flammable, hydrogen brings even more complex safety issues that should not be ignored. The residence time of the gas is also different, and it is necessary to generate models, simulations, and tests that understand the effectiveness of storage in these contexts. Mineralogical studies that evaluate the fluid-rock interaction considering the Brazilian reservoirs are necessary, and it is also essential to evaluate the effectiveness of this stockpiling by capping the initial petroleum systems. Also, the existence of microorganisms may consume hydrogen nd generate other gases, reducing the stored amount and lowering the hydrogen purity. Noticeably, evaluating other geological storage



Base shapefiles: EPE (2020); IBAMA (2022)
Geographic Coordinate System: SIRGAS 2000
Scale: 1:10,200,000

Esri, HERE, Garmin, FAO, NOAA, USGS

Fig. 3 – Offshore wind energy potential and hydrogen storage capacity in Brazil.

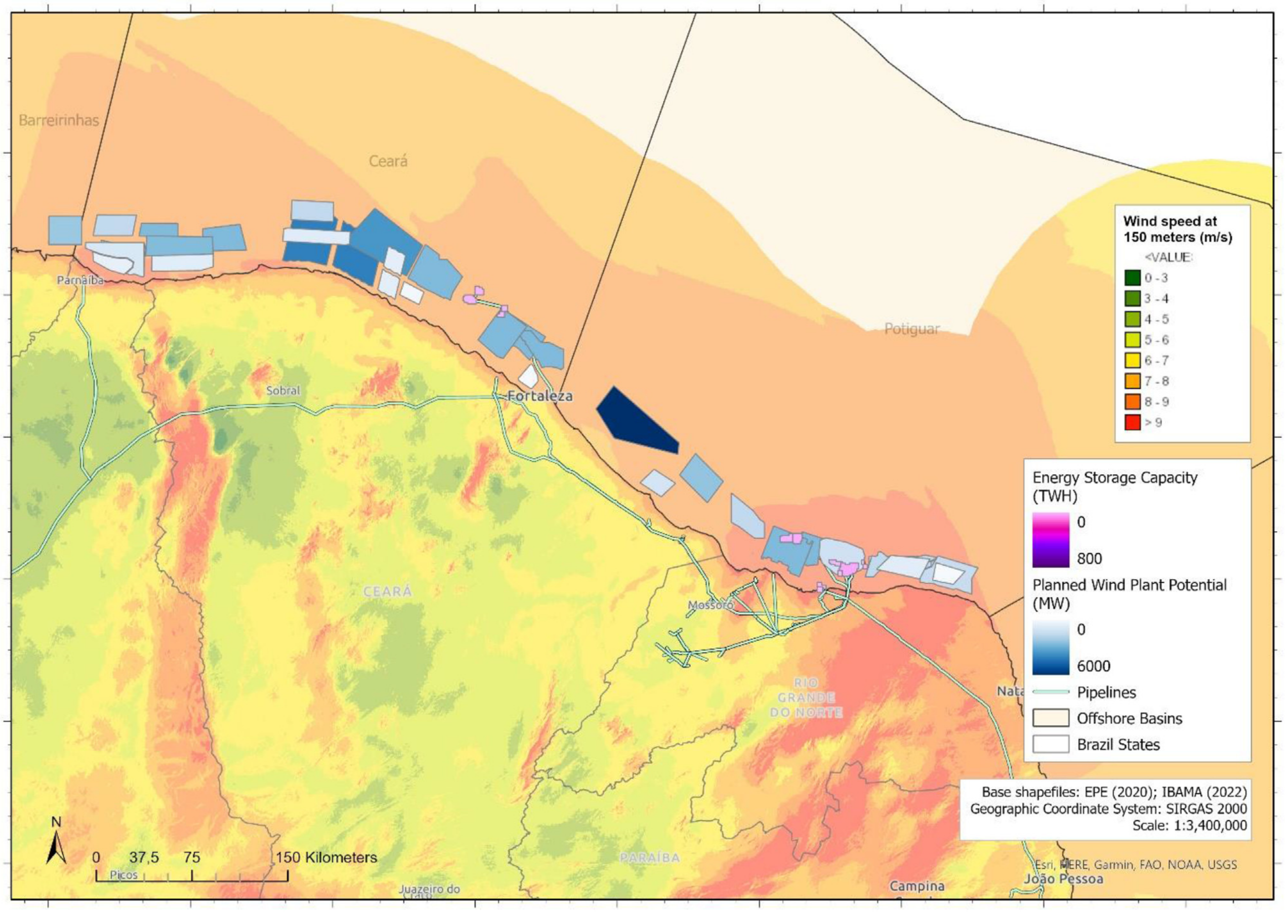


Fig. 4 – Offshore wind energy potential and hydrogen storage capacity in Brazil: Northeast region.

possibilities in the country is relevant. However, starting from the greater economy, greater technical-geological know-how and proximity to the future green hydrogen generating zones of the country, the gas fields appear as an important and obvious alternative to be evaluated in the first moment.

Furthermore, there are also several challenges that Brazil will need to overcome to realise its potential as a green hydrogen exporter or its derivates. These challenges include the high upfront costs of green hydrogen production and the need to develop regulatory frameworks and policies to support the growth of the green hydrogen economy. There are also logistical obstacles to overcome, such as the requirement to move great amounts of hydrogen across a long distance. Despite having a high energy density, hydrogen is a fuel with a large volume, making transportation both expensive and difficult. Ultimately, it is notable that the production of green hydrogen requires a large amount of renewable energy. Brazil has great potential for wind generation on its offshore, but technical, financial, and regulatory obstacles may constrain the implementation of large-scale projects.

At last, the use of green hydrogen has the potential to play a significant role in Brazil's energy mix and help address the intermittency issues associated with renewable energy sources. By storing renewable energy in the form of hydrogen, Brazil can effectively balance its energy supply and demand and ensure a consistent, reliable source of electricity. Looking to the future, green hydrogen adoption in Brazil will likely continue to grow as the technology becomes more cost-effective and the regulatory environment becomes more favorable. This could lead to the development a robust green hydrogen industry in Brazil, with significant economic and environmental benefits. Regarding energy security, using green hydrogen could also help the country reduce its reliance on fossil fuels and other imported energy sources. By producing hydrogen from domestic renewable resources, Brazil can increase its energy independence and reduce its vulnerability to price fluctuations and supply disruptions. Overall, the use of green hydrogen in Brazil has the potential to provide numerous benefits and will possibly become a key component of the country's energy strategy, and geological storage is an essential aspect of this perspective.

Moreover, in general terms, the outcomes of this research are related to SDG 7 (Clean and Affordable Energy), which aims to ensure access to reliable, sustainable, and modern energy for all while increasing energy efficiency and promoting the use of renewable sources. We can also mention the correlation with SDG 9 (Industry, Innovation and Infrastructure) by promoting research and development of new technologies. As for SDG 13 (Climate Action), the relationship is that by offering a clean, renewable alternative to fossil fuels,

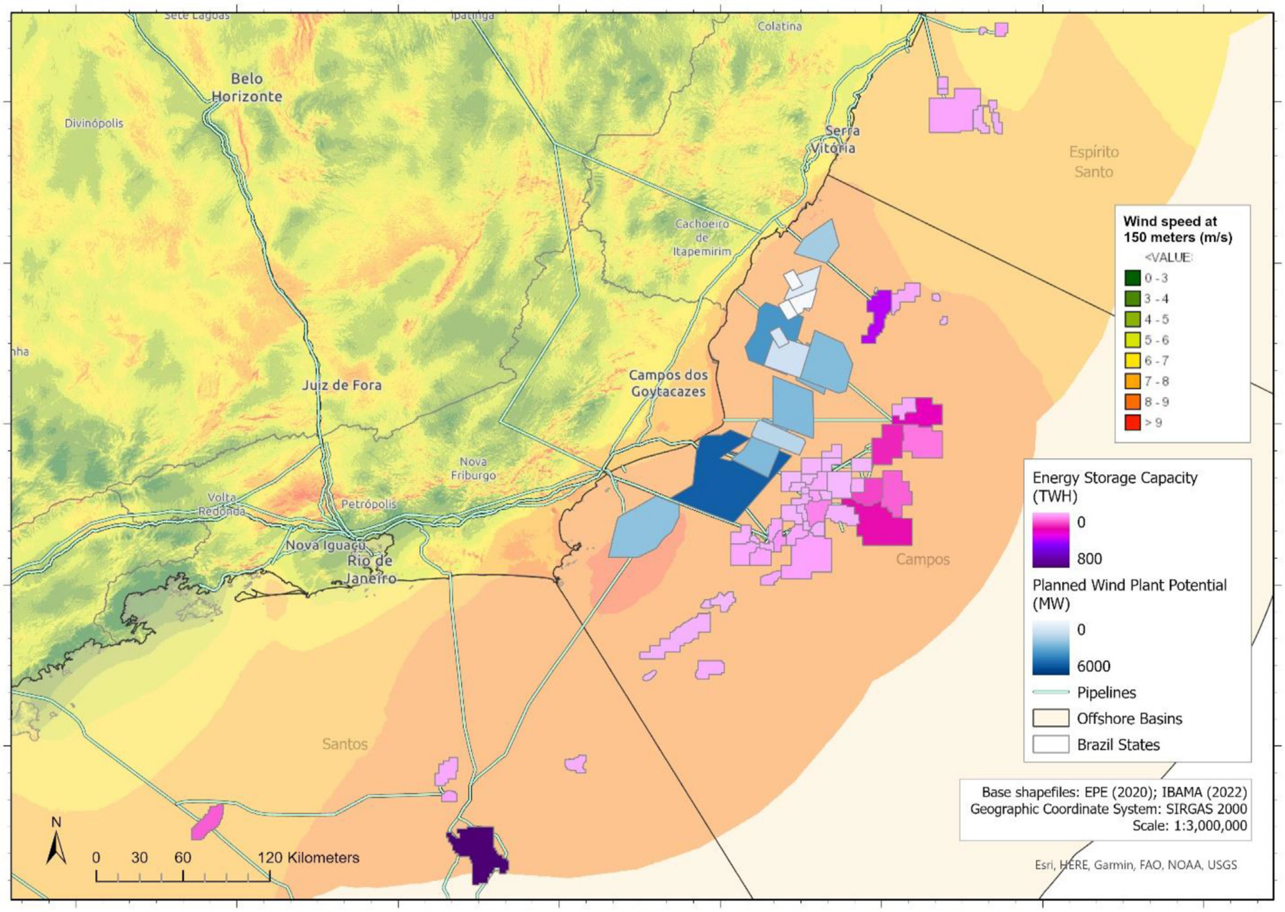


Fig. 5 – Offshore wind energy potential and hydrogen storage capacity in Brazil: Southeast region.

the project can contribute to reducing greenhouse gas emissions and mitigate the effects of climate change.

6. Final considerations

Determining the hydrogen storage capacity in Brazil and identifying strategic storage hubs are essential steps towards positioning hydrogen as a potentially critical means to ensure energy security in the presence of the use of intermittent renewables, as well as towards ascertaining its role as a viable alternative for fossil fuel consumption. In this article, we evaluate the hydrogen storage capacity of Brazilian offshore depleted gas fields and assess where these fields are located, against the perspective of required infrastructure and the positioning of these fields concerning future green hydrogen generation projects using the offshore wind energy potential that could be exploited in the coming decades. Our study of hydrogen storage capacity in association with an analysis of the national hydrogen implementation context allows us to formulate the main findings of this work.

1. Looking for hydrogen storage solutions is relevant to establish itself as a viable alternative to replace fossil fuels, while addressing the intermittency of renewable forms of energy like wind power. To accomplish this, it is essential to search for strategic locations that have high storage capacity, reasonable proximity to hydrogen-generating regions, as well as acceptable proximity to consumer centers and distribution infrastructure;
2. Brazilian offshore depleted gas fields can store around 5483 TWh worth of hydrogen, about ten times the country's electricity consumption in 2021. This storage level allows the Brazilian government to have the capacity to satisfy its internal demand while still being able to export the surplus;
3. The main hydrogen storage clusters are located in the Northeast region of Brazil. It is necessary to carefully consider how hydrogen generation will be associated with offshore wind energy generation. Estimating the storage capacity of depleted gas fields can make the selection of hydrogen production sites more pertinent;
4. Hydrogen storage can help Brazil reduce its dependence on fossil fuels by mitigating the intermittency of renewable energy sources and contributing to energy security, mainly for the electricity sector. The development of hydrogen storage has the potential to contribute to the country's energy security and support its transition to a cleaner energy mix, replacing the recent increase in the use of natural gas that thus far has guaranteed the reliability and constancy of power supply;

5. Even if hydrogen does not end up primarily serving domestic demand, it can turn into a relevant export product. In this sense, besides becoming an essential resource for the country itself, the hydrogen stored in Brazil can also emerge as a means for attaining energy decarbonisation and energy security in other countries in the world, including especially neighboring Latin America countries.

7. Suggestions for future research

We suggest that future work addressing this topic applies a methodological framework that also considers the regulatory, environmental, social, economic, safety, and technical dimensions of this subject matter, even if, in some cases, this information is lacking and needs to be studied along the way. It is also essential to explore in greater depth how to balance the use of hydrogen in the domestic market in Brazil versus its use as an export product. A detailed study on the integrity of the reservoirs that we considered is fundamental for efficient and safe hydrogen storage, and a case-by-case study including an advanced mineralogical and structural analysis is necessary.

CRediT authorship contribution statement

Mariana Ciotta: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft.

Luis Guilherme Zacharias: Data curation, Software, Visualization, Writing – review & editing.

Drielli Peyerl: Conceptualization, Project administration, Writing – review & editing.

Bob van der Zwaan: Validation, Writing – review & editing.

Colombo Tassinari: Validation, 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

Ciotta gratefully acknowledge support from FAPESP through the Research Centre for Gas Innovation (RCGI) (FAPESP Proc. 2014/50279-4 and 2020/15230-5), hosted by the University of São Paulo. This work was partially financed by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES).

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