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Assessing the research performance of Petrobras' programs on research, development, and innovation (RD&I)

Marcos Eduardo Melo dos Santos [a,b,*], Patrícia Pereira da Silva [c,d,e], Hirdan Costa [f], Edmilson Moutinho dos Santos [g]

[a] Institute of Energy and Environment, University of São Paulo, Av. Prof. Luciano Gualberto, 1289 - Vila Universitaria, São Paulo, SP, 05508-900, Brazil
[b] Virtual University of São Paulo, Av. Prof. Almeida Prado, 532 - Butantã, São Paulo, SP, 05508-901, Brazil
[c] University of Coimbra, CeBER, Faculty of Economics, Av Dias da Silva 165, 3004-512, Coimbra, Portugal
[d] INESC Coimbra, DEEC, Polo II, University of Coimbra, Coimbra, Portugal
[e] EfS Initiative, University of Coimbra, Coimbra, Portugal
[f] PRH 33.1USP/ANP/FINEP, Institute of Energy and Environment, University of São Paulo, Av. Prof. Luciano Gualberto, 1289, Vila Universitaria, São Paulo, SP, 05508-900, Brazil
[g] Institute of Energy and Environment, University of São Paulo, Av. Prof. Luciano Gualberto, 1289 - Vila Universitaria, São Paulo, SP, 05508-900, Brazil

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ABSTRACT

This paper assesses the existence of a relationship between recent research on the Research, Development, and Innovation (RD&I or R&D) sector of Petrobras with the quantitative data available in the company's reports and the Brazilian regulatory agencies. For this, 44 articles were selected using two main criteria: addressing the RD&I subject and being published in indexed peer-reviewed journals between 2000 and 2022. There are three perspectives from which the company RD&I (state development, human resources, and innovation clusters), increase in patents and production, and cost reduction are directly related to the qualitative and quantitative variation of innovation networks, state policies, and the improvement of internal human resource policies. Additionally, it was discovered that short-term outcomes could not be correlated with the level of training or R&D spending. However, a long-term drop in investment could lead to hazards such a decline in researchers, technical advancement, oil reserves, and the rate of output growth.

1. Introduction

The innovation clusters or networks understood as groups of companies united by common points, such as sector, location, or technology, have been studied by researchers in the Brazilian upstream industry [1–3]. In Petrobras, we can find the expansion of innovation networks in two distinct scenarios: a period of investment growth and another reduction. As the largest investor in R&D in Latin America [4], it justifies the relevance of examining its investment in research. Since 2004, the company's investments in R&D have been reached approximately the same levels as ExxonMobil, BP, Chevron, Baker Hughes, and Halliburton [3]. Considering companies' reports between 2006 and 2018, the reduction in Brazilian investment is also related to the devaluation of the Brazilian currency, since investment obligations are counted in current currency. Shell and BP's reductions are related to the average price of Brent. ExxoMobil and Chevron maintain an investment pattern not associated with average barrel prices (Table 1). According to the [5]; in 2021, Brazil remains among the largest investors in energy R&D when compared to OECD countries (Table 2) (see Table 3).

As a result of the company's efforts and research network, it has become the largest producer of patents on the continent [6]. The firm has become a world leader in technologies and oil production in deep and ultra-deep waters (OTC, 2015). This production and technology leadership has been evidenced through the major international awards in the area, including in 2016 for exploring the pre-salt, a large reserve in ultra-deep waters off the Brazilian coast (Ramírez-Cendrero and Paz, 2017). Even though it is based in a location where resources in hydrocarbons and investments are scarce, as is the case of Brazil in the 20th century, the firm is one of the leading companies in the sector today, especially among national oil companies [7,8]. The magnitude of these

* Corresponding author. Post-doc, Institute of Energy and Environment, University of São Paulo, Av. Prof. Luciano Gualberto, 1289 - Vila Universitaria, São Paulo, SP, 05508-900, Brazil.
E-mail address: marcosedu.pro@gmail.com (M.E. Melo dos Santos).

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investments by one of the world's largest energy firms is being studied not just in economics, management, and administration, but also in development economics, because the Brazilian government has used the company as a socioeconomic and technical development factor. What are, consequently, the potential management improvements and RD&I strategies in oil and gas exploration and production in Brazil?

Recent case studies were carried out regarding the firm's R&D [1–3, 9]; Rocha and Ruiz, 2011 [6,10]; Turchi and Porto, 2013 [11,12]; Mancini and Paz, 2018; Trojbicz and Loureiro, 2018; Pündrich et al., 2021). Other studies deal with the dimension of RD&I in the Brazilian context (Etzkowitz et al., 2005; Nagano et al., 2014; Marcon et al., 2017). We also took into account some articles that deal with RD&I from a global perspective or in comparison with other nations (Colodel et al., 2009, Wong et al., 2013a; Wong et al., 2013b; Perrons, 2014 [13]; 2020; Mohammed et al., 2021). They give analyses with remarkable results based on interview data, always impacted by the unique perspective of each body of interviewees. They are revealed in the company's reports or those of national and international agencies, with the exception of the Mancini and Paz (2017) article. The reports include information such as production, reserves, R&D and training investment, costs, patents, and workers solely committed to research, as well as their educational levels. All of these elements have an impact on R&D. In turn, R&D attempts to have a beneficial impact on these variables, although through intangible assets like patents and brands. The increase in investment in R&D experienced from the 1970s onwards positively impacted the company's production output [10]. However, increased investment was constant from the 1990s to 2013. It is, therefore, appropriate to research how the R&D sector behaved with the drop in investment and how it impacted the company's results in terms of profit and production. In this case, the relationship between performance and R&D has not yet been explored by the literature. The paper's novelty is to provide relationships between investment in R&D and the level of company results between the years 2006 and 2020. The hypothesis is that the increase (or decrease) in the investment level and the innovation network have different impacts on important quantitative aspects of R&D and other outcomes such as production, costs, reserves, patents, and profit. Previous literature reports that the variation of investments also has controversial short-term and long-term results.

In this article, the discussion of the company's R&D follows the literature review (section 2) and methodology (section 3). (section 4). First, we focus on the organization's innovation networks with suppliers, academic institutions, government regulators, and other stakeholders (4.1); then, we look at investment variations and policies (4.2); and last, we concentrate at its human resources and management perspective (4.3). An examination of the immediate and long-term risks is part of the findings analysis. The conclusion and policy recommendations are in Section 5.

Table 2
Energy RD&I investment by country, OECD + Brazil.

Country	millions USD (2021)	Country	Millons by GDP unit (2021)
United States	9.185	Norway	1263
Japan	2.842	France	0,697
European Union	2.481	Finland	0,621
France	1.910	Japan	0,564
Germany	1.601	Belgium	0,546
United Kingdom	1.272	Sweden	0,523
Canada	1.049	Canada	0,522
South Korea	769	Swtizerland	0,513
Brazil	646	Denmark	0,509
Italy	619	Czech Republic	0,508
Norway	566	United Kingdom	0,442
Switzerland	413	Hungary	0,432
Nederlands	357	South Korea	0,425
Sweden	323	**Brazil**	0,421
Belgium	314	Austria	0,409
Australia	307	United States	0,400
Denmark	200	Germany	0,382
Austria	188	Nederlands	0,371
Finland	177	Portugal	0,313
Poland	148	Italy	0,284
Czech Republic	140	Poland	0,226
Spain	101	Australia	0,191
Portugal	78	Lithuania	0,184
Hungary	76	New Zeland	0,091
Turkey	32	Slovakia	0,085
Ireland	27	Spain	0,075
New Zeland	21	Ireland	0,06
Mexico	20	Latvia	0,05
Lithuania	11	Turkey	0,043
Slovakia	10	Mexico	0,015
Latvia	2		

Source: [5]; 2021.

Table 3
PICO framework.

Population or Problem	Intervention	Comparison	Results
Petrobras Brazil	PESTEL Factors for RD&I	Companies in the oil and gas sector operating in Brazil Oil and gas producing countries	Improving production, reserves, patents, innovation network, and brand recognition. Decreased costs and risks.

Source: authors.

Table 1
R&D investment by company.

	Petrobras Obligatory	Petrobras	ExxonMobil	BP	Chevron	Shell	Average Brent cost
2006	613	730	733	ND	ND	ND	65.16
2007	–	881	814	ND	ND	ND	72.44
2008	853	941	847	ND	ND	ND	96.96
2009	–	685	1050	ND	1342	ND	61.74
2010	735	989	1012	780	1147	1029	79.61
2011	990	1454	1044	636	1216	1123	111.26
2012	1148	1143	1042	674	1728	1307	111.57
2013	1161	1132	971	707	1861	1318	108.56
2014	1247	1099	1058	663	1985	1222	98.97
2015	898	630	1008	418	3340	1093	53.03
2016	715	523	1058	400	1033	1014	45.13
2017	1034	572	1063	391	864	922	54.71
2018	1505	641	1116	429	1210	986	71.34

Source: Companies annual reports and [5].

2. Bibliography review

The research on innovation networks is a recent development in a long line of studies on R&D in the oil industry [14]. In some studies, the Triple Helix model—which was created as a compromise between the free market and centralized planning—presents the oil research network idea (Etzkowitz and Leydesdorff, 2000; Etzkowitz et al., 2005). According to this viewpoint, economic progress is dependent not only on a new cycle of innovations, but also on an innovative structure that is intimately tied to basic and applied research. The concept of "open innovation" emerges inside the upstream business for a reason [15], defined as a collaborative R&D strategy that accepts ideas from other industries, universities, suppliers, and even technical disciplines [16, 17]. R&D activities involve a variety of stakeholders, including government agencies, universities, suppliers from a wide range of industries, and competitors [18–20].

Technology clusters are assumed to be essential for innovation and technological development, according to many authors [1,21]; Dantas and 2009, 2011 [11]; Turchi and Porto, 2013; Mancini and Paz, 2018).

[21] investigated the possibility of cooperative R&D with Petrobras, which represented a chance for developing-country firms to participate in technical innovation. In technical cooperation agreements with academic institutions and suppliers, the company would have transitioned from co-sponsor to articulator of the invention process [21]. [2,3] investigated the evolution of knowledge networks from 1953 to 2001. In a given collection of oil industry suppliers [1], looked into the relationship between proximity geography and innovation. Various Brazilian universities and the company together conducted cooperative research initiatives, which were the subject of other investigations [22]; Turchi and Porto, 2013). Mancini and Paz (2018) aimed to represent the research on the effects of the R&D clause by examining how it affected the actors' strategies.

The degree of change brought about by innovation is another crucial distinction in R&D research. There are both "radical" and "incremental" innovations in this regard. The former necessitates that innovative businesses develop fundamentally new skill sets. It introduces wholly new performance features, considerably improves existing performance features, significantly saves costs, or significantly alters the world around them, resulting in entirely new lines of business [23,24]. "Incremental" innovations offer comparatively modest cost or resource improvements [25]; Oslo Manual, paras. 76, 106, *in* OECD, 1997). Previous discussions of the oil and gas industry explain that the inherent risk of the sector has resulted in a pronounced emphasis on incremental innovation over the years at the expense of more radical advances [26–28]. Changes in the product or its building process, such as in business organization, production, or marketing techniques, are another important distinction [23,29,30]. Some studies on Petrobras or Brazilian RD&I are based on the Triple Helix, Innovation Clusters [Networks], and Open Innovation theories developed by Schumpeter (Etzkowitz et al., 2005 [1,3]; Nagano et al., 2014; Marcon et al., 2017; Mancini and Paz, 2018 [31,32]. [1]; examine two decades of exploration in the Campos Basin (1989–2009), a region with limited oil and gas resources and production that was transformed into a world leader in deep and ultra-deep offshore exploration and production capabilities, resulting in Brazilian energy self-sufficiency. Petrobras-affiliated enterprises operate under high technical dynamism, offering technologically complex items and services to the region's main oilfield operators. According to Silvester and Dalcol (2009), there is a subset of businesses whose proximity to one another has a favorable impact on innovative activity. The company is the most significant organization in this network [1–3, 11]. According to Ref. [6]; who used the database of the National Institute of Industrial Property, information on patents including the company's authorship or co-authorship is highlighted. Based on information from the ISI Web of Science and the CNPQ Lattes Platform, Turchi and Porto (2013) examine the Brazilian academic output in the oil sector. Although this study provides methodologically sound data on the link of research institutes with the innovation cluster, it does not explicitly address the company's perspective on these ties. The coordinators recognize that a lack of awareness of the firm's internal processes makes understanding the flows of innovation difficult, and even suggests a lack of input from the company on the research group's results [6]. However, it is obvious that, in the opinion of the firm managers polled, the majority of technologies are created within the firm [6,12]; and Turchi and Porto, 2013).

The local features of innovation and the exceptionally global nature of the upstream oil and gas industry are also extensively studied in the field of technology management (Stuart and Sorenson, 2003 [33–36]; Goldstein, 2009). Several examinations of the numerous technology hubs and clusters that have arised in various regions of the world have been the subject of much of the R&D-related research that specifically investigates the industry (Elliott, 2011; Hinton, 2012; Steen et al., 2013 [37,38]; Cumbers, 2000 [39,40]; Chapman et al., 2004; [36,41–45]. These surveys aid in the assessment of the case in the face of qualitative variables such as the impact of political and economic conditions on firm performance or R&D returns.

It is possible to confirm that the studies share the flaw of not utilizing the range of qualitative and quantitative information in corporate and regulatory agency reports by looking at the Brazilian oil and gas exploration and production industry. Studies frequently lack a meaningful comparison with quantitative data and are based primarily on interviews. It was also required to screen out research that had received positive international reviews and had been published in high-impact journals. Consequently, a bibliometric analysis and a thorough evaluation of these works were required. They can then be compared to the quantitative data after this process. This work innovates this discussion because the bibliography must sufficiently address this point.

3. Methodology

The area of energy savings implies an analysis of several factors, which often requires the application of combined methodologies to solve a research question. This work used a structured case study [46], as is usual in the Energy domain (Ramírez-Cendrero and Paz, 2017; [37, 47].

For the constitution of the research questions, the problem, the objectives, and the keywords, we used the PEST (Aguilar, 1967), SWOT, and PICO methodologies. The PESTEL method has been used to analyze Petrobras' RD&I area. In business analysis, this analysis describes a framework of macro-environmental factors used in strategic analysis or market research and offers an overview of the different factors to be considered (Nandonde, 2019). It is a strategic tool for understanding market growth or decline, business position, potential, and direction of operations. PEST analysis was developed by as an environmental scanning framework. Companies should scan the economic, technical, political, and social (ETPS) categories that can affect strategy, defining environmental scanning as follows, weight information about events and relationships in a company's external environment, knowledge of which would help management in its task charting the company's future course of action.

The research questions considered a composition of the SWOT (Weihrich, 1982) and PESTEL methodologies. Strengths, Weaknesses, Opportunities, and Threats analysis is a strategic planning and management technique related to business competition or project planning. The PICO can evaluate the quality of the research questions. Shamseer et al. (2015) recommend the use of this framework, according to which research questions must present population or problem (P), intervention (I), comparison (C), and a result (O).

The research question stems from the analysis tools.

What are the possible improvements in Petrobras' and Brazil's RD&I policies in oil and gas exploration and production?

The systematic literature review is a scientific method indicated because it adopts criteria to search, filter, and analyze the literature [48, 49]. This methodology does not exclude the possibility of further verification, improvement, and updating [50,51]. We also considered the bibliometric analysis methodology in the analytical part of the systematic review. This consists of applying statistical methods to analyze the evolution of a given topic of scientific research, establish the profile of publications and detect trends in future research based on the evolution of evidence and detected gaps [52–54].

The selection of the Scopus database (https://www.scopus.com/search/, accessed December 12, 2022) can be justified by three reasons.[1] Pertinence and global reach of the platform among academics from different areas [55]. [56,57] argue that the Scopus database is suitable for carrying out bibliometric analysis.

First, only peer-reviewed scientific articles published in English between 2000 and 2022 were considered. Only the names of the articles were used to choose those that were most closely connected to the study questions. The selection of keywords for the tools include the Population or Problem (P= Brazil, Brazilian, Petrobras) and Intervention (I=Oil and Gas, Energy, RD&I, Knowledge Network) from PICO methodology data filtering criteria. For Research, Development, and Innovation, researchers have used several corresponding acronyms ("RD&I" "R. & D." "RD" "R&D" "RDI").

The following criteria were used to choose the studies for the literature review: a preliminary search using the aforementioned keywords in the Scopus database yielded the following formula:

(TITLE (brazil OR Brazilian OR Petrobras) AND TITLE ("RD&I″ OR "R. & D." OR "RD" OR ″R&D″ OR research OR development OR network OR innovation OR knowledge) AND TITLE (energy OR gas OR oil OR Petrobras)) AND PUBYEAR >1999 AND PUBYEAR <2023 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "bk"))

Within this sample of papers, various trends in the bibliometric analysis can be seen. cable 7 in Annex 1 contains information on the quadrant in which the journal is ranked by Scimago, the amount of citations, the temporal scope, the technique utilized, and the comparison framework in this category's case studies.

The increase in publications over time indicates an increase in interest in the objects being studied. Six authors' names were associated with publications.

Six of the authors' affiliations' origins were unknown, thus that information was not included. The authors are connected to organizations in 20 different nations across practically every continent (with the exception of Africa). The World Bank classifies 34% of affiliations as coming from developed nations. Brazil accounts for 71 % of the researchers, while 18.8 % are from the United States and the United Kingdom.

The majority of the authors are affiliated with universities in Brazil, with a focus on São Paulo University and the Federal University of Rio de Janeiro, which has more than 11 authors.

Environmental sciences, social sciences, energy, economics, and administration have the largest incidence, accounting for 67.5% of the documents.

The main organizations that provide financing for researchers are the Coordination for the Improvement of Higher Education Personnel (CAPES), the São Paulo Research Foundation (FAPESP), and the National Council for Scientific and Technological Development (CNPq). Together, they contributed to 38.8 % of the periodicals' funding. 20 % of the documents, nevertheless, were funded outside of Brazil.

Only two of the ten research institutions with the greatest affiliations are not Brazilian. Seventeen of the 90 articles have more than 20 indexed citations.

When sending the keywords for the articles to the VOS Viewer

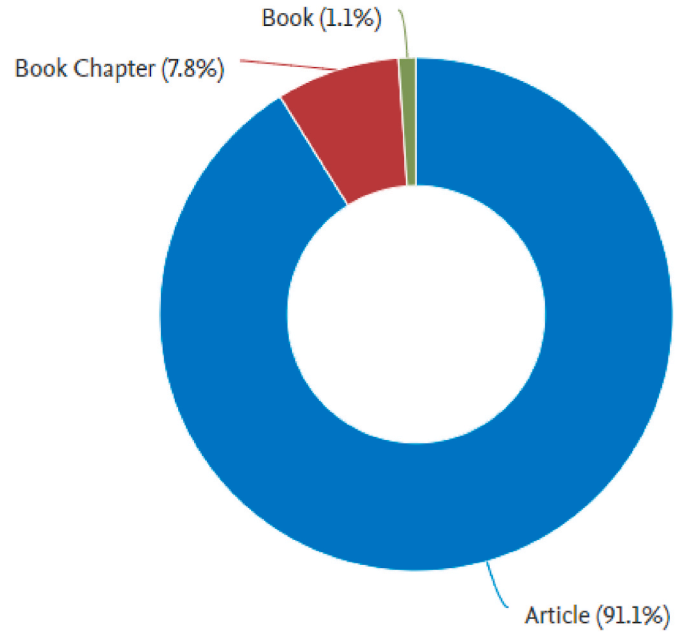


Fig. 1. Documents by type: 2000–2022.
Source: elaborated by authors through the Scopus dashboard.

program, the co-occurrence of keywords with the total count was utilized as a criterion.

Then, only repetitions that totaled 5 times or more were chosen. Obtaining the table below, which only takes into account occurrences greater than 6.

The following graph was obtained.

Within the analysis of keywords, the application selected Brazil and sustainable development with 47 and 17 occurrences respectively. However, the occurrence of words in the singular and plural reduced the weight of the words. With this correction, renewable energies (14) and investment (11) would have greater weight in the graph. The keywords reinforce the connection between the words investment and development and the apparent contradiction between development and sustainability and environmental protection, sometimes resolved with the expression sustainable development within development economics. Alternative and renewable energies, with a special focus on wind energy, also seem to be the solutions to resolve the economic and environmental contradiction. Energy policies, innovation, and planning seem to be the strategies for sustainable development.

Step 2, through the screening methodology, we limited ourselves to articles whose main focus was the exploration and production area of the oil and gas industry, obtaining a body of 57 articles. However, it was still noticed that some of the articles were not published in high-level academic journals.

Step 3, qualitative analysis was performed, limited to texts published at Q1 and Q2 levels in Scimago Journal and Country Rank. From this selection, only 44 divided titles and 27 journals remained.

The successive limitation of the bodies also took into account the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. This framework aims to help systematic reviewers transparently report research filtering procedures [58]. Based on this guideline, it was possible to execute the following diagram of the Identification and Screening steps.

As shown in the graph, the repetition of themes in journals such as the Journal of Cleaner Production, The Extractive Industries, and Society and Energy Policy show not only the pertinence of the theme of the present thesis but also the possibility of dialoguing with points of view published in high level. Of the 44 articles selected, 90 % are at the best level of the Scimago Ranking (Q1). Within this universe, the journals

[1] This study is limited to articles published in high-quality journals indexed in Scopus, other bibliographic reviews may consider other documents, including other sources such as the Web of Science.

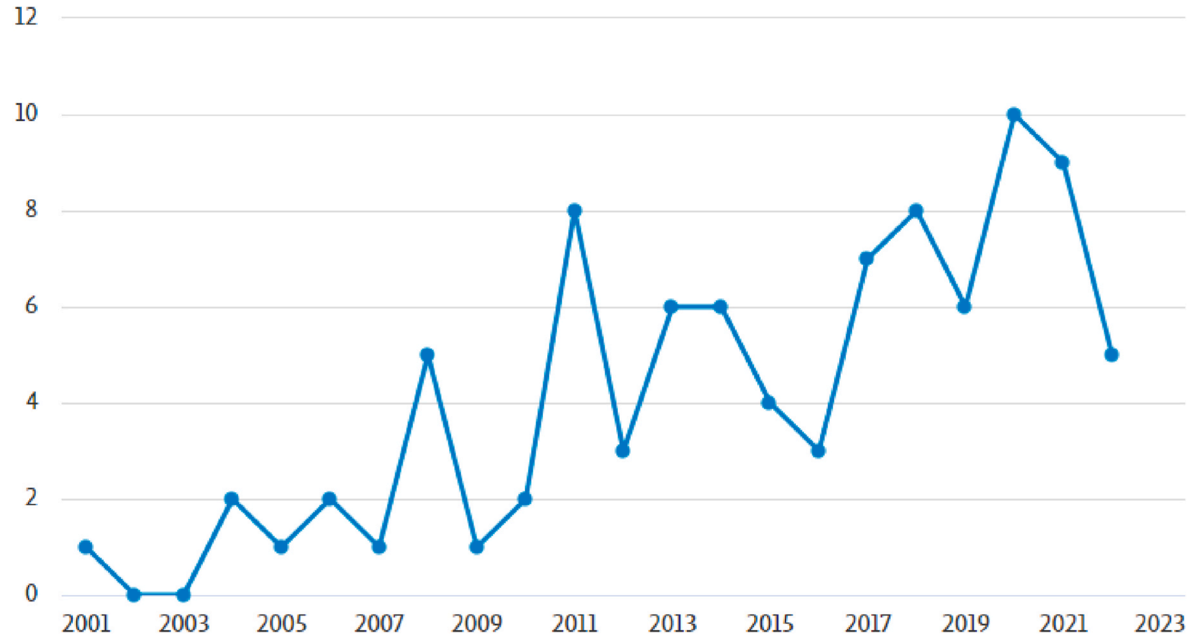


Fig. 2. The number os articles published by year: 2000–2022. Notes z-axis respects years of publication and y-axiz considers the number of articles published on each year.
Source: authors through the Scopus dashboard.

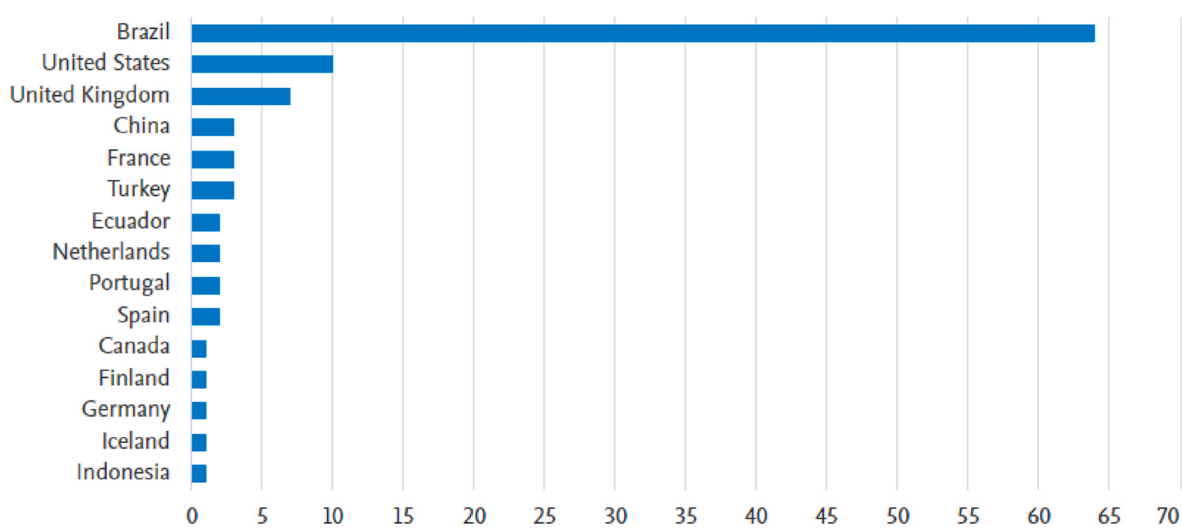


Fig. 3. Documents by country: 2000–2022. Notes: The x-axis considers the number os articles published by th affiliation country of the authors and the y-axis represents those countries. Elaborated by the authors through the Scopus dashboard.

with the most articles published were Energy Policy (8), The Extractive Industries and Society (5), Journal of Cleaner Production (4), Resources Policy (2), Research Policy (2), and Journal of Technology Transfer (two). These peer-reviewed journals in the energy area concentrate 52 % of the publications and reveal the quality of the selection made.

4. The predominance of methodologies

In these studies, 22 % of the articles dealt with Brazil or Petrobras without evoking comparisons with other companies or countries, while 77 % compared with other countries or companies. Of the 44 articles, 22 % of the articles used semi-structured interviews with the board of directors and 77 % were restricted to reporting data from companies and governmental and non-governmental institutions.

Among the methodologies explicitly mentioned in the studies are.

- Quantitative analysis of performance, data analysis, empirical analysis or causal analysis of performance (10);
- Analysis or comparative approach (5);
- Case study (5);
- PESTEL (3) and
- Best case, worst case and average case (2).

Some methodologies were mentioned at least once such as the analysis of regulatory frameworks; multi-criteria evaluation; the articulation of discussions about aspects not captured by quantitative results of the existing literature; forecast demand, production, and costs; descriptive and causal study; analysis of laws and results; and econometric analysis.

The firm was compared to other companies, such as oil companies or suppliers organized by innovation clusters, continents, or Brazilian

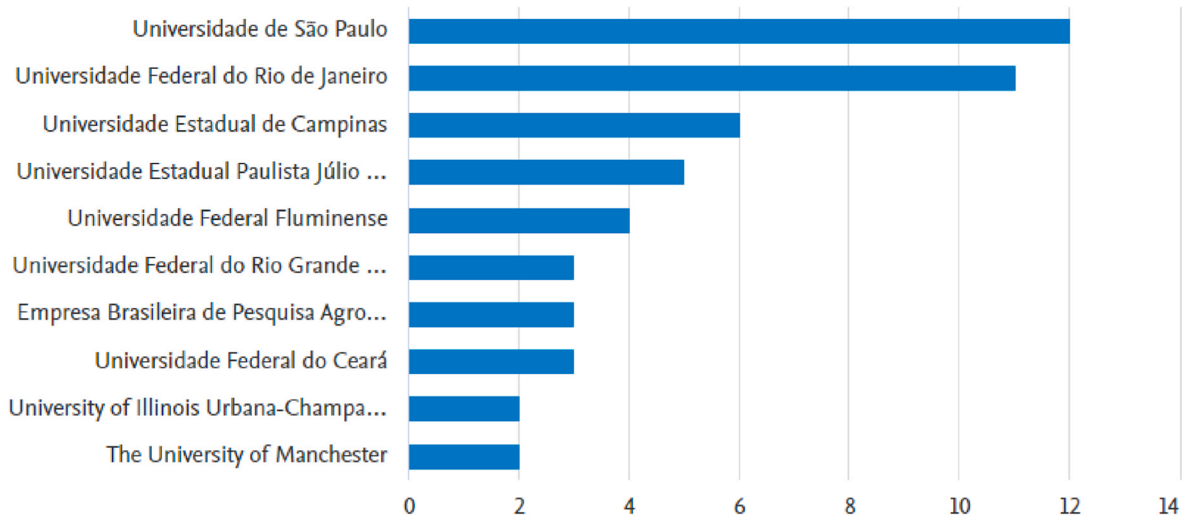


Fig. 4. Documents per year by affiliation: 2000–2022. Notes: The x-axis considers the number of documents published by the top documents published by affiliation of all authors under the sample selection method and the y-axis identifies those affiliations.
Source: Elaborated by authors through the Scopus dashboard.

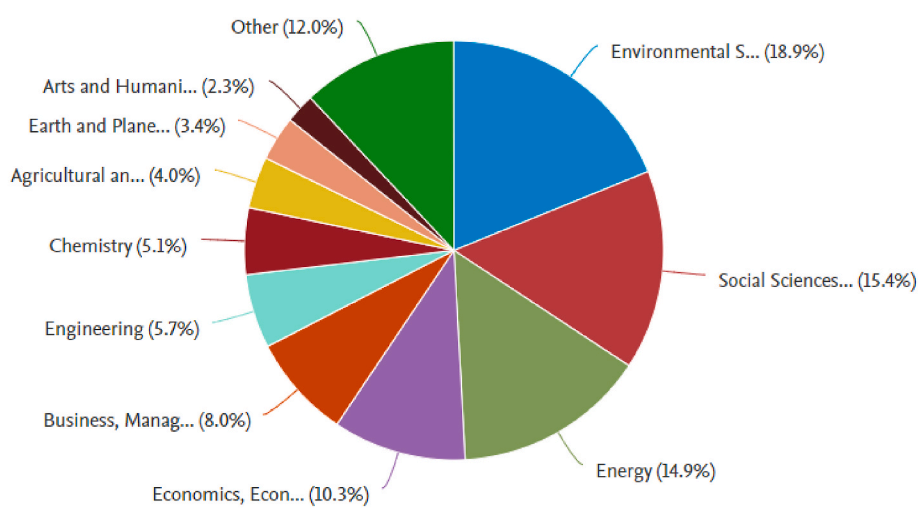


Fig. 5. Relative share of areas to which articles belong: 2000–2022.
Source: Elaborated by authors through the Scopus dashboard.

energy companies. Latin American, G20, OECD, and oil-producing countries were included in the country comparison analysis.

In this sense, Sá (2005), Gomes and Veugelers (2012), [7]; Emodi et al. (2015), Moralles and Rebellato (2016), Rapini et al. (2017), [31]; Mancini and Paz (2018), Massi and Nem Singh (2018) [32], examine the changing strategies of developing states using Brazil's oil-based industrial policy. The case study technique was bibliographic and only investigated some quantitative data such as production and relative amount of local material. However, they do so within the framework of Brazil's industrial growth strategy focused on the oil industry, where they analyze the interaction between the State, the firm, and the industrial elites [8]. Brazil's problem is to manage severe governmental interventions that destroy corporate autonomy and maintain the institutional capacity to focus investments toward investment and innovation given the difficulty of privatization as a remedy for the (bad) governance of state-owned companies [7,8]. The research by Mancini and Paz (2017) analyzes the legislative change, the amount of investment, and the main technological achievements of the company based on awards, production, patents, and the number of researchers and relationships with universities to evaluate the technical performance of the company. These results also consider essential variables such as the variation of oil prices, the regulatory context, and Brazilian politics. Disregarding these variables could oversimplify the considerations about the company's R&D area. It has an investment power capable of impacting the economic performance of the Brazilian State itself [7]; Ramírez-Cendrero & Paz, 2017; Mancini and Paz, 2017; [8]. Some studies focus on the spillover of investments and regulatory incentives for the Brazilian State (Sá, 2005; Gomes and Veugelers, 2012; Moralles and Rebellato, 2016). Some selected studies on Brazilian state company have dealt with externalities, such as political instability or public policy reflections (Pascual and Zambetakis, 2008; Wolf, 2009; [7,8]. Waterworth and Bradshaw, 2018; Hennart, Sheng and Carrera, 2017). Another part of the literature is related to legal aspects (Costa, 2020 [59]; Mariano and al., 2018), whether in the fiscal (Ramírez-Cendrero and Paz. 2017; Bøe and al., 2018) or local content (Lebdioui, 2019 [60]; 2020; [61].

As a result, various studies based on quantitative data from the company's annual reports and regulatory bodies are available for a more in-depth examination of performance (Kalyuzhnovaand and Nygaard, 2008; Ahmad, Rezaei, Sadaghiania and Tavasszya, 2017; Ramírez-

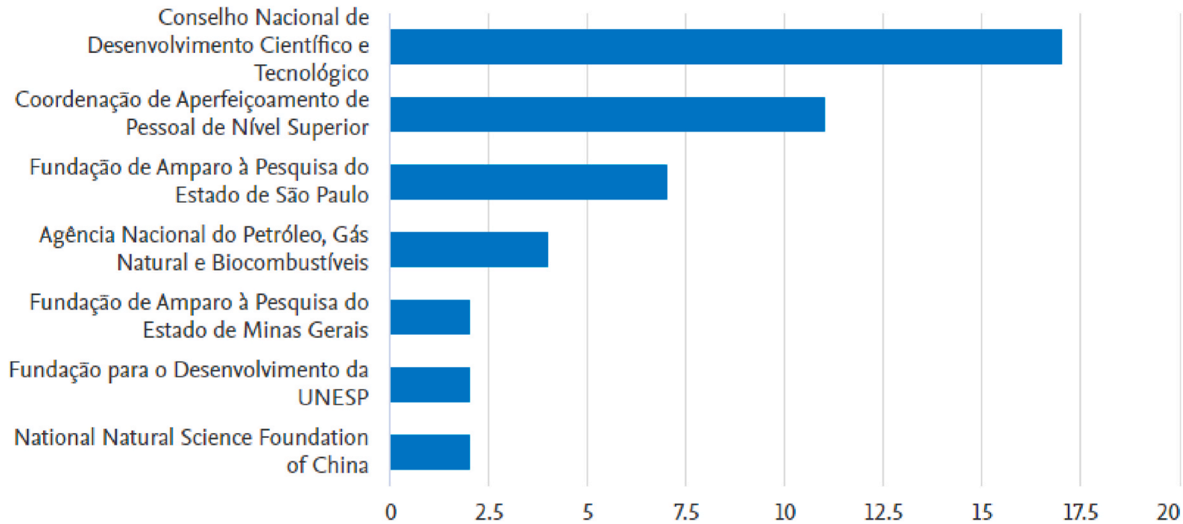


Fig. 6. Documents by sponsor: 2000–2022. Notes: The x-axis considers the number of documents published and the y-axis identifies those institutions.
Source: Elaborated by authors through the Scopus dashboard.

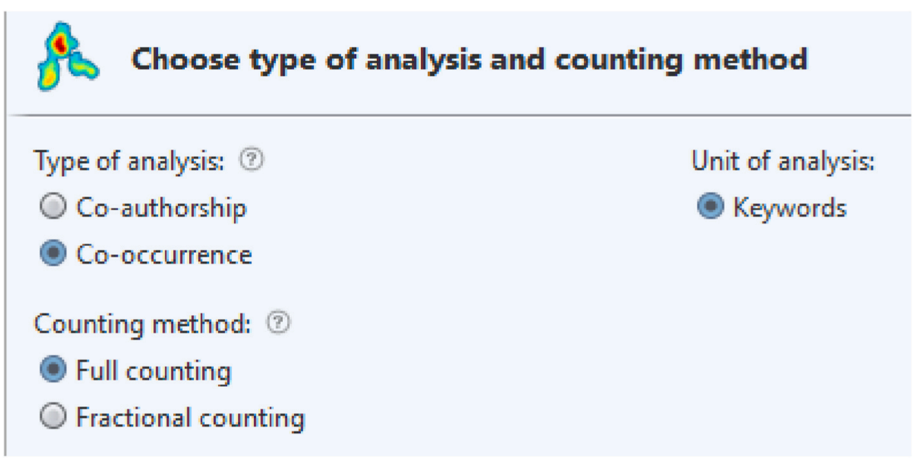
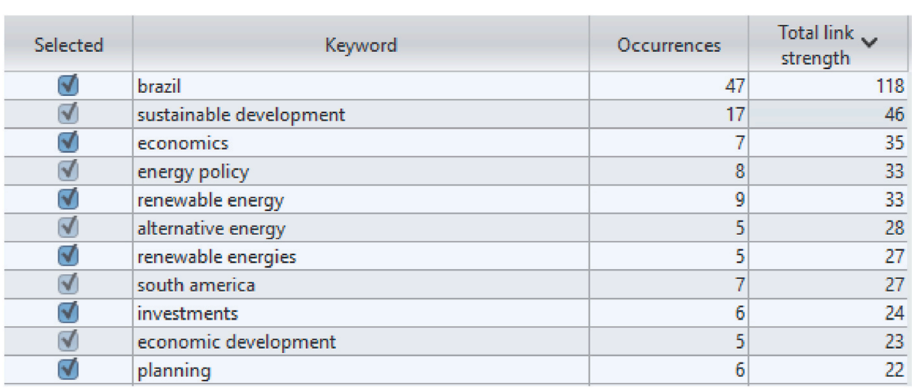


Fig. 7. Represent the option selected on the Vosviwer application.
Source: Elaborated byauthors through the VOSviewer dashboard.



Selected	Keyword	Occurrences	Total link strength
☑	brazil	47	118
☑	sustainable development	17	46
☑	economics	7	35
☑	energy policy	8	33
☑	renewable energy	9	33
☑	alternative energy	5	28
☑	renewable energies	5	27
☑	south america	7	27
☑	investments	6	24
☑	economic development	5	23
☑	planning	6	22

Fig. 8. Represent the keywords identified by VOSviewer application and the number of occurrences and link strength.
Source: Elaborated by authors through the VOSviewer dashboard.

Cendrero and Paz, 2017; Paz Antolín and Ramírez Cendrero, 2013 [11]; Chávez-Rodrígueza, Garaffa, Andrade, Cárdenas and al., 2016). On the other hand, research on Petrobras' R&D has been done [1–3,10–12]; Trojbicz and Loureiro, 2018; Pündrich et al., 2021 [6]; Turchi and Porto, 2013). These studies all have one thing in common: they don't not use a wide range of qualitative and quantitative data in firm and regulatory agency reports. Interviews are frequently used in studies without being adequately contrasted with quantitative data. Interviews are required,

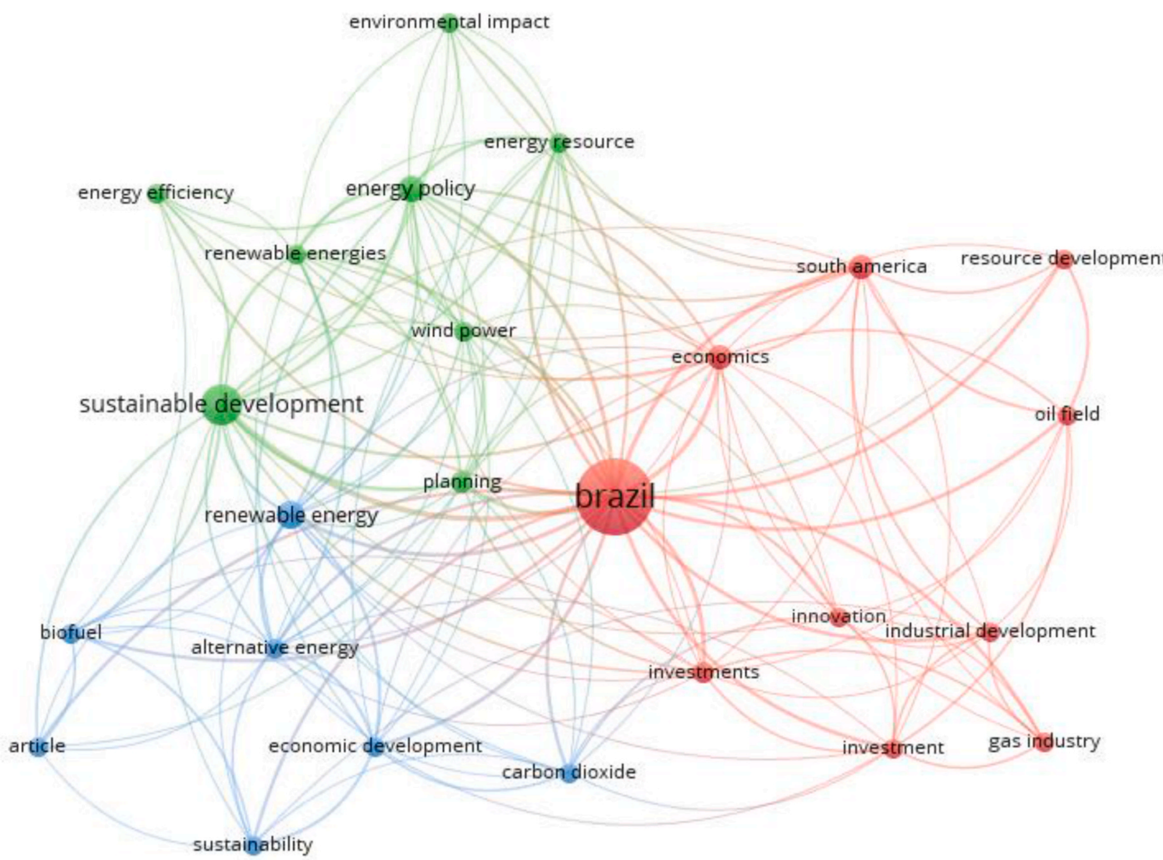


Fig. 9. Keywords occurring in titles, abstracts and keywords.
Source: Elaborated by authors through the Vosviewer dashboard.

but they must be linked to one another and to the quantitative data. As a result, while focusing on the company's relationships with the innovation cluster developed around it and with the Brazilian government, particularly from a political and regulatory standpoint, these past studies have yet to be linked to quantitative consequences. Because the bibliography has not thoroughly examined this point, our work adds to the debate.

Regarding data analysis, studies from the [5]; OPEC, OECD, and the World Bank can be used to place Brazil and the company in a global context. These organizations provide information on the exploration and production of energy, oil, and gas, as well as data on demand, supply, patents, investment, and oil and gas production and refining. Due to the data in the firms' annual reports, comparisons with other international oil companies are available. Data on oil production and demand, total and RD&I investments, as well as investment requirements of businesses doing business in Brazil, are all presented in the [62] reports. The specific regions and organizations taking part in the RD&I projects can also be found. EPE reports present data related to demand and the Brazilian energy matrix, which can be related to production and investment information in the oil and gas area [62]. website provide the primary sources for considering the legal aspect. In this sense, in addition to the laws, it is necessary to take into account the regulations of the regulatory agency.

When analyzing the reports from Petrobras and the Brazilian regulatory agencies, some variables directly related to the R&D area were noticeable (Table 4).

Aside from identifying the variables, substantial work was done to standardize the measurement units used over fourteen years of reporting and translate US dollar values into current prices. Because our analysis spans 20 years, we must account for the dollar's depreciation, or give revised data. Furthermore, certain tables and graphs lack data since they are not included in agency or company reports. The two institutions, according to business reports, have a specific relationship with advancing R&D. The Leopoldo Américo Miguez de Mello Research, Development, and Innovation Center is the company's first research facility (Cenpes). Second, Mancini and Paz (2018) remark that initially, the center concentrated on the downstream industry under the name Corporate University, also known as Petrobras University (e.g., refining). Brazil's state-owned corporation increased its E&P investments in response to the 1973 oil shocks, ensuring the nation's energy security.

5. Results and discussion

This section will cover the significant findings as well as the gaps they reveal. The R&D studies conducted by oil companies have been classified into four categories: first, the firm's innovation networks with suppliers, universities, regulatory agencies, and other stakeholders (4.1); second, state regulation, regulation, and investment amounts (4.2); and third, through the human resources area (4.3). The examination of the outcomes includes a comment on the hypotheses provided in the studies as well as the short and long-term risks.

5.1. From the perspective of the innovation clusters

[32]; who focused their study on Brazilian companies, came to the conclusion that collaboration with suppliers, universities, and research organizations is the most frequently mentioned method of removing obstacles to innovation. Geographical factors can be used to spatially constrain studies of innovation systems depending on the technology,

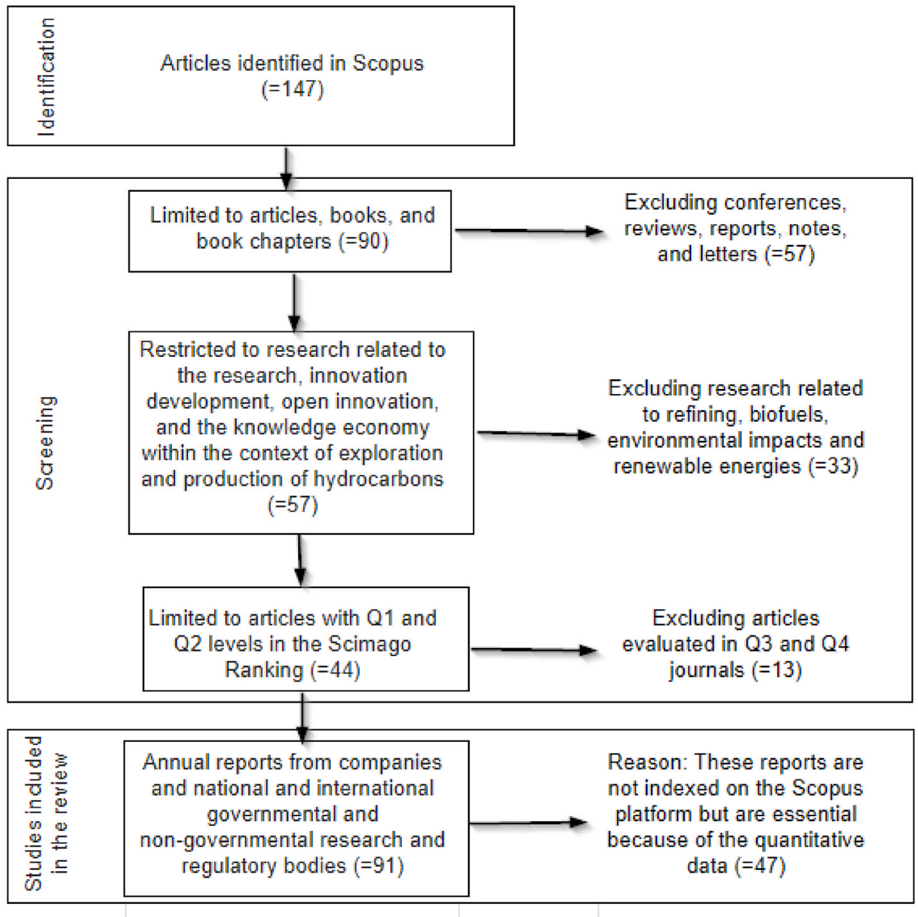


Fig. 10. Methodological approach used to determine the screaming process according to PRISMA methodology. The numbers (=x) represent the number of texts considered.
Source: Elaborated by authors.

Table 4
Quantitative data present in Petrobras reports.

Three-year patents in Brazil	Three-year patents abroad
Cost	Oil and Gas Production
Oil and Gas Reserves	Number of Employees
Nominal total investment	Obligation to invest in RD&I
Investment in Training	Investment in RD&I
Number of employees dedicated exclusively to research	Number of partner institutions of the Petrobras Research Center (Cenpes).
Employee Compensation Employee	Education Level

Sources: Petrobras, various reports (2006–2020).Source: Elaborated by authors.

industry, or company being studied [1]. The triple helix hypothesis is used by several authors (Etzkowitz et al., 2005; [2,6]. The government is a source of contractual agreements that ensure stable interactions and exchanges; the university is a source of new information and technology, the generative principle of knowledge-based economies. The industry is a member of the triple helix as a locus of production. These important players each play a unique role in every innovation strategy (Etzkowitz et al., 2005). National innovation systems can be classified as mature (those observed in rich nations) or immature (those observed in developing countries) based on the intensity of the relationships between agents [1].

[3] attempted to analyze the Petrobras innovation system while rejecting a static perspective and taking into account the dynamics of knowledge networks. The authors' main information source for evaluating the systems' dynamism was interviews with corporate managers or Brazilian regulatory organizations. The strategic nature of contacts between businesses or industries, as well as the function that these interactions play in propagating technological advancements, are additional factors for evaluating systems (Nagano et al., 2014). The most determining criteria of the systems, according to Ref. [31]; are internal characteristics of companies (size, intramural R&D, extramural R&D, product innovation, process innovation) and external characteristics of markets and policies (economic risk, cost of innovation, government financing) and state support for the capacity to absorb innovation [31]. Mancini and Paz (2018) based their analysis on quantitative criteria such as the amount of investment, the number of employees, the number of contracts between stakeholders, the circumstances of the company's research center, and the generation of patents, in addition to interviews. Other authors discuss corporate-university cooperation based on patent research and academic production. [22]; Turchi and Porto, 2013).

In their 2009 article, Dantas and Bell discussed the establishment and growth of company-centered knowledge networks in Brazilian learning and innovation systems. It is followed by a data analysis to draw conclusions about business activity over a period of around 50 years (1953–2001). They showed how the company's skills have both facilitated and constrained the potential networking forms at different points in time. Increased capabilities, on the other hand, served as "entrance tickets" to new networking activities. Knowledge networks, in turn, helped to increase capability margins and consolidate new capabilities at any given time [3]. Essential components of the innovation cluster and the idea of open innovation were also articulated in earlier research. According to Ref. [11]; when the company responds to stakeholder demands more effectively, it achieves more effective results in terms of disruptive and incremental innovations.

On the other side, studies by Lenz (2016), [6]; and Turchi and Porto (2013) discovered major inefficiencies in the company-university relationship, such as company managers' mistrust of the pace of responses and the research coordinators' intentions. Academic research impedes managers' desire for fast and short-term results. The organizers of the research groups, for their part, regard academic institutions' bureaucratic slowness as one of the barriers to deepening relationships [12]. [12] proposed valuing internal knowledge as one of the key steps to boost R&D. The emphasis on the company's university, on the other hand, appears to indicate a disdain of university expertise. Researchers identified company executives who complained about the sluggishness and inefficiency of initiatives in partnerships with universities during interviews (Lenz and al. 2016). The administrators of the university research teams were aware of this discrepancy [6]. The attempt to contact the company does not appear to be very successful. The endeavor to communicate the company's aims to the research centers through meetings and workshops appears to be an effort to address this partnership's inefficiencies. (Petrobras, several reports, 2008–2012). Despite the relationship challenges, which frequently involve issues of personal prestige within the company and the formation of the technical staff leadership ethos (Trojbicz and Loureiro 2018), the company reports show a steady increase in institutions collaborating with the company-led innovation cluster. Employees expanded from approximately 100 institutions in 2006 (Petrobras, Annual Report, 2006) to around 200 in 2020 (Petrobras, Annual Report, 2006). (Petrobras, Annual Report, 2020). In ten years, the research center received a $128 million investment (Mancini and Paz, 2018). Beginning in 2000, CENPES signed 802 research cooperation agreements with 58 science and technology organizations (STOs) and 119 companies, motivated by regulatory obligations [63]. In addition to 173 comparable contracts with international organizations, CENPES had 1145 scientific partnership agreements with local organizations in 2014. (Mancini and Paz, 2018).

Partnerships with universities, however, should be emphasized or noted in reports beginning in 2018. (Petrobras, several reports, 2018–2020). It is clear that the corporation strives to improve the quality of its relationships with research institutions while also expanding the open innovation network. In this regard, a growing tendency was discovered over the chosen time period (see Fig. 1).

5.2. *From the perspective of state development*

The extension and deepening of the link with the innovation cluster, as well as the development of open innovation techniques, cannot be regarded as the sole determinant of beneficial outcomes. This requires considering the role of the Brazilian government during the research period. In this way, the executive government has an impact on Petrobras' decisions from the outside in. The Lula governments (2002–2010) and the first Rousseff administration (2010–2014) were defined as national developmental governments by the secondary literature, despite having engagement with foreign capital investment [7]; Ramrez-Cendrero and Paz. 2017; [8]. By selecting the Production and Exploration Refining sectors as the primary sectors to boost the Brazilian

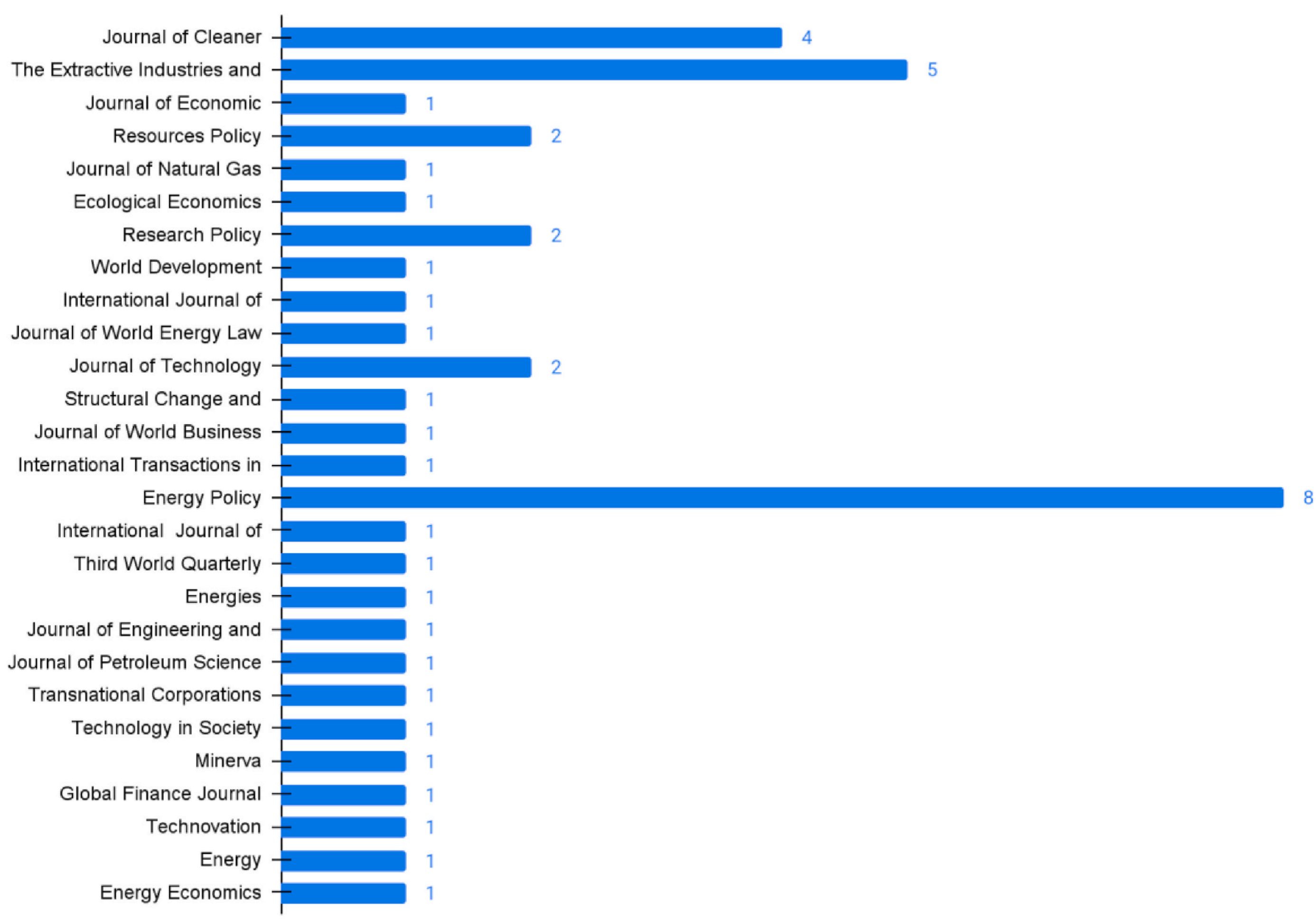


Fig. 11. Number absolute of documents by source title: 2000–2022.
Source: Elaborated by authors through the Scopus dashboard.

economy, these authors contend that investment selections reflect the interests of these governments. In this sense, the amount invested has increased, particularly in these two areas (Fig. 12) (see Fig. 3) (see Fig. 4) (see Fig. 5) (see Fig. 6) (see Fig. 7) (see Fig. 8) (see Fig. 9) (see Fig. 10) (see Fig. 11) (see Fig. 2).

The company's good and bad performance may have been influenced by a decline in investments beginning in 2014, which was spurred by a drop in oil prices and a shift in the second Dilma administration's stance. According to the bibliography, this shift is due to three factors: saturation of the developmental model [7,8], the impact of corruption scandals involving the company's governing body and the Workers' Party [61], and the sudden drop in oil prices, which has a direct impact on the company's profit (Petrobras, Annual Reports, 2012–2016). The impact of the oil price decline on the company's profit and investments is clear. This behavior can also be seen in other companies in the industry, including the majors. (Ramírez-Cendrero & Paz, 2017; Massi, E. and J. Nem Singh. 2018).

The protection provided by Brazilian law has prevented a dramatic decline in overall R&D spending. The national regulatory agency regulated the contractual obligation clause in 2006, mandating that at least 1 % of gross revenue from new, highly productive wells be set aside for investments in R&D, with up to 50 % of these funds going to the research facilities of oil firms. At least half are going to Brazilian institutions of science and technology. Government incentives notwithstanding, the amount invested yields contentious outcomes. The decrease is also connected to the depreciation of the real (Table 5).

Mancini and Paz (2018) had previously observed that partner institutions got participation that was marginally above the R&D clause's minimal requirement of 50 % of the obligatory amount. On the other hand, oil firms, particularly Petrobras, spend the majority of the funds not allotted to universities in internal projects. The majority of the money the company did not have to transfer to universities was put into its research facility. It stands in contrast to other oil firms, which only made modest internal investments. Finally, less than 10 % of the total funding was given to service businesses to carry out research projects resulting from the R&D provision (Mancini and Paz, 2018). Furthermore, based on the interviews, Mancini and Paz (2018) discovered that the majority of international oil firms invested in R&D with sufficient accuracy to meet their obligations. Oil firms only spent in R&D because the clause compelled them to. Unlike the Brazilian company, four oil companies - BP, Chevron, Shell, and Statoil - invested more than the statutory R&D clause required. BP and Statoil also developed a research center in Rio de Janeiro. It is BP's first research facility outside of the United Kingdom, and Statoil's first in a developing country. (Mancini and Paz, 2018).

Table 5
Petrobras R&D investment (in millions, current and corrected values).

	Obligatory	Brazilian Reais	US Dollar	US Dollar (corrected)
2006	613	1533	730	929
2007	–	1673	881	1077
2008	853	1693	941	1.174
2009	–	1500	685	815
2010	735	2400	989	1173
2011	990	2400	1454	1655
2012	1148	2200	1143	1288
2013	1161	2377	1132	1248
2014	1247	2600	1099	1201
2015	898	2020	630	684
2016	715	1826	523	563
2017	1034	1831	572	603
2018	1505	2345	641	660
2019	1408	2268	576	583
2020	1059	1819	356	356

Sources: [62]; several reports 2006–2020; Petrobras, several reports, 2006–2020. The authors created them. Values corrected based on December 2020, IPEA, and several reports.

The company has invested more in this area than what the regulatory body has estimated. It should be noted that the company only provided data in dollars for the years 2018–2020 and no data in Brazilian real for the years 2006–2008 and 2013. This omission is probably made to conceal or mitigate the impact of the decline in US dollar investment on investors. According to the data in the reports, investments increased until 2011, with the exception of a decline in 2009 that may have been caused by the global financial crisis. For the following few years, investments were stable when measured in Brazilian real. However, as measured in dollars, investment in research, development, and innovation has dropped to half of what it was in 2006 and 20 % of what it was in 2011. When we consider compounded inflation, the annual drop in R&D investment becomes even more apparent. The annual level of investment between 2015 and 2019 is lower with corrected numbers than the period between 2006 and 2009. Given the COVID-19 pandemic, the 2020 values are even lower. In corrected data, there is a noticeable decrease in investment to levels lower than 2006. Surprisingly, demonstrated reserve volumes did not rise between 2006 and 2020. One

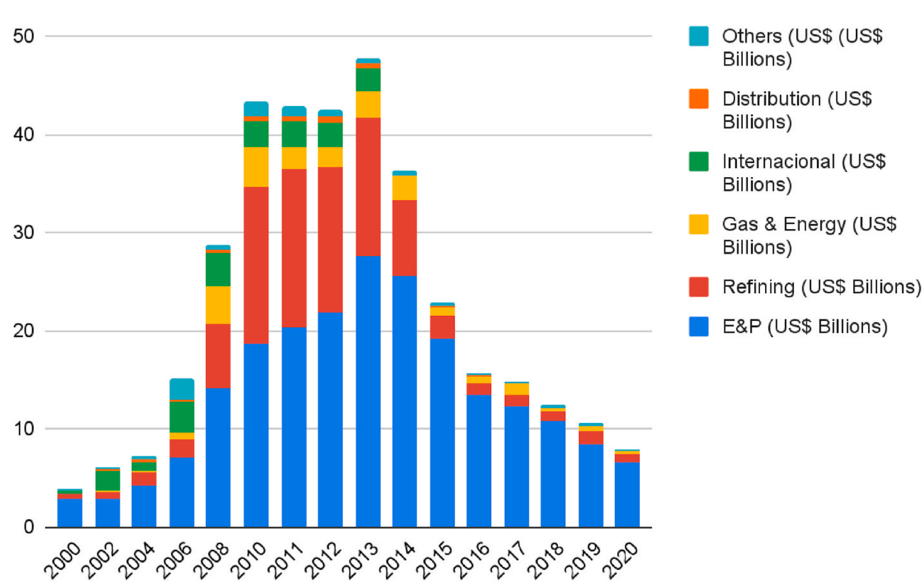


Fig. 12. Petrobras - Nominal investment in current values (2000–2020).
Sources: Sources: Petrobras (2000–2020). Source: Elaborated by authors.

explanation for the apparent decline in reserves and the short-term drop in output growth could be this reduction in investments.

Furthermore, reducing investments in terms of American currency can lower the company's long-term competitiveness within the sector and impede the discovery of new areas and technologies with implications for production (Table 6). The decrease in investments did not result in a decrease in the number of patents obtained (Table 7), possibly due to learning in acquiring patents and inventions [2,3]. Without a doubt, the increase in R&D investments has resulted in a record number of patents being filed (Mancini and Paz, 2018). However, because to data confidentiality, the study's authors found it challenging to ascertain the precise number of patents coming from research initiatives supported by the R&D clause. The data in the reports also show that Brazil's patents are becoming more concentrated in line with the cessation of foreign investments starting in 2013. The company's option to specialize is indicated by the decline in foreign investments and the concentration of Brazilian patents, which can speed up the drilling and completion of oil wells in the pre-salt region and result in margin increases and cost reductions (Mancini and Paz, 2018). On the other hand, it also symbolizes the long-term desire to give up on international competition in other industries with inherent hazards.

Based on interviews, Mancini and Paz (2018) identified the leading patented technologies, such as the Steel Lazy Wave Riser (SLWR), the world's first steel riser of its kind, which was connected to a floating production, storage, and offloading (FPSO) unit, with a spread mooring designed to resist the floating vessel's movement in the harsh pre-salt conditions. The company's oil and gas production will set new milestones in 2020. Although, as previously stated, output growth has stalled. On the other side, one of the impacts addressed by technologies is cost reduction [1,64–68].

The findings reported in the reports and the OTC international awards (given in 2015 and 2022) demonstrated that the focus of investment in exploration upheld the industry's technological and production leadership in deepwater oil and gas exploration. Long-term outcomes are jeopardized by the decline of researchers, total investment, R&D investment, staff headcount, and compensation. These concerns are highlighted by the decline in proven reserves and the rapid increase in output. There is still uncertainty as to whether the corporation will continue to produce the technologies needed to explore the pre-salt layer and whether there will be a decrease in the number of patents.

5.3. *From the perspective of human resources*

When addressing sustainability in their business models [11], offer strategies to help Petrobras management better engage with stakeholders and overcome the problems of competing interests. Finally, the authors proposed a combination of measures that encourage the participation of a diverse variety of local stakeholders. To overcome the issues of opposing stakeholder interests, it is critical to encourage learning and capacity growth, as well as move stakeholder values from single to numerous goals [11].

Questions about innovation management in the fields of economics, administration, and human resources have also been raised by the literature on innovation in Brazil and Petrobras (Wong et al., 2013b, 2013a; Marcon et al., 2017; Nagano et al., 2014; [1,32]. With this strategy, the management of the business is the main concern rather than the innovation network or the viewpoint of the State [9]. claims that one of the secrets to the company's success is operational management. Wong et al. (2013a) further noted that R&D sectors use human resources and the body of knowledge already in existence to produce technical innovation. According to studies, there are degrees of novelty associated with the changes made, hence verifying the concepts of gradual and radical innovation (Marcon et al., 2017). The technology or technique may differ somewhat or dramatically from its predecessors (Marcon et al., 2017). While it is true that I incremental innovations are the result of new organizational arrangements, (ii) radical innovations are the result of extensive R&D operations (Marcon et al., 2017). The implemented innovations are classified into four types: I product innovations, (ii) process innovations, (iii) organizational innovations, and (iv) marketing innovations. While organizational and marketing innovations include a broader range of management factors, product and process innovations are intimately linked to technology breakthroughs. (Marcon et al., 2017). Only a complex combination of human, technological, organizational, and market variables can produce innovation performance (Nagano et al., 2014 [1]. [32]; highlight internal hurdles to innovation at the firm level in addition to external impediments to innovation caused by the government and the business environment. Internal innovation obstacles are anything that interferes with an organization's ability to innovate. As a result, they primarily concern management, organization, and corporate competences [32]. Since establishing technological excellence is tied to both R&D and organizational and managerial skills, Moralles and Rebellato (2016) link the requirement for investments in R&D to management costs.

On the other hand, there is a requirement for human capital formation in companies. According to Goedhuysa and Veugelers (2012), one of the initial barriers to effective R&D and innovation performance in Brazil is a shortage of skills, particularly in natural and exact sciences and engineering, which are required for the technical development of technology-intensive businesses. On the other hand, the limitations of Brazilian enterprises and the shortage of labor supply can result in insufficient know-how (Rapini et al., 2017).

[12] provided a study based on interviews with firm 10 managers from different levels and areas, staying within the context of innovation

Table 7
Patents granted to Petrobras for three years (2004–2020).

Triennium	Brazil	Abroad	Total
2004–2006	48	179	227
2005–2007	43	169	212
2006–2008	48	148	196
2007–2009	No data	No data	196
2008–2010	45	109	154
2009–2011	52	128	180
2010–2012	75	152	227
2011–2013	97	139	236
2012–2014	100	134	234
2013–2015	118	113	231
2014–2016	106	118	224
2015–2017	124	108	232
2016–2018	186	94	280
2017–2019	214	113	327
2018–2020	259	51	310

Source: Petrobras, several reports, 2006–2020.2007–2009 triennium, the locations of the patents needed to be specified, only the total number.

Table 6
Petrobras oil and gas reserves and exploration costs (2000–2020).

Year	2000	2002	2004	2006	2008	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Cost (US$/boe)	–	–	–	7,2	10,2	9,4	13,2	15,4	14,9	15,3	11,2	10,8	11	10,9	9,8	6,8
Oil reserves (Trillion boe)	8,2	9,5	11,6	12,3	12,5	13,4	13,7	10,5	10,7	13,9	10,9	8,2	8,4	8,3	8,1	7,5
Petrobras Oil production (Bb/year)	447	530	519	616	647	675	759	801	748	749	775	771	783	780	822	844

Sources: [62]; several reports (2000–2020); Petrobras, several reports (2006–2020).

clusters but opportunely focusing on the importance of individuals inside institutional networks. According to the authors' research, establishing a sense of worth among employees, competing within the company, and interpersonal interactions are the three biggest obstacles to open innovation [15,69,70]. The study has the advantage of stressing how important networks and social capital are for fostering creativity, despite the fact that it does not compare anything and does not employ quantitative methods. Internally amongst the firm's professionals and externally between these professionals, suppliers, and universities, relationships of fear, mistrust, and diversity can have an impact. The study proposes solutions to mitigate these challenges to increase R&D performance [12].

However, the management measures applied by the Corporate University, such as those pointed out in the company's reports, can explain the positive aspects of the performance compared to the negative ones. There are mentions of improvement and specialization courses in project management (Petrobras, Activities report, 2006: 50). In 2008, the corporate university building was expanded, and its courses were specially accredited by the Brazilian Educational System (Petrobras, Activities report, 2008). In this way, the company started to offer specialization courses in Petroleum and Natural Gas Engineering, Oil and Natural Gas Geophysics, and Oil and Natural Gas Processing (Petrobras, several reports, 2012–2020). The Corporate University developed at the General Assembly of the Globally Responsible Leadership Initiative Foundation. It is a methodology for training globally responsible leaders based on the principles of the UN Global Compact (Petrobras, Activities report, 2008). These initiatives are related to the attempt to enhance the firm's knowledge with projects that are valued internal agents (Petrobras, several reports, 2012–2020).

There is a movement toward human resources maturation and a gradual shift in the direction of innovative knowledge production within the firm. The reports also noted that the corporate university needs to prioritize technical knowledge in the first reports. Until 2012, it was more concerned with workplace safety issues, perhaps motivated by the pressure to reduce fatal accidents and leaks (Petrobras, several reports, 2008–2012). Following the corruption scandals in 2013, Petrobras University promoted a course on anti-corruption legislation (Petrobras, Administration report, 2015). In recent reports, the Corporate University's concern for lowering production costs and the investment reduction restructuring relations with the Research Center. Petrobras University continued to offer technical-educational services to bring research closer to the operational areas, reinforcing its role in generating value for the firm's units. In this process, technicians work with the units to resolve technical and management issues, intending to apply the knowledge generated in the preparation or updating of development actions (Sustainability Report, 2017).

From a quantitative point of view, the human resources area had to make its practices more effective in the context of reduced investments from 2013 onwards. There was a drastic downward trend in resources, dropping from about US$ 196 million until they reached values of around US$ 49 million and US$ 6 million in 2019 and 2020 (Petrobras, Annual Reports, Several Years). The decline in the amounts invested in training is not only related to the devaluation of the Brazilian currency against the US currency and the improvement of practices in the human resources sector. The cost cut is related to the decrease in hiring new employees, with the consequent decrease in the number of employees and the other controlled companies. From 68,931 employees in 2007, the company increased to 86,111 in 2014. From 2015 to 2020, a downward trend in the number was identified, from 80,908 to 57,983, numbers below the 2007 level (Petrobras, Annual Reports, Several Years). Such measures impacted the amounts related to employee remuneration, from US$ 10.424 million in 2011 to US$ 4.937 in 2020, a level lower than the US$ 4.256 million recorded in 2006 (Petrobras, Annual Reports, Several Years). Mancini and Paz (2018) noted an increase in the number of researchers hired by the company's research center, which rose from 1142 to 1775 between 2001 and 2016. According to the company reports, between 2006 and 2020, there was an employee number drop (Table 8). Today, with 1100 researchers, the number is slightly lower than in 2006 and 30 % lower than the peak of 1648 in 2016. Such elements, as mentioned above, present positive results in the accounting aspect, with the reduction of operating costs and beneficial effects on the company's profit. From the point of view of local content, however, these are worrying numbers for the Brazilian State. The reduction is still noticeable in the Exploration and Production area (see Table 9).

Petrobras delivers favorable data in the short term, according to the company's management, such as cost reduction (employee number and remuneration), profit rise, and output increase. However, the company's strategies appear to sacrifice RD&I in the long run by cutting investments and people committed solely to research. Salary reductions and the research center also tend to hurt the firm's competitiveness in the long run.

6. Policies recommendations

The purpose of this research was to address the following research question: What are the potential improvements in Petrobras' and Brazil's RD&I policies in oil and gas exploration and production?

The Legislation does not protect investments made in foreign currency, making them vulnerable to depreciation of the Brazilian currency. Due to Brazil's political and economic uncertainties beginning in 2013, the Act became effective in ensuring the expansion and even the maintenance of RD&I investment (Pascual and Zambetakis, 2008). When the values are expressed in Brazilian currency, they remain at the 2010 level, although this does not ensure the same level of investment as in other nations. However, RD&I investments in the O&G industry tend to fall globally with the reduction in oil prices.

Due to their expanded production, other companies in the sector have successfully boosted their share of RD&I contributions. However, this is also a result of the company's slower rate of expansion, which is clearly connected to a reduction in overall investments, particularly in exploration and production.

It is also important to highlight that the legislation takes into account the firm's decline in the number of researchers. On the other hand, it does not safeguard employment. Since 2014, the number of staff has decreased. Employees' compensation is not protected under the law because their salaries have devalued along with the Brazilian currency.

By producing in scale and concentrating on the industries that are the most productive, the company lowers expenses in this manner and also greatly lowers costs by hiring and training personnel. If this drop is the

Table 8
Employees and researchers at the Petrobras research center (2006–2020).

Year	Total	Researchers	Proportion
2006	1811	No data	No data
2008	2000	1160	58 %
2009	2100	1176	51 %
2010	1800	738	41 %
2011	1814	1342	73 %
2012	1897	1420	74 %
2013	1959	1466	74 %
2014	1862	1648	74 %
2015	1808	1638	90 %
2016	1458	1345	92 %
2017	1301	1197	92 %
2018	1289	1204	93 %
2019	1358	1216	89 %
2020	1237	1100	88 %

Source: Petrobras, Several reports, 2006–2020. Authors create them. It should be noted that the 2006 reports do not include the number of researchers. In the 2017 reports, the number of employees was not mentioned. In 2010, only the proportion of postgraduates in stricto sensu, master's, and doctoral courses was presented.

Table 9
This table helps to visualise the relationship of the quantitative variables with the bibliographical discussions.

Variable	Quantitative Data tendency	RD&I correlation	Literature correlation, discoveries and deepening suggestions
Patents in Brazil and abroad	Brazil's patents constantly increased throughout the period, surpassing the downward trend in international patents. Total patents tended to fall to a minimum in the three years 2008–2010 and tended to increase between 2010 and 2020.	The patent growth from 2010 can be correlated to the constant increase in local currency investments and the number of partner research institutions. The drop in the number of patents abroad is due to the sale of assets abroad and the concentration of activities in the Brazilian pre-salt [60]; 2020)	This aspect was considered in only two works (Mancini and Paz, 2018; [6].) because the increase in investment and the number of partnerships with research institutions correlate with the rise in the number of patents. However, the bibliography did not consider the effects of the concentration of patents in Brazil nor the reduction of the company's patents abroad. This aspect should be deepened in future studies.
Cost	Production costs tended to increase until the first years of pre-salt operations. However, there was a constant fall in levels before the discovery of reserves in ultra-deep waters. Costs are competitive when compared to other offshore exploration areas.	The ongoing search for innovations, learning by doing and the increase in relationships with partner institutions can cause a reduction in production costs. In addition, from 2012, the company began to sell less profitable assets, and in 2016, it began to reduce the number of funders, including researchers. The cut in expenses was linked to the company's indebtedness scenario due to the investment in new exploration areas and the reduction in profits related to the oil price drop from 2014 [71].	The cost aspect was considered in some studies because it is one of the objectives of the RD&I and one of the main obstacles to exploration in ultra-deep waters. The bibliography, however, did not consider the social and economic effects on Brazil's industrial policy with the divestment decision taken by Petrobras, especially since the Temer government (Rocha et al., 2016). The recovery of the company's profit had social costs for Brazil, such as the reduction of jobs, the increase in energy prices due to the adoption of international price parity and the inflationary effect [7].
Proven reserves, Oil and Gas Production	The period showed a constant increase in production, making Brazil self-sufficient in energy and an exporter of crude oil. In addition to the concentration of production in the country, the reduction in productivity in mature fields accelerated the concentration of production in the pre-salt region.	Increasing production with cost reduction is undoubtedly one of the best results aimed at the RD&I area (Hennart and al., 2017). There was an increase in reserves until the start of pre-salt exportation (Emodi et al., 2015). However, proven reserves began to be reduced from 2012 onwards, denoting the impact of declining investments in new abandoned fields with the divestment programs and the company's fight against indebtedness [8]; Ramírez-Cendrero and Paz. 2017; Fontaine and al., 2017). The reduction in investments related to the decrease of proved reserves is linked to political factors such as the corruption scandals and the change in the economic model after Dilma's impeachment (Lima-deOliveira; 2019).	Although oil and gas production increased steadily over the period, it increased below the company's expectations (Emodi et al., 2015). Furthermore, divestments in the refining sector made the country an exporter of crude oil and continued to import part of refined fuel. The plan of the Workers' Party government to make the country an exporter of refined fuel was discontinued, especially after Dilma's impeachment (Bøe and al., 2018). Adopting the crude oil export model means Brazil still depends on diesel and gasoline imports. In addition, the productive potential of gas is not properly used, causing about half of the production to be reinjected into the wells (Waterworth and Bradshaw, 2018).
Oil and Gas Reserves	There was an increase in reserves until the start of pre-salt exportation. However, reserves began to be reduced from 2012 onwards, denoting the impact of reducing investments in new abandoned fields with the divestment programs and the company's fight against indebtedness.	The reduction in investments is linked to political factors such as the corruption scandals (Lima-deOliveira; 2019) and the change in the economic model after Dilma's impeachment (Araujo; Leoneti, 2019). The company has announced interest in exploring Brazil's equatorial margin to reduce stagnation in proved reserves.	Only the present review study identified the fall in proven reserves may be related to the stagnation of investment in research. The bibliography justifies the reduction in total investments in production and exploration because of the political factors (LebdiouI, 2019), Petrobras' indebtedness and the losses in the three years following the 2014 price drop [13]; 2020).

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Table 9 (*continued*)

Variable	Quantitative Data tendency	RD&I correlation	Literature correlation, discoveries and deepening suggestions
Number of Employees	The number of employees increased during the administrations of Lula and Dilma. However, after Dilma's impeachment, the company began to adopt a policy of reducing staff and selling assets in addition to retirement programs, reducing the number of employees by about 30 %	One of the objectives of RD&I is to increase the efficiency of operations (Marcon et al., 2017). The increase in production, with the reduction in staff and costs, can also be considered a result of the area. However, it is also necessary to consider that the sale of assets and the reduction of investments and hiring because of the increase in the company's debt also seek to recover the profit of the state-owned company, especially since the Temer government (Ahmad and al., 2017).	The bibliography not identified on the RD&I did not relate to the number of employees decrease [12]. It is necessary to determine to what extent the reduction in the number of employees may have impacted the companies' results. The price control and international parity policy greatly affected the company's profitability [32].
Investment Obligation to invest in RD&I	Nominal investment tracks four variables: oil price, investment obligations, production and exchange rate. Investment obligations are directly linked to production value. When considering the scenario in the current currency, there was a constant increase in investment until 2014. With the reduction in oil prices in 2014, investment maintained an average of the numbers from 2015 to 2020.	When considering American currency, the reduction in the exchange rate reduced these investments to a third of what was practised in 2014 and half of what was practised in 2006. Undoubtedly, this aspect undermines the possibility of investing in research in new fields (Mariano and al., 2018) and can be associated with the constant drop in proven reserves.	The bibliography sufficiently presented the aspects of the investment obligation as an industrial development policy [31]; Sá, 2005). However, until the present study, the bibliography did not identify that devaluation and inflation reduced Petrobas' investment in PDI between 2018 and 2020 to half the values practised in 2006. The impacts in the short term can be the frustration of production below the strategic plan and the reduction of proved reserves (Mariano and al., 2018).
Investment in Training	There was a significant reduction in investment in training after the hiring stoppage and a reduction in the number of employees in 2016.	The nature of the training was also modified, starting from the emphasis on operations and the safety of operations for governance, especially regarding compliance, from 2018 onwards.	Previous studies have identified that the company's internal training and learning by doing are the greatest creators of innovation (Nagano et al., 2014; Lenz and al. 2016; [72]. However, the effects of reducing investments in training from 2016 onwards should have been considered. This aspect deserves to be studied in future studies.
Nominal total investment	Total investments in the Exploitation and Production area constantly grew until 2014 due to the start of pre-salt operations. From 2015, the economic crisis, the economic and consumption stagnation, and the the governance crisis of the company and the federal government itself from the media scandals of corruption, investment began to be reduced. The oil price reduction is the main factor in other large international oil companies. In addition, Petrobras' indebtedness and the losses between 2014 and 2016 also justify the reduction in investments. From the Temer government, with the intention of private capital entering the sector, assets and concepts were made to reduce the size of the state-owned company. The change in the economic model can also be considered a factor in reducing investments.	Although production was not impacted, the reduction in investments helped reduce operating costs (Mariano and al., 2018). Still, it negatively impacted the constant reduction of proved reserves.	The drop in investments in exploration, production and refining directly affected lower-than-expected production, the company's multi-year plans and a drop in proved reserves. Furthermore, as the value of production is one of the critical factors for calculating mandatory investments, international oil prices in the context of International parity or the devaluation of the Brazilian currency also count as a restrictive factor for investments, mainly when denominated in foreign American currency [71].
Number of employees dedicated exclusively to research	There was a decrease in the number of employees dedicated exclusively to research. However, the company increased their relative participation in the research centre.	The trend towards a relative increase in the number of researchers and an absolute decrease in the number of researchers within the research centre may have aimed at a better use of resources. However, although the cost of	None of the previous studies considered the composition, training and number of researchers at the Petrobras research centre [11]; [72]. There needs to be more public

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Table 9 (*continued*)

Variable	Quantitative Data tendency	RD&I correlation	Literature correlation, discoveries and deepening suggestions
	The company also showed improvements in the researchers' academic level.	production and production has been satisfactory, the new exploratory areas have yet to compensate for the reduction in production in mature fields, causing a revenue drop. The question is whether the drop in the number of employees is related precisely to the drop in proved reserves.	information on these aspects, and future research could identify trends and suggest improvements.
The number of partner institutions of the Petrobras Research Center	There was a constant increase in partner institutions, increasing the innovation cluster across the country and associating with partners abroad, especially in areas with offshore production, the Gulf of Mexico, the China Sea, and the North Sea.	Despite directors' distrust regarding the effective contribution of academic institutions to Petrobras' RDI, the company increased the number of relationships, probably motivated by the obligation to invest. This effort may have contributed to the increase in patents in Brazil despite maintaining investment levels in the Brazilian currency.	Although studies [2,3,11]; Etzkowit z et al., 2005) identify that the company's board of directors identify that the most significant source of innovations does not come from the contribution of academia to Petrobras' innovation system, some studies link the increase in patents to the rise in relations with research institutions (Moraes Silva et al., 2018). However, future studies may consider the consequences of the concentration of patents in Brazil and the drastic decrease verified in the number of patents abroad.

norm or on pace with other multinational corporations that refrain from overstaffing and overpaying, it would still be required to compare to other businesses (Eller et al., 2011; Waterworth and Bradshaw, 2018).

Disinvestment in RD&I and human capital can have an impact on future results, as seen by the decline in reserves and the rate of output growth.

As prior studies have done, additional studies might qualitatively evaluate firm patents requested, refused, and obtained over the time, focusing on the leading technologies in the judgment of the company's managers [1]. On the other hand, as this study is limited to articles published in high-quality journals indexed in Scopus, other bibliographic reviews may consider other documents, including other sources such as the Web of Science.

It is also vital to highlight the regions in which the company has made RD&I investments. Such information may be made more visible in the company's reports. However, at least in terms of necessary investments, there is relevant information in the reports of the Brazilian oil regulatory body. Such specifications may be the object of further studies.

The impact of divestiture for innovation clusters, particularly for Brazilian businesses subject to significant changes implemented by the Brazilian government, is another issue that still need further exploration in future studies (Costa and Bautzer, 2016). The influence on the RD&I network is expected to be greater when taking into account smaller enterprises because they have less economic clout than large industrial suppliers. It is also required to conduct a questionnaire-based survey of the company's management and institutions involved in the innovation system to learn more about the effects of government divestitures on RD&I.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marcos Eduardo Melo dos Santos reports administrative support and article publishing charges were provided by The Visiting fellowship at ISS/Erasmus University Rotterdam. Marcos Eduardo Melo dos Santos reports administrative support and writing assistance were provided by University of Coimbra. Hirdan Katarina de Medeiros Costa reports financial support was provided by University of São Paulo. Edmilson Moutinho dos Santos reports financial support was provided by University of São Paulo. Patricia Pereira da Silva reports financial support was provided by University of Coimbra. Patricia Pereira da Silva reports financial support was provided by Fundação para a Ciência e a Tecnologia. Hirdan Katarina de Medeiros Costa reports financial support was provided by Shell Brazil Oil. Hirdan Katarina de Medeiros Costa reports financial support was provided by National Agency of Petroleum, Natural Gas and Biofuels. Edmilson Moutinho dos Santos reports financial support was provided by Shell Brazil Oil. Edmilson Moutinho dos Santos reports financial support was provided by National Agency of Petroleum, Natural Gas and Biofuels.

Data availability

Data will be made available on request.

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Annex 1. Bibliographic sources analyzed

This table provides information on the quadrant in which the journal is located in the Scimago ranking, the number of citations, the temporal scope, the methodology used and the comparative framework in the case studies of this category.

Authors and year	Article title	Journal	Scimago Level and indexed citations	Methodologies	Research Univers	Period considered
[21]	The catch-up strategy of Petrobrás through cooperative R&D	Journal of Technology Transfer	Q1, 14	Case study	Petrobras	1970–2000
Etzkowitz et al., 2005	Towards "meta-innovation" in Brazil: The evolution of the incubator and the emergence of a triple helix	Research Policy	Q1, 178	Extensive analysis of Brazilian Incubator Association databases, documents and interviews	Petrobras	1990–2003
Sá, 2005	Research policy in emerging economies: Brazil's sector funds	Minerva	Q1, 6	Case study	Petrobras	1970–2004
Kalyuzhnovand Nygaard, 2008	State governance evolution in resource-rich transition economies: An application to Russia and Kazakhstan	Energy Policy	Q1, 41	Performance anlysis withi Model framework	10	1990–2008
[1]	Geographical Proximity and Innovation: Evidences from the Campos Basin Oil and Gas Industrial Agglomeration-Brazil	Technovation	Q1, 81	Interviews related to 10 technologies related to 25 events considered important	10	1989–2009
[9]	A Brazilian experience: 40 years using operations research at Petrobras	International Transactions in Operational Research	Q1, 11	Case study and performance causal analysis based on reports and interviews	Petrobras	1960–2000
Wolf, 2009	Does ownership matter? The performance and efficiency of State Oil vs. Private Oil (1987–2006)	Energy Policy	Q1, 88	The econometric analysis and use of panel-data regression analysis and performance analysis	44	1987–2006
Colodel et al., 2009	R&D decision support by parallel assessment of economic, ecological and social impact - Adipic acid from renewable resources versus adipic acid from crude oil	Ecological Economics	Q1, 10	Data analysis based on european countries reports	European Union	Not specified
[2]	Latecomer Firms and the Emergence and Development of Knowledge Networks: The Case of Petrobras in Brazil	Research Policy	Q1, 72	114 semi-structured interviews with Petrobras employees, suppliers and	10	1980–2002
Rocha and Ruiz, 2011	The role of the network coordinator in the attraction of foreign investment in R&D: The case of the Brazilian oil and gas industry	Transnational Corporations	Q2, 3	Interviews and reports analysis	Petromas, Baker Hughes and Schlumberger	1991–2020
[3]	The Co-Evolution of Firm-Centered Knowledge Networks and Capabilities in Late Industrializing Countries: The Case of Petrobras in the Offshore Oil Innovation System in Brazil	World Development	Q1, 54	114 semi-structured interviews with Petrobras employees, suppliers and university representatives	10	1980–2002
Goedhuys and Veugelers, 2012	Innovation strategies, process and product innovations and growth: Firm-level evidence from Brazil	Structural Change and Economic Dynamics	Q1, 106	Interviews with managers	Brazil	2000–2002
Paz Antolín and Ramírez Cendrero, 2013	How important are national companies for oil and gas sector performance? Lessons from the Bolivia and Brazil case studies	Energy Policy	Q1, 15	Comparative approach. Performance analysis with annual reports	10 firms	2000–2010
Wong et al., 2013a	Energy consumption, energy R&D and real GDP in OECD countries with and without oil reserves	Energy Economics	Q1, 52	Analysis of annual data on OCDE reports	OCDE	1980–2021
Wong et al., 2013b	Energy consumption and energy R&D in OECD: Perspectives from oil prices and economic growth	Energy Policy	Q1, 29	Analysis of annual data on OCDE reports	OCDE	1980–2010
[11]	Managing Stakeholder Relations when Developing Sustainable Business Models: The Case of the Brazilian Energy Sector	Journal of Cleaner Production	Q1, 168	Interviews with 138 stakeholders from the two companies analyzed. Discursive analysis.	2	2003–2010
Nagano et al., 2014	Innovation management processes, their internal organizational elements and contextual factors: An investigation in Brazil	Journal of Engineering and Technology Management	Q1, 51	Empirical study based on interviews and reports	Four Brazilian companies	2010
Perrons, 2014	How innovation and R&D happen in the upstream oil & gas industry: Insights from a global survey	Journal of Petroleum Science and Engineering	Q, 38	An online survey was carried out in collaboration with the Society of Petroleum Engineers (SPE) to answer the research questions presented in the previous section.	141 countries	Not specified

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Authors and year	Article title	Journal	Scimago Level and indexed citations	Methodologies	Research Univers	Period considered
Emodi et al., 2015	Energy technology innovation in Brazil	International Journal of Energy Economics and Policy	Q1, 5	Analysis of patent, and research and development based on reports	6 countries	2005–2015
Chávez-Rodríguez and al., 2016	Can Bolivia keep its role as a major natural gas exporter in South America?	Journal of Natural Gas Science and Engineering	Q1, 14	Forecast natural gas demand, production and costs, considering the Bolivian fiscal regime.	3	2012–2030
Lenz and al. 2016	Open Innovation and the challenges of Human Resource management	International Journal of Innovation Management	Q2, 13	Interviews with 10 managers from different areas and discourse analysis.	1	1976–2016
[7]	Technology and Innovation in the Brazilian Oil Sector: Ticket to the Future Or Passage to the Past?	Journal of World Energy Law and Business	Q2, 7	Analysis of legal documents, Interviews, Comparison between three countries (Brazil, Venezuela and Norway)	3	2010–2016
Rocha et al., 2016	The effects and time lags of R&D spillovers in Brazil	Technology in Society	Q2, 0	A panel of Brazilian capital goods companies (classified as "industrial goods" by the São Paulo stock exchange - BOVESPA) and other manufacturing companies.		1998–2010
Fontaine and al., 2017	Explaining public accountability deficit in extractive policies: The Ecuadorian case	The Extractive Industries and Society	Q1, 6	20 empirical tests composing the overall on policy instruments of nodality, authority, treasure and organization	5	2007–2017
Ramírez-Cendrero and Paz. 2017	Oil fiscal regimes and national oil companies: A comparison between Pemex and Petrobras	Energy Policy	Q1, 12	Case study and comparison from reports and bibliography.	2	2000–2010
Hennart and al., 2017	Openness, international champions, and the internationalization of Multilatinas	Journal of World Business	Q1, 33	Performance analysis	173	2002–2011
Ahmad and al., 2017	Evaluation of the external forces affecting the sustainability of oil and gas supply chain using Best Worst Method	Journal of Cleaner Production	Q1, 134	Pestel and Best Worst Method	9	No data
Marcon et al., 2017	Innovation and environmentally sustainable economy: Identifying the best practices developed by multinationals in Brazil	Journal of Cleaner Production	Q1, 49	descriptive and causal study based on data previously collected for purposes other than the problem at hand. The data used in this analysis come from a comprehensive study carried out by the Center for Sustainability Studies at Fundação Getúlio Vargas		2011–2015
[8]	Industrial Policy and State-Making: Brazil's Attempt at Oil-Based Industrial Development	Third World Quarterly	Q1, 13	Case study based on Bibliography and Report	10	2002–2016
Bøe and al., 2018	Do political risks harm development of oil fields?	Journal of Economic Behavior & Organization	Q1, 5	The data are obtained from Rystad Global Upstream Oil an Gas Database UCube (28,000 oil and gas reservoirs and 13,269 assets).	115	1970–2012
Mariano and al., 2018	Fiscal Regimes for Hydrocarbons Exploration and Production in Brazil	Energy Policy	Q1, 8	Análise de leis e resultados em relatórios da companhia e das agências reguladoras. Fiscal Regimes Adopted in 37 countries (production sharing agreement vis a vis Concession Regime)	37	1938–2018
[72]	Brazilian oil sector reforms: The role of technical know-how and corporate ethos in Petrobras's dominance	Energy Policy	Q1, 4	case of study and in-depth interviews and document analysis in public agencies and Petrobras	4	1995–2001
Waterworth and Bradshaw, 2018	Unconventional trade-offs? National oil companies, foreign investment and oil and gas development in Argentina and Brazil	Energy Policy	Q1, 13	semi-structured interviews conducted in Buenos Aires, Sao Paulo and Rio de Janeiro over two weeks in November 2016. Documentary analysis and sisteeninterviews (2017)	2	No data
Moraes Silva et al., 2018	University-industry R&D cooperation in Brazil: a sectoral approach	Journal of Technology Transfer	Q1, 25	Brazil's Innovation Survey to provide empirical support on the basis of two groups of independent variables: internal characteristics of firms, and external characteristics of markets and policies	Brazilian Firms	Not specified
Mancini and Paz, 2018	Oil sector and technological development: Effects of the mandatory research and development (R&D) investment clause on oil companies in Brazil	Resources Policy	Q1, 7	Reports and Interviews analysis. Data on R&D investment directly from the annual financial statements available on the website of the Brazilian Securities and Exchange Commission	Brazil	1998–2015

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Authors and year	Article title	Journal	Scimago Level and indexed citations	Methodologies	Research Univers	Period considered
[31]	R&D investment and risk in Brazil	Global Finance Journal	Q2, 4	Study includes all the stocks listed on the São Paulo Stock Exchange (Bovespa	Brazil	2005–2014
[61]	Corruption and local content development: Assessing the impact of the Petrobras' scandal on recent policy changes in Brazil	The Extractive Industries and Society	Q1, 7	It conducts a process-tracing of policy changes based on 15 interviews, financial reports, and court documents	13	1999–2019
Araujo; Leoneti, 2019	How attractive is Brazil's oil and gas regulatory framework to investors?	The Extractive Industries and Society	Q1, 3	comparative analysis of regulatory frameworks. Multi-criteria assessment	1	2000–2019
LebdiouI, 2019	Local content in extractive industries: Evidence and lessons from Chile's copper sector and Malaysia's petroleum sector	The Extractive Industries and Society	Q1, 11	qualitative comparative analysis in fieldwork interviews with local suppliers, Petronas staff and public agencies	30	1986–2020
[13]; 2020	Heterogeneous effects of energy efficiency, oil price, environmental pressure, R&D investment, and policy on renewable energy – evidence from the G20 countries	Energy	Q1, 27	Process panel data and time series data based on OCDE Databasis, World Bank Database, and BP Review of World Energy Statistics.	G20	1990–2015
[32]	Assessing the impacts of innovation barriers: a qualitative analysis of Brazil's natural resources industry	Resources Policy	Q1, 7	Articulate discussions on aspects which are not captured by quantitative results from existing literature, particularly on studies aimed in Latin American countries	Brazil	2015–2017
[60]; 2020	Local Content in Developing and Middle-Income Countries: Towards a More Holistic Strategy	The Extractive Industries and Society	Q1, 14	qualitative comparative analysis in fieldwork interviews with local suppliers, Petronas staff and public agencies	6	1990–2019
[71]	Global oil price and innovation for sustainability: The impact of r&d spending, oil price and oil price volatility on ghg emissions	Energies	Q1, 6	panel data of 22 oil-exporting countries, 26 European Union countries, China, including Hong Kong, and the USA	50 countries	1991–2015

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