Utilities Policy 87 (2024) 101728

Contents lists available at ScienceDirect

Utilities Policy

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

Full-length article

The critical drivers of the Brazilian electricity sector's transition through 2050: A Delphi study

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ARTICLE INFO

Handling editor: Janice A. Beecher

Keywords:
Brazil
Energy transition
Delphi method

ABSTRACT

This work presents 21 critical drivers influencing the transition of the Brazilian electricity sector through 2050. The information is processed using a two-round Delphi method involving experts from government, regulated companies, service providers, and academia. Statistical analysis revealed expert consensus, and stability was achieved between inquiry rounds. The European Union and China emerged as the primary external sources of influence, with policies and regulations identified as the main risks. Additionally, the importance of Brazil's accession to the OECD is on par with other critical drivers. The gathered evidence can provide valuable data and insights for policymaking, regulation, and future studies.

1. Introduction

Brazil has a noteworthy renewable electricity generation matrix with low greenhouse gas (GHG) emissions. Despite its size, rapid expansion rate, diversity of active agents, and other complexities, the electrical system operates in an interconnected and integrated manner. Moreover, in recent years, the transformations within the electricity sector have accelerated significantly, driven by several factors encompassed under the designation 'energy transition.' This transition has essential elements, typically called the 3Ds – Decarbonization, Digitization, and Decentralization (Dameto et al., 2020; di Silvestre et al., 2018).

This work aims to investigate and pinpoint the most significant drivers among a broad array of possibilities, aiming to enhance the understanding of the prospective evolution of the Brazilian electricity sector and contribute to carrying out studies on the energy transition in the context of a developing nation.

Evidencing the drivers of a country's energy transition is complex, especially if the analysis horizon is distant. We have selected 2050 as the target year to account for the emergence and maturity of new technologies, the design of new business models, the alteration of old ones, and the lifespan of several existing projects. This year also coincides with many net-zero emission pledges from many countries. However, the results obtained from the literature may deviate significantly from the expectations of sector experts. This complex setting offers a relevant research opportunity.

This study aims to discern the critical drivers that will shape the Brazilian electricity sector by 2050 within the 3Ds framework from the viewpoint of qualified experts.

Building on a previous meta-synthesis of selected national and international outlooks, we aim to provide a broad array of the keystones within Brazil's energy transition process through a structured approach. For this purpose, we employ the Delphi method in two rounds of questioning among selected panelists to gain insights into the future (De Loë et al., 2016; Flostrand et al., 2019) and a more stable perception of the subject under investigation.

In the energy field, the Delphi method has been extensively employed in studies in several countries, such as China, where the country's renewable energy development strategy towards 2030 had the Delphi survey integrated into scenario planning by Chen et al. (2020). The method was used in the United Kingdom to analyze divergent expert expectations and preferences regarding energy futures (Kattirtzi and Winskel, 2020). Delphi was used in the European Union (EU) in studies

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https://doi.org/10.1016/j.jup.2024.101728
Received 29 March 2023; Received in revised form 8 February 2024; Accepted 8 February 2024
Available online 23 February 2024

regarding biomethane technologies and policies for a smarter grid environment (Billig and Thrän, 2016; Pereira et al., 2018a; 2018b). The method was also used in Brazil while studying policies for smart grid deployment (Dias et al., 2018; Galo et al., 2014).

While strengthening the literature viewpoint with experts' experiences and knowledge, the Delphi method study also sheds light on additional aspects, such as the possible sources of influence, risks, and relevance of Brazil's accession to the Organization for Economic Cooperation and Development (OECD).[1] This ongoing process holds great significance, yet a gap exists in understanding its impacts on the Brazilian electricity sector.

Through exploring and characterizing the critical drivers, this work enriches the debate, fosters a better-informed decision-making process, and enables a better-targeted and more efficient allocation of public policies and regulation resources.

Following the methodology and methods described in section 2, section 3 presents the design and procedures employed in this research to use the chosen method. Section 4 provides the findings derived from the two rounds of questioning and covers a thorough discussion of the results. Subsequently, section 5 presents the conclusions drawn from the study, policy recommendations, and suggestions for future research.

2. Methodology and methods

The results from a previously performed meta-synthesis combined with the use of the Delphi method supported identifying the critical drivers of the Brazilian electricity sector by 2050. The information about the study's design and the use of those methods are detailed in the following subsections.

2.1. Preliminary groundwork through meta-synthesis

This research is based on a meta-synthesis that incorporates various international perspectives and Brazil's long-term energy planning (BP, 2020a, 2020b; Cole et al., 2020; EPE/MME, 2020; IEA, 2021, 2020; IRENA, 2021, 2020). Meta-synthesis can be described as an interpretation or comparison of findings from multiple studies according to specific criteria, allowing new conclusions to emerge (Dinçer, 2018).

Thus, as a foundation for this research, the initial groundwork selected the outlooks provided by the Brazilian Energy Planning Company (EPE), the multinational BP, the United States Energy Information Administration (EIA/DOE), the National Renewable Energy Laboratory (NREL), the International Renewable Energy Agency (IRENA), and the International Energy Agency (IEA).

Evaluating the different outlooks for the year 2050 allowed for identifying several potentially relevant drivers considered by the various institutions within the analysis horizon. Using the frequency of these drivers among the outlooks and considering Brazil's inherent characteristics, an initial list with 48 items was filtered down to 21 critical drivers depicted in Table 1.

Once the initial set of drivers was identified, the Delphi method was used to assess the perception of a broad group of experts.

Table 1
The set of 21 critical drivers synthesized from selected outlooks (BP, 2020a, 2020b; Cole et al., 2020; EPE/MME, 2020; IEA, 2021, 2020; IRENA, 2021, 2020).

Decarbonization-related drivers	Digitalization-related drivers	Decentralization-related drivers
Electrification	Smart grids	Consumer behavior
Electric vehicles	Artificial intelligence	Distributed energy resources
Penetration of solar and wind sources	Big data	New business models
Role of natural gas	Cybersecurity	Demand-side management and demand response
Carbon capture, use, and storage	Information & Communication Technologies	International integration
Greenhouse gas emissions		
Role of hydroelectricity		
Biofuels		
Hydrogen		
Energy efficiency		
Evolution of storage technologies		

2.2. The Delphi method

The Delphi method is a technique that helps experts address complex issues through a structured communication process (Linstone and Turoff, 2002).

The Delphi method helps to identify determining factors (driving forces or drivers) by engaging many qualified participants from multiple backgrounds. It can also help to avoid ignoring potentially critical determining factors, thereby improving the effectiveness and credibility of the scenario-building process (Chen et al., 2020). The method has shown many positive aspects, including the ability to gather asynchronous responses from geographically dispersed participants while preserving anonymity, which limits the influence of dominant individuals, manipulation, coercion, and other effects (Dinwoodie et al., 2013; Hsu and Sandford, 2007), favoring result consistency.

Nevertheless, despite its widespread adoption, the method has received criticism, including the absence of direct interaction among participants, the possible long duration, and the sensitivity to the questioning process (Fernández-Ávila et al., 2020).

The Delphi method does not specify the ideal number of invited experts. The traditional approach generally uses few experts from a given area (Linstone and Turoff, 2002). Some argue that the group should have at least 20 experts to mitigate the risk of contamination of aggregate responses by individual solutions (Akkermans et al., 2003). Ogden et al. (2005) note that studies typically involve 5 to 30 experts since larger groups may create few additional ideas and limit the exploitation of existing ones. They chose to use 70 to 75 respondents to enhance the significance of the feedback. Other studies have employed a more significant number of participants. For instance, Celiktas and Kocar, (2010) invited 1900 experts to their research on renewable energy in Turkey, with a 20.1% success rate. Beiderbeck et al. (2021), in a study on the impact of COVID-19 on the European football ecosystem, invited 678 experts, of whom 276 viewed the research and 110 participated. The number of people involved depends on different factors, including the scope of the search, the desired heterogeneity, and the availability of experts in the field, as highlighted by Jiang et al. (2017). Most studies use convenience as the primary criterion for recruitment, and statistical representativeness is not necessarily a requisite (De Loë et al., 2016).

In the present study, the design of the questionnaire and feedback rounds aimed at having a quick-to-respond and straightforward process. The goal was to minimize the withdrawal rate, keeping it within acceptable bounds without losing the quality of contributions (Schmalz et al., 2021).

Some statistical analyses must be performed to check for the consistency and stability of the responses (Yang, 2003). Different techniques are available for qualitative and quantitative analysis (De Loë et al., 2016). The level of consensus was calculated using the coefficient of variation (CV) following Beiderbeck et al. (2021), and stability was evaluated through the change in the level of consensus between rounds,

[1] Brazil submitted a formal application to begin the accession process on May 29, 2017. After almost five years, Brazil received a positive answer on January 25, 2022, indicating that the OECD Council decided to open the accession discussions in accordance with the respective roadmap (OECD, 2022).

as mentioned in previous studies (Cerè et al., 2019; Scheibe M. et al., 1975; Vogel et al., 2019; Von der Gracht, 2012).

Since the method allows for the anonymous interaction of a diverse group of experts in rounds of questioning and feedback to obtain a judgment based on this collective information (Linstone and Turoff, 2002), the first practical step in applying the Delphi method involved selecting the panel of experts to be consulted. This step is demonstrated in the next section, which addresses the design and procedures adopted in this research.

3. Design and procedures

Models should capture the fundamental aspects and align with the perspectives of energy experts and the public (Xexakis et al., 2020). Expert-based approaches are valuable for gaining insights when facing data uncertainty, inconsistencies in development paths, unexpected events, discontinuities (Meng et al., 2021), and complexity under more stringent assumptions (van Sluisveld et al., 2018). The elicitation of forecasts by experts can provide additional estimates that complement those generated by more traditional quantitative models (Zhou et al., 2019). The central idea is to access the collective intelligence of the expert group (Surowiecki, 2005).

The planned steps for applying the Delphi method are visually presented in Fig. 1.

The initial practical step in applying the Delphi method involved selecting the panel of experts to be consulted throughout the rounds of questioning. This selection process was performed in partnership with the Study Group on the Electric Energy Sector (GESEL) from the Rio de Janeiro Federal University (UFRJ) Economics Institute.

The work was executed between June and November 2021 and, due to restrictions on movement imposed by the pandemic, involved intense online communication. The performed activities are summarized in the following subsections.

3.1. The initial panel of experts and first-round

The panel consisted of 175 experts individually selected from the National Electricity Regulatory Agency (ANEEL), Ministry of Mines and Energy (MME), EPE, and Academia, and a list of experts provided by GESEL with over 2800 names. Therefore, the preliminary list comprised 2899 individuals. The process of consolidation and removal of duplicates resulted in a list of 2846 experts categorized into the following groups.

- Government: Regulatory and Government public policy makers: professionals working at ANEEL, MME, EPE, the National System Operator (ONS), the Electric Energy Trading Chamber (CCEE), State Agencies associated with ANEEL, legislative consultants, Federal Court of Auditors, or other structures of the Federal Government;
- Regulated companies: companies from the electricity sector: professionals in the generation, transmission, distribution, and commercialization companies, including holding companies dedicated to the sector;
- Service providers: professionals employed in relevant consultancies; significant suppliers of equipment and services, especially those with higher technological density; and
- Academia: academics, researchers, and teachers with relevant knowledge about the Brazilian electricity sector.

The composition of this preliminary group was approximately 50% of experts from regulated companies, 20% from service providers, and the remainder was equally divided between academia and regulation and public policy professionals.

Before the first round was launched, it was subject to several tests. The link to the preliminary survey was sent to a small group of six professionals from academia, consulting companies, and ANEEL to obtain qualitative feedback. Based on the perceptions of this test group, the survey form was modified to its final composition.

The first round was performed with an invitation e-mail sent to all 2846 pre-selected experts. A dedicated e-mail address was created for communication with the experts, and all correspondence and questions were written in Portuguese. Although recommended (Gargon et al., 2019; Hsu and Sandford, 2007), no intermediary reminder or encouragement e-mails were sent to minimize non-response in the first round. This decision was made due to the large size of the initial panel, which allowed for a significant dropout rate, and to comply with a recently approved Brazilian Data Protection General Law, which addresses spam-related concerns.

The first-round questionnaire consisted of five main parts.

- Experts' qualification questions to confirm the primary contact data (name and e-mail), the work segment, and experience in the Brazilian electricity sector;
- Questions related to the energy transition process to provide context to the experts about the research theme and to obtain general perceptions about the Brazilian electricity sector;
- Questions about the drivers, aimed at identifying the ten most relevant among the original set of 21 and uncovering potentially omitted critical drivers;
- Questions about nine analysis criteria, with an assessment of their importance and relevance, on a scale from 0 to 10 and
- Questions about parameters for a future application of a Multi-Criteria Decision Analysis Method (MCDA).

Delphi's first round yielded results consistent with the existing literature. Of the 2846 invited experts, 294 responses were obtained, resulting in a response rate of 10.33%. Despite the low initial level of participation, which was not uncommon in other studies (Haines et al., 2013; Hupkes, 1974), the final number of participating experts was significant and adequate for the study's objectives.

The result in terms of time to answer the questions was similar to the one initially projected (15 min). The experts took, on average, 22 min to answer, with a median time of nearly 13 min. Fig. 2 depicts the daily

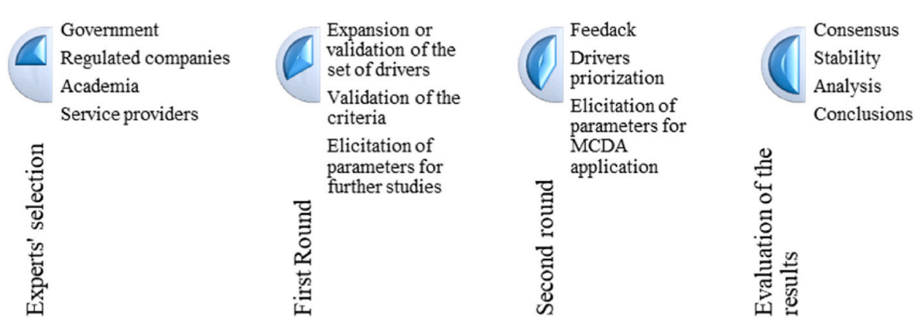

Fig. 1. Steps of the Delphi method application.

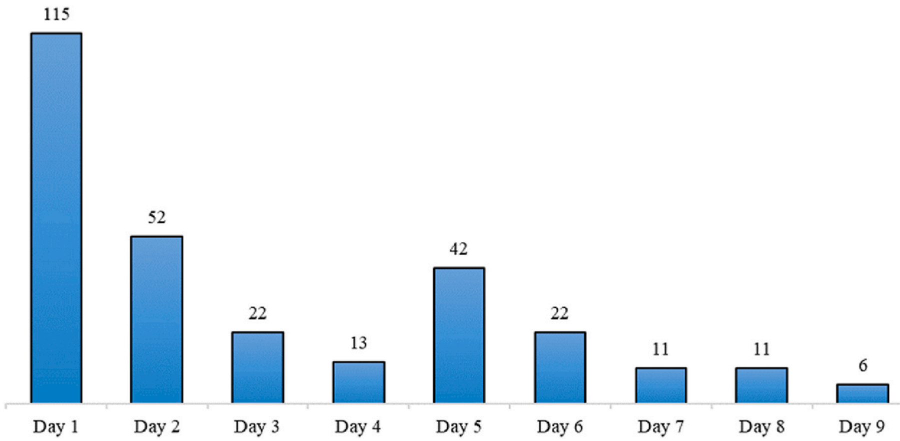

Fig. 2. First round daily responses (total = 294).

number of answers, showing that most were obtained at the beginning of the data collection period. The weekend (days 3 and 4) also influenced the overall performance of the first round, highlighting that timing is relevant in such studies (Schmalz et al., 2021).

The group was also reasonably balanced across the desired categories (Table 2), with the majority of experts from regulated companies (39.8%), followed by members of service providers (28.6%), academia (19.7%), and government (10.9%). This distribution ensured a varied range of perspectives.

The self-declared experience of the experts was well-distributed (Table 3), and almost a quarter of them reported having more than 30 years of experience in the Brazilian electricity sector, which allows for incorporating knowledge from past sectoral dynamics. However, nearly 20% of the group also declared less than five years of experience, thus providing a less conservative and more attentive view of innovative technologies.

Although the number of answers obtained was a small fraction of the initial number of invited experts, it was still possible to benefit from the voluntary collaboration of almost three hundred experts, distributed across the desired categories and with varying degrees of experience in the field.

3.2. The second round

The extensive amount of information collected and the substantial number of panelists who answered the call to collaborate in the first round provided many insights. They were condensed into a concise report for controlled feedback.

The second round was conducted nearly one month after the first one. This interval is consistent with those reported in the literature (Eggers and Jones, 1998; Gordon, 1994; McMillan et al., 2016; Taylor, 2020). The short interval time for this two-round Delphi was intended to maintain the group's focus, enhance enthusiasm, keep the panelists engaged, and reduce dropouts (Hung et al., 2008).

The second-round questionnaire consisted of five main parts.

Table 2
Experts' categories in the first round.

Category	Quantity	Ratio
Regulated companies	117	39.8%
Service providers	84	28.6%
Academia	58	19.7%
Government	32	10.9%
Sub-total	291	99.0%
Did not disclose	3	1.0%
Total	294	100.0%

Table 3
Experience of the first-round experts.

Experience	Quantity	Ratio
<5 years	51	17%
5–10 years	59	20%
10–20 years	76	26%
20–30 years	37	13%
>30 years	71	24%
Total	294	100%

- A question to elicit the concordance with the findings from the first round;
- Questions to further explore the influences of other countries on Brazil, emphasizing China and the United States;
- Assessment of the performance of the 21 drivers based on the nine criteria;
- Assessment of the performance of the driver "accession to the OECD" according to the nine criteria;
- Identification of risks associated with the energy transition in Brazil.

In the second round, a reminder was sent to foster participation due to fewer participating experts and a lower risk regarding spam characterization. The time the experts took to answer the questionnaire was different than initially expected. The experts took 32 min to answer on average, and the median time was approximately 24 min. The number of daily answers is depicted in Fig. 3. It shows that, unlike the first round, the answers were well distributed over the five days. Of the 294 experts who participated in the first round, 102 responses were obtained in the second round, corresponding to a return rate of 34.7%. The level of participation between the two rounds is consistent with other studies (Abadie et al., 2010; Schneider et al., 2012; Wilenius and Tirkkonen, 1997). While the voluntary nature of the expert's participation could influence the response rate (Linstone and Turoff, 2002), the final result (102 experts) was still significant compared to most documented Delphi studies.

The final set of experts in the second round remained substantial and acceptable for the study's objectives. The group was also reasonably distributed among the desired categories (Table 4), with a higher predominance of experts from regulated companies (35%), followed by members of the government (29%), service providers (22%), and academia (14%). From the first to the second round, the government category maintained a higher response rate, leading to an increase in its relative participation and a reduction in all other categories.

The level of expert participation in both rounds reached numbers consistent with those reported in the literature, and the results are discussed in the subsequent section.

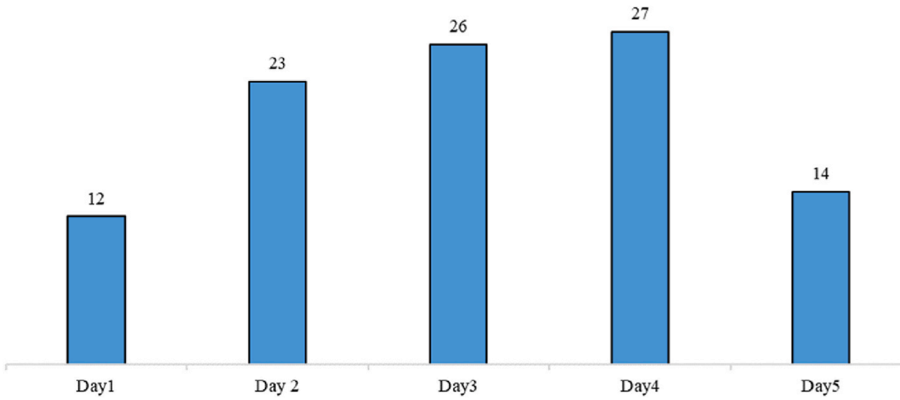

Fig. 3. Second round daily responses (total = 102).

Table 4
Experts' categories in the second round.

Category	Quantity	Ratio	Difference from the first round
Regulated companies	36	35%	−4.8%
Government	30	29%	18.1%
Service providers	22	22%	−6.6%
Academia	14	14%	−5.7%
Total	102	100%	–

4. Results and discussion

This section addresses the results obtained from the questions in the first and second rounds. The results are discussed progressively, along the questioning sequence and with the information obtained from the experts.

4.1. The first round

Following the initial section, which involved the expert's qualification, the second part of this round focused on questions related to the energy transition process. In the first question, the experts were asked about the impact of the energy transition in the Brazilian electricity sector. The available response alternatives were presented on a five-point importance Likert scale, ranging from "no impact" to "substantial impact." The distribution of answers is depicted in Fig. 4, leaving a clear visual representation of the perceived importance of the energy transition.

The group demonstrated substantial convergence: 56% (166 experts) believe that the impacts of the energy transition in Brazil will be extensive, and 25% (74 experts) consider the impacts to be substantial. Only 17% (49 experts) expect a moderate impact. Five experts (2%) envision a small effect, but no one responded that no impact is expected. The representative impact foreseen by the experts (81% extensive or substantial) demonstrates the importance of studying the path of energy transition in Brazil.

The next question addressed the polarity of the energy transition, meaning the expected positive or negative tendency of this process in the Brazilian context. The panelists were given four alternatives, as illustrated in Table 5.

Although the proximity of the results between specialists who considered that the energy transition would have only positive effects (49%) and those who answered that the energy transition would have positive and negative effects (48%) requires caution in the assessment, the prevailing belief among the experts is that the Brazilian energy transition process will be predominantly an opportunity: 49% consider the effects to be exclusively positive. In comparison, only 2% view the transition negatively.

Furthermore, the expert panel was also asked about the timing of these effects. One of the options stated that the impacts would unfold gradually and accumulate over time, without a specific acute period, while the other three options aimed to identify the timeframe of the impacts (before 2030, between 2030 and 2050, and after 2050). The four alternatives were presented randomly to mitigate any order bias (Coulter et al., 2013; Huber, 1985).

The results, presented in Table 6, confirm the soundness of the year 2050 as the target of the present research. While 30% of experts consider that the process will take place gradually and cumulatively, 46% report expecting the majority of impacts between 2030 and 2050. Only two experts believe the effects will materialize after 2050.

In the survey's final exploratory and context-creating question, the experts were asked about the sources of the influences related to the energy transition. Historically, the Brazilian electricity sector has been dominated by its idiosyncrasies (e.g., the historical predominance of hydraulic generation, limited access to coal, and extensive use of biomass and biofuels). Furthermore, it has always been greatly affected by developments in Europe and the United States (de Castro et al., 2019). However, the findings presented in Table 7 reveal a different perspective.

The panelists confirmed the prevalence of internal questions as the primary source of influence. This finding emphasizes the Brazilian electricity sector's particularity; therefore, any analysis should consider its distinct characteristics. However, the external influences were also regarded as significant, and the results showed primacy from the European Union, followed by unspecified countries or groups of countries, China and the United States, as depicted in Fig. 5.

China has gradually expanded its influence worldwide, including in South America (Roett and Paz, 2008). Brazil has become the target of growing Chinese direct investments in hydroelectric plants in recent years (Li et al., 2020) and the transmission and distribution segments (Silveira, 2018). The finding about China's apparent preponderance over the United States as a source of influence over Brazil may represent a paradigm shift and serve as a reminder for Brazil to be more attentive to the growing relevance of Asia.

Once the context was established, the experts were presented with a preliminary list of critical drivers sourced from the literature. They were asked to select ten drivers, among the randomly presented 21, that they considered the most relevant for the design of the Brazilian electricity sector through 2050. The objective was to gather an intuitive and unrestrained evaluation.

A slight decrease in the response rate was observed for this set of questions, as 286 answers were received. The results allowed for a primary ordering of the drivers based on the number of experts who included each driver among their top ten choices (or the number of votes each driver received from the experts), as depicted in Fig. 6. The evolution of storage technologies, the penetration of solar and wind sources, and the distributed energy resources stand out. Brazil has been

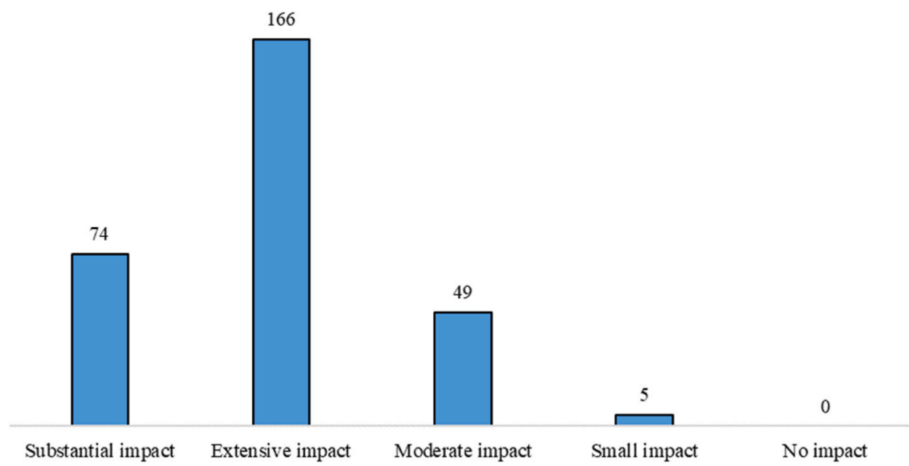

Fig. 4. Impacts of the energy transition on the Brazilian electricity sector.

Table 5
Effects of the energy transition in Brazil.

Effects of the energy transition	Quantity	Ratio
Positive effects	145	49%
Both positive and negative effects	141	48%
Negative effects	5	2%
No effect	3	1%
Total	294	100%

Table 6
Moment of the energy transition impacts in Brazil.

Moment of the impacts	Quantity	Ratio
Before 2030	69	23%
Between 2030 and 2050	134	46%
After 2050	2	1%
Gradually over time	89	30%
Total	294	100%

Table 7
Sources of influence on the Brazilian energy transition.

Sources of influence	Quantity	Ratio
Brazilian internal aspects	162	55%
European Union	51	17%
China	33	11%
United States	8	3%
Other individual or grouped countries	40	14%
Total	294	100%

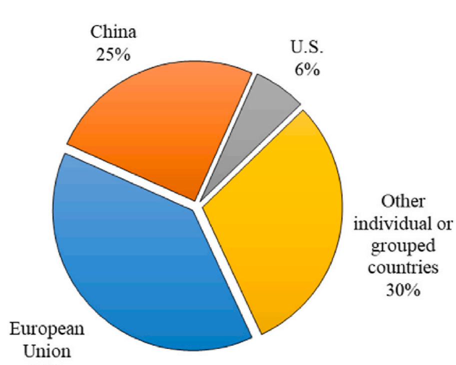

Fig. 5. Distribution of the external sources of influence.

experiencing a decline in its storage capacity in water reservoirs (de Castro et al., 2010), which introduces risks associated with the hydrological regime. In addition, solar and wind sources (whether in the form of concentrated plants or distributed resources) are intermittent. These circumstances challenge the system's planning and operation, reinforcing the importance of storage.

The different expert categories displayed a strong correlation in their positions, with the government category behaving slightly uncoordinated with the other groups. Big data, Information & Communication Technologies, smart grids, and hydrogen demonstrated higher concordance levels among the expert categories. The more significant disagreements included artificial intelligence, biofuels, penetration of solar and wind sources, and demand-side management and demand response. The results are depicted in Fig. 7.

The experts were subsequently asked whether they considered that any important driver was missing from the 21 initially presented; 286 experts responded to this question. A 76% majority was achieved in the responses (Table 8), indicating agreement with the initial driver list and confirming consensus with the results obtained from the literature.

The panelists who indicated that a driver was missing from the initial list could present up to two suggestions in an open-text format. A total of 107 propositions were collected, categorized, and evaluated. It was found that the original drivers already contemplated most of the suggestions (e.g., solar and biomass). Some were considered relevant as evaluation criteria (e.g., environmental impacts and changes in public policies and regulations). A small subset of the collected suggestions comprised original drivers, such as nuclear energy, transmission systems, technological innovations, and education. The consolidated answers are depicted in Fig. 8.

Nuclear energy emerged as a notable suggestion, with 15 mentions. The number was not representative enough for this driver to surpass international integration (which had received 35 votes in a previous question). However, it does offer an indication for further studies since nuclear energy has recently gained importance worldwide (Elhegazy and Kamal, 2022; NEA and OECD, 2021).

The fourth part of the survey sought to take advantage of the interaction with the group of experts to elicit parameters and additional information for a future application of an MCDA method to sort the drivers based on their merit. This step involved defining the evaluation criteria and their parameterization, including assessing their relative importance to derive weights. Thus, the experts were presented with a list of nine criteria. An importance assessment was requested on a scale from 0 to 10, as in Tendero and Plottu (2019).

The goals of this evaluation were twofold: i) identifying the most representative criteria and, eventually, removing criteria of minor importance as indicated by the panelists, and ii) using the assigned scores as an approximation for the direct assessment of the weights for

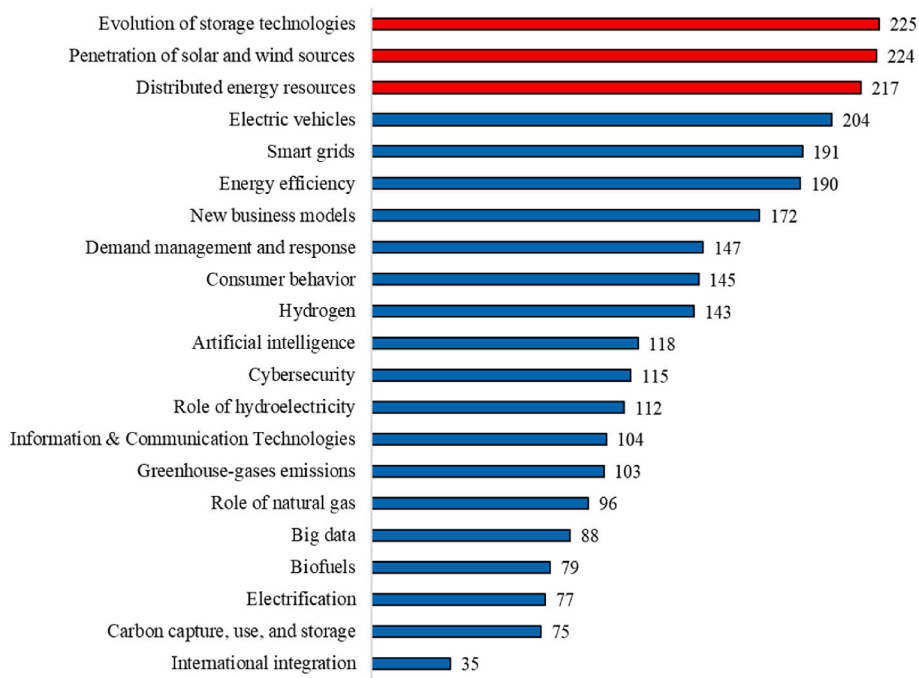

Fig. 6. Ordered drivers by votes from the experts.

an MCDA application. Direct rating is a simple and straightforward method to estimate the weights without involving trade-offs, as highlighted in previous studies (Németh et al., 2019; Odu, 2019; Ribeiro et al., 2013; van Til et al., 2014).

The nine criteria presented to the experts aimed to provide a comprehensive analysis and were defined under a PESTLE framework (Marttunen et al., 2017; Thungngern et al., 2015), encompassing Political, Economic, Social, Technological, Legal, and Environmental factors. The initial set included the following criteria.

1. Political:
   - o Impact on energy security in Brazil (supply capacity and external dependence). This criterion seeks to assess whether a given driver significantly influences the system's service capacity (resilience) or affects aspects related to external dependency (e.g., the need for fuel and equipment imports or exports limited to few markets).
2. Economic:
   - o Impact on investment capacity (consumption of financial resources). This criterion seeks to assess whether a given driver significantly increases the need for investments in the Brazilian electricity sector;
   - o Economic impact (system cost, tariffs). This criterion assesses whether a given driver greatly influences the Brazilian electricity sector's costs, significantly affecting tariffs.
3. Social:
   - o Social impact (social acceptance, jobs, and benefits). This criterion assesses whether a given driver significantly influences aspects related to job creation and social benefits.
4. Technological:
   - o Impact on the ability to plan and predict (uncertainty). This criterion assesses whether a given driver introduces difficulties for long-term planning by having uncertain consequences and increasing unpredictability.
   - o Extent of the impact on the sector chain (horizontal and vertical). This criterion evaluates whether a given driver significantly impacts all generation, transmission, distribution, and trading segments or drastically affects at least one.
   - o Impact on Research and Development (R&D) initiatives. This criterion assesses whether a given driver, despite its importance to the sector, is highly dependent on research and development initiatives while requiring relevant investment and technological maturation.
5. Legal:
   - o Impact on public policies and regulation (new laws and regulation). This criterion evaluates whether a given driver requires developing and complex negotiation of public policies, legislation, and related regulations.
6. Environmental:
   - o Impact on the environment and sustainability. This criterion evaluates whether a given driver is significantly related to environmental aspects and the perception of the sustainability of the Brazilian electricity sector.

Table 9 summarizes the panelists' perspectives on the proposed criteria.

The average importance assigned by the experts for the criteria ranged from 7.38 to 8.54, with only a 16% difference between the highest and lowest-ranked criteria. Therefore, since no criterion lagged far behind the rest of the group, all criteria were regarded as relevant, and none was discarded from the subsequent evaluations. The Coefficients of Variation (CV)[2] ranged from 0.2 to 0.3, indicating a high level of consensus (Bouhaddane and Mili, 2018; Von der Gracht, 2012). The agreement level provided the confidence to calculate each criterion's weight (w_n), ranging from 0.10 to 0.12.

The last part of the first round presented a challenge regarding communication with the panel of experts. The objective of the final three questions was to elicit the Indifference (q), Preference (p), and Veto (v) thresholds[3] for the subsequent application of the ELECTRE-TRI MCDA method.

[2] CV is a measure of dispersion and is the ratio of the standard deviation to the mean.

[3] "q" is the maximum difference in the rating between drivers that would still be negligible, thus establishing the indifference threshold; "p" is the difference defining a rated driver as clearly better or worse than another, the preference threshold; and "v" is the minimum discordant difference in a criterion that prevents the outranking even if compensated by better ratings in other criteria.

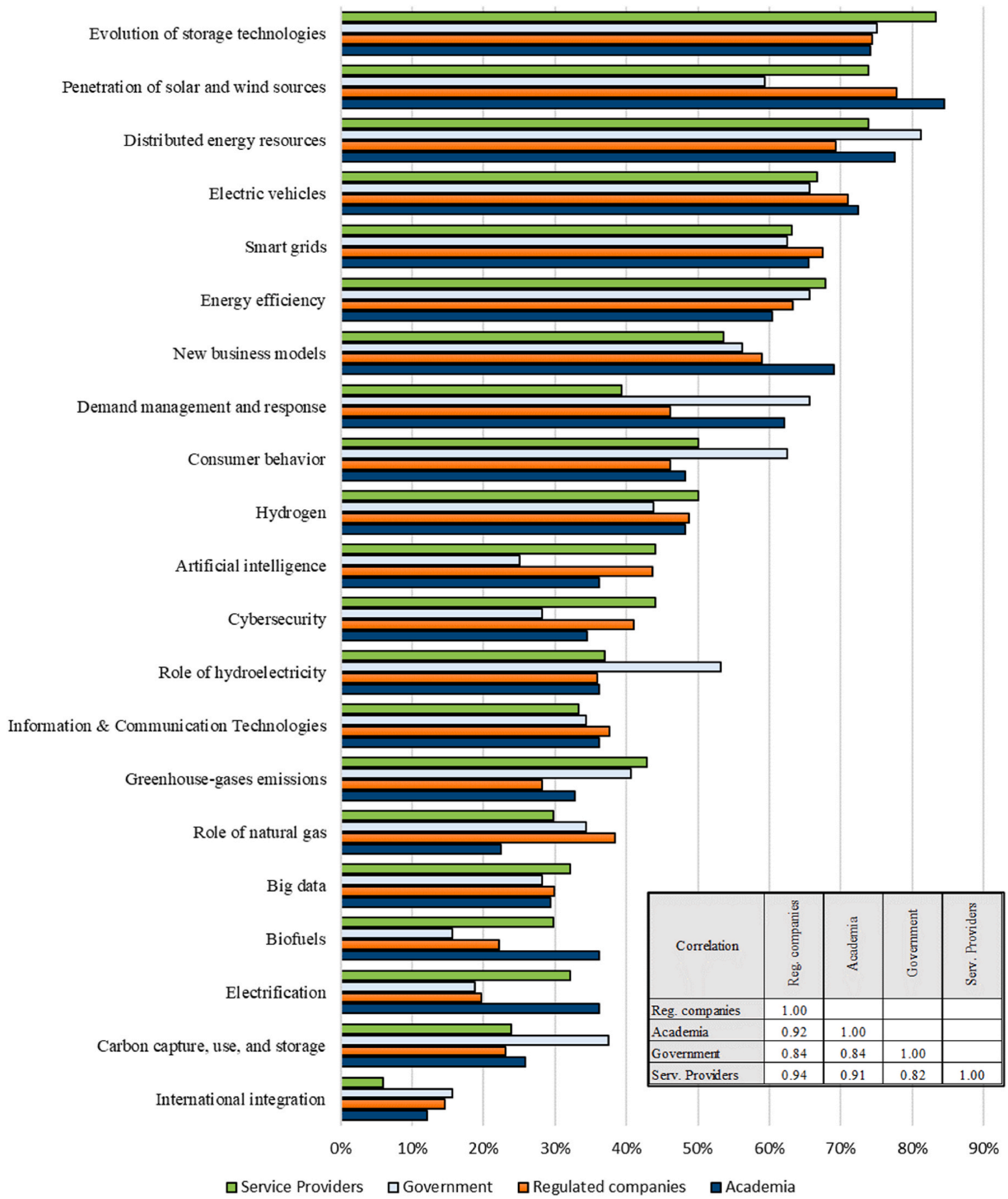

Fig. 7. Drivers by expert category.

Table 8
Concordance with the initial driver's list.

Is there any essential missing driver?	Quantity	Ratio
Yes	68	24%
No	218	76%
Total	286	100%

Dias et al. (2002) warned that panelists might face difficulties defining precise values for these parameters due to data imprecision, insufficient understanding of their meaning, changes in opinions, and lack of consensus in group decisions. Oliveira et al. (2013) suggested using analysts with expertise in the methodology when eliciting these parameters. Moreover, Mousseau et al. (2000) affirmed that setting their values and effectively understanding the impacts in the analysis results is complex, even if the definitions are well interpreted. Nevertheless, several studies have used values provided by experts (Kaya and Kahraman, 2011; Sánchez-Lozano et al., 2014; Silveira et al., 2021).

After a brief written explanation about the thresholds, the panelists were asked to provide their perception on a scale from 0 to 10 (the same scale used for the criteria). The panelists were also reminded that the answers should be in the order $q \leq p \leq v$. The results were heterogeneous. Due to the characteristics of the survey platform, some crucial mistakes in the responses were allowed and collected. For example, several panelists provided veto values lower than the preference and

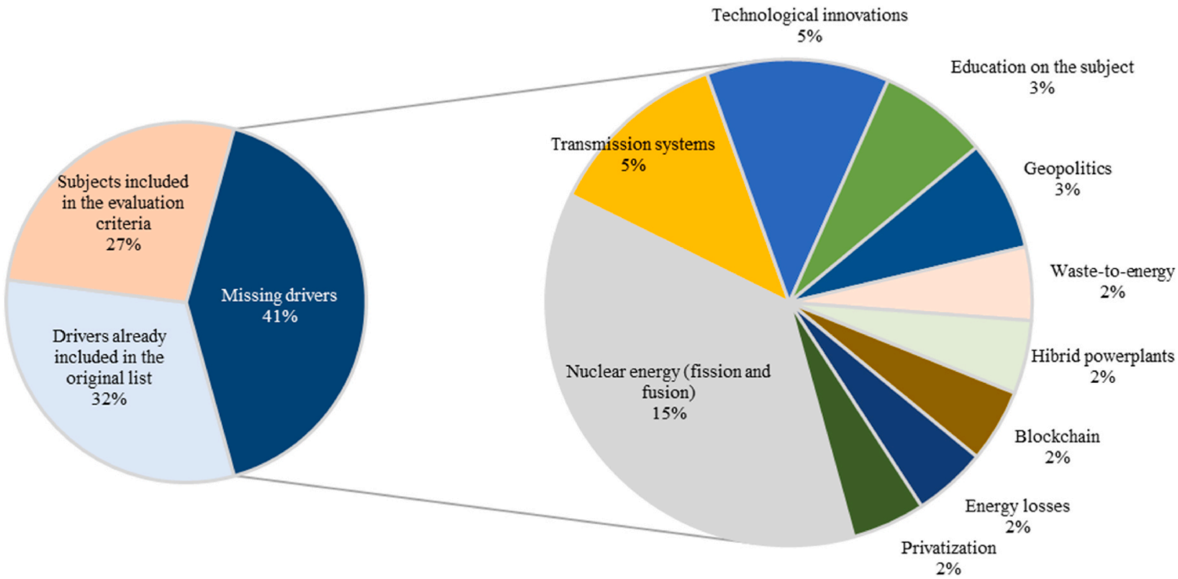

Fig. 8. Missing drivers suggested by the experts.

Table 9
Experts' perspectives on the proposed criteria.

Data	Public policy and regulation	Economic impact	Environment and sustainability	Energy security	Planning uncertainty	Investment capacity	Horizontal and vertical impact	Social impact	R&D initiatives
Mean (μ)	8.54	8.22	8.20	8.08	8.00	7.80	7.58	7.40	7.38
Standard deviation (σ)	1.74	1.68	1.73	1.90	1.69	1.91	1.90	1.99	2.24
Coefficient of Variation (CV=μ/σ)	0.20	0.20	0.21	0.23	0.21	0.25	0.25	0.27	0.30
Weight ($w_i = \mu_i/\Sigma\mu$)	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.10	0.10

indifference thresholds. Others scaled the responses up to the higher end of the 10-point scale, indicating they misinterpreted the meaning of the thresholds. This outcome is understandable since the communication with the experts was limited to a concise questionnaire, and the definition of these thresholds is not commonly known to the group.

Therefore, a data filtering process was implemented to identify and exclude non-conforming responses. The answers excluded from the 254 received in this part included the cases in which the values for indifference exceeded the preference threshold (33 instances), the values for preference surpassed the veto thresholds (46 instances), the indifference reached half of the evaluation scale (113 instances), and the veto threshold was set to zero (3 instances). Several cases violated more than one of these rules.

This procedure resulted in 111 ″valid" responses (44% of the initially received answers for this part). The adjusted average indifference threshold (q) resulted in 1.9, while the preference threshold (p) was 3.0, and the veto threshold (v) was 4.0.

The results showed a moderate level of consensus evidenced by the Coefficient of Variation (0.53 and 0.58 for the indifference and preference thresholds, respectively, and 0.44 for the veto threshold). However, the Interquartile Range (IQR)[4] for all three parameters resulted in 2, suggesting an acceptable degree of consensus for this scale (Diamond et al., 2014; Hung et al., 2019).

4.2. Results from the second round

As mentioned in the previous section, 102 experts participated in Delphi's second round. In this round's first question, the panelists were asked to indicate their level of concordance with the ordering of the drivers obtained in the first round. A slider bar with a range from 0 to 100 was used to collect the answers, where 0 represented total discordance and 100 complete concordance.

The results revealed an average concordance level of 84.7%. The statistical parameters derived from the responses, particularly the CV (0.19), indicate a high degree of expert consensus (Von der Gracht, 2012).

Regarding the stability between the rounds, a variation under 10% between round group responses was used as a reference by Vogel et al. (2019), and a 15% change was considered stable by Scheibe et al. (1975). Other studies considered further evaluation unnecessary once a 70% consensus is reached (Campbell et al., 2018; Lee et al., 2013).

This study resorted to the accuracy of the initial driver list (76% - Table 8) and the average concordance level obtained in the second round (84.7%), comparing these results to verify stability. The difference between these values was 8.7%, indicating stability between rounds was achieved despite the slight increase in the concordance level. The experts' evaluations are depicted in progressive order in Fig. 9.

The relative frequency histogram in Fig. 10 illustrates the different categories' rating behavior, demonstrating similar patterns and a strong positive correlation (Ratner, 2009).

The results indicate that experts from academia, regulated companies, government, and service providers presented similar perspectives regarding their concordance with the set of drivers without any identifiable collective bias or domination. Furthermore, the correlation between rounds increased, which is compatible with the search for a consensus.

The second part of this round was designed in response to the findings from the first round. Previously, the experts preferred China over

[4] The IQR is the difference between the first and third quartiles and expresses the range which contains the middle half of the data.

the United States as a source of influence on Brazil. In the second round, the group was initially informed about the results of the first round. Subsequently, a direct question with three response alternatives was posed: will China be more influential than the United States in the Brazilian energy transition? The options were yes, no, and both equally influential. The results did not indicate an absolute majority for any option, but the preference for China over the United States remained high and significant. China will be more influential for 41% of the experts, while 15% preferred the United States. Nevertheless, 44% thought both countries would be equally influential, but without identifying how this influence would occur.

Therefore, in an open follow-up question, the experts were asked to identify the nature of the influence exerted by China, the United States, or both. The answers were analyzed and categorized. The result reveals the expected impacts of these two countries concerning Brazil's energy transition.

As shown in Table 10, the major impacts mentioned were related to equipment and technologies, investment, trade, and the environment. When considering the United States, the most mentioned impact was environmental. China was associated with impacts on equipment and technology, investments, and trade.

The last question about this issue sought to expand the list of countries or groups of countries that could have a representative influence on Brazil's energy transition. The panelists were allowed to present two suggestions, which were collected, grouped, and shown in Fig. 11.

Out of the 168 received suggestions, the majority (75%) focused on South American countries, Japan, India, Germany, Canada, Australia, the United Kingdom, and Russia. Regarding the South American countries, the most individually mentioned countries were, in order, Chile, Argentina, Bolivia, Colombia, and Paraguay.

The results indicate that, besides encompassing commonly considered countries such as the EU and the United States, the Brazilian energy transition requires a look toward Asia, particularly China, Japan, and India. Moreover, Brazil's neighbors must not be neglected, which aligns with the importance of "international integration" as one of the 21 critical drivers.

The third part of this round was more extensive. The experts had to evaluate each of the 21 drivers according to the nine criteria in a Matrix/Rating Scale Question for each driver. Each criterion was assessed on a single-row rating scale ranging from 1 to 10.

The results were derived from 78 panelists (12 from academia, 13 from service providers, 25 from government, and 28 from regulated companies). This step had an intra-round dropout, probably due to the number of evaluations required. In total, these 78 panelists graded 189 rows. The ratio among the categories showed a slight variation, and the main drop was observed within the service provider's segment. The CV for the evaluations ranged from 0.13 to 0.40, indicating a reasonable degree of consensus across the entire set of evaluations (English and Kernan, 1976; Yang, 2003).

It should be acknowledged, however, that the IQR ranged from 1 to 4, indicating noticeable dispersion in some of the evaluations (Becker and Roberts, 2009; Birko et al., 2015; Giannarou and Zervas, 2014; Ramos et al., 2016). When evaluating the behavior of the CV over the 189 rated items, a progressive decrease in consensus is perceived, which may support the hypothesis of growing fatigue among the experts.

While including a successive round could have potentially improved the results for this part of the questionnaire, increasing the level of consensus in all evaluations, many studies indicate that increasing the number of rounds can lead to panelist fatigue (Anderhofstadt and Spinler, 2019; Gill et al., 2013), likely leading to confusion and indifference (Long, 1970). For our purposes, it was assumed that the dispersion observed in the evaluations remained within an acceptable range.

The evaluations allowed for constructing a performance matrix (Table 11), where the panelists' average scores for each criterion were used as a proxy for performance. The weights (w_i) obtained for each criterion in the first round are also presented.

Even with relatively small amplitudes of evaluation (the most significant amplitude is recorded in the environmental and sustainability criterion, with 2.96 points), it is not immediately and unequivocally possible to order the drivers or even indicate which outranks or is outranked by the others. Each driver exhibits very distinct performances across the criteria. This behavior favors the use of MCDA to assist in the analysis.

The next question addressed Brazil's accession to the OECD. The panelists were informed about the formal request for accession placed by the country, possible general impacts mentioned in the literature, and the lack of studies about the potential effects of this accession on the electricity sector. Subsequently, an evaluation was requested using the same nine criteria employed for the other drivers. The accession to the OECD was labeled a_{22} and received evaluations ranging from 8.13 (public policy and regulation criterion) to 6.68 (social impact criterion), demonstrating considerable consensus. The average evaluation and corresponding statistical data are shown in Table 12.

Since the results for this driver were comparable to those obtained for the 21 critical drivers, the accession to the OECD may be considered

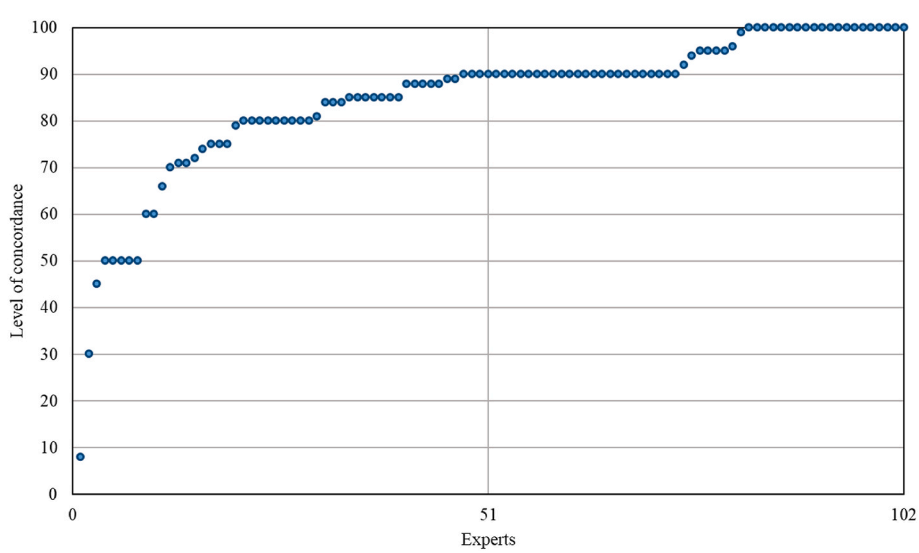

Fig. 9. Progressive distribution of the concordance level (102 panelists).

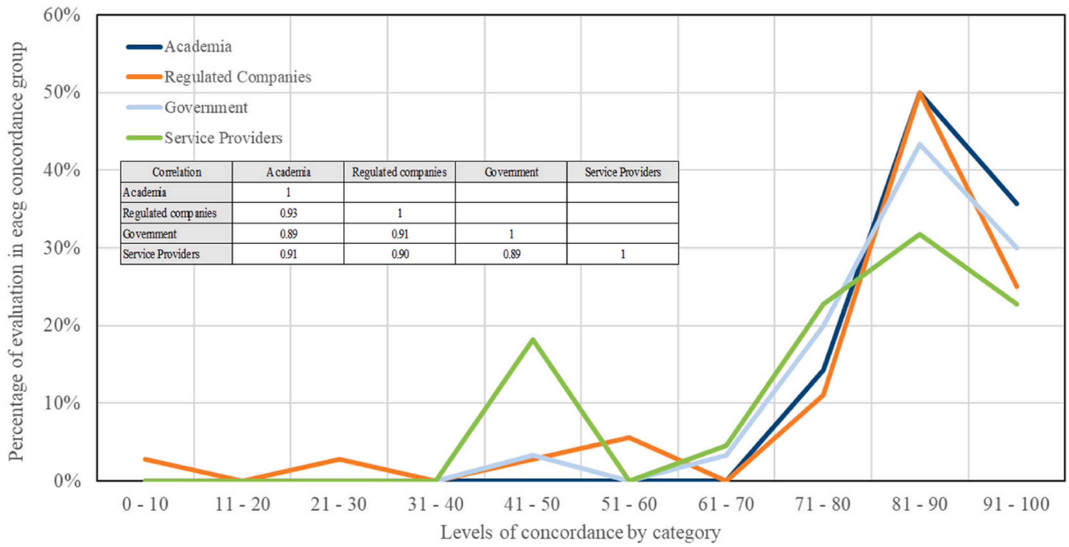

Fig. 10. Relative frequency histogram of the concordance by category.

Table 10
Main impacts from China and the U.S

Main impacts	Mentions		
	Both	China	United States
Equipment and technology	31	16	1
Investment	13	11	–
Trade	6	3	1
Environment	4	–	4
Other impacts	13	4	3

one of the significant drivers for the Brazilian electricity sector by 2050. When considering a weighted average, it is placed alongside cybersecurity and consumer behavior.

The second round concluded with an exploratory question about the main risks involved in the Brazilian energy transition process. Risk identification is an essential part of effective risk management (Romanova and Masalkova, 2021) and holds potential benefits for Brazil's electricity sector (Kruger et al., 2021; Losekann et al., 2013; Su et al., 2021). To this end, open-text boxes were provided to collect up to two risk suggestions per expert. The survey collected 139 diverse mentions, grouped into 19 categories to assist visualization and analysis. The variety of identified risks underscores the challenges associated with the energy transition process. Energy transitions are not smooth, straightforward processes. They are "irreducible to a single cause, factor, or blueprint" (Sovacool, 2016, p. 211). Implementation and consequential risks permeate transition pathways at various levels, in every theme, and for every stakeholder. Nevertheless, risks and uncertainties are often intertwined, and uncertainties can also be associated with positive outcomes (Lieu et al., 2020; Song et al., 2020).

The findings regarding risk identification are depicted in Fig. 12, highlighting the prevalence of regulatory and public policy risks, followed by those involved in the sector configuration and operation. Both encompass pivotal choices that can significantly influence the future generation mix. Since policy and regulatory design and adaptation are complex and time-consuming tasks, and most projects in this sector

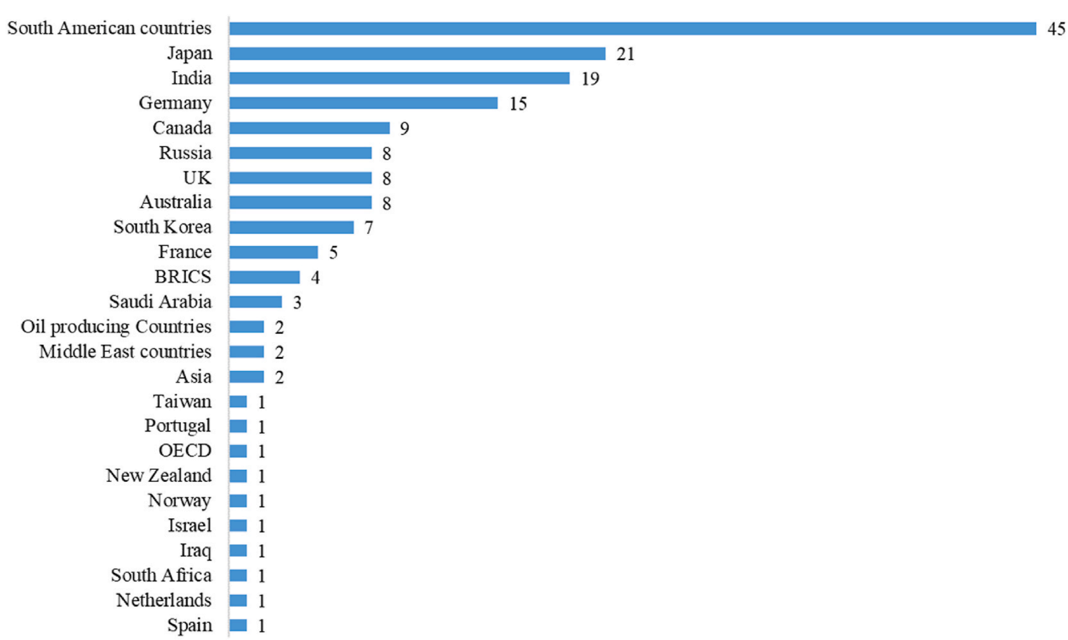

Fig. 11. Influences in the Brazilian transition (beyond the EU, China, and the United States).

Table 11
Performance matrix (drivers x criteria).

Drivers		Criteria								
		Public policy and regulation	Economic impact	Planning uncertainty	Environment and sustainability	Energy security	Investment capacity	Horizontal and vertical impact	R&D initiatives	Social impact
		g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
Evolution of storage technologies	a_1	8.41	8.42	8.58	8.24	8.68	7.63	7.73	8.40	7.28
Penetration of solar and wind sources	a_2	8.36	8.40	8.33	8.62	8.23	7.64	7.91	7.41	7.58
Distributed energy resources	a_3	8.59	8.47	8.55	8.08	8.21	7.68	8.14	7.87	7.71
Electric vehicles	a_4	7.99	8.12	7.45	8.21	7.09	7.21	7.47	7.99	7.17
Smart grids	a_5	7.76	7.94	7.45	8.23	7.67	7.26	7.13	7.73	7.28
Energy efficiency	a_6	8.19	8.22	8.54	7.36	8.26	8.04	8.06	8.53	7.28
New business models	a_7	8.38	8.51	7.92	7.45	7.32	7.78	7.78	7.59	7.47
Demand management and response	a_8	7.94	8.00	8.29	7.40	8.23	7.35	7.29	7.51	7.00
Consumer behavior	a_9	7.62	8.01	7.79	7.49	7.32	7.18	7.13	6.94	7.41
Hydrogen	a_{10}	7.67	7.56	7.14	7.79	7.17	7.36	6.99	8.31	6.35
Artificial intelligence	a_{11}	7.19	7.46	8.12	7.01	7.69	7.29	7.24	8.23	6.67
Cybersecurity	a_{12}	8.00	7.92	7.45	6.08	8.13	7.37	7.40	8.17	7.18
Role of hydroelectricity	a_{13}	7.82	7.87	8.19	8.35	8.64	7.91	7.21	6.73	7.17
Com. & information technologies	a_{14}	7.29	7.23	7.35	6.53	7.37	6.96	7.04	7.60	6.73
Greenhouse-gases emissions	a_{15}	8.59	8.33	7.78	9.04	7.55	7.96	7.40	8.24	8.01
Role of natural gas	a_{16}	7.76	7.91	7.76	8.14	8.05	7.55	7.08	6.67	6.91
Big data	a_{17}	7.23	7.33	8.03	6.64	7.49	7.08	7.15	7.88	6.55
Biofuels	a_{18}	7.56	7.72	7.04	8.03	7.12	6.99	6.76	7.09	6.99
Electrification	a_{19}	8.37	8.26	8.15	7.95	7.81	7.72	7.79	7.40	8.23
Carbon capture, use, and storage	a_{20}	7.83	7.64	6.67	8.38	6.36	7.01	6.37	7.76	6.99
International integration	a_{21}	7.83	7.58	7.56	7.09	7.77	7.40	7.19	6.64	6.62
Brazil's accession to the OECD	a_{22}	8.13	7.88	7.34	7.84	7.03	7.69	7.04	7.23	6.68
Criteria Weights	w_i	0.12	0.12	0.11	0.12	0.11	0.11	0.11	0.10	0.10

Table 12
Brazil's accession to the OECD - evaluation and data.

	Criteria								
Driver and parameters	Public policy and regulation	Economic impact	Planning uncertainty	Environment and sustainability	Energy security	Investment capacity	Horizontal and vertical impact	R&D initiatives	Social impact
	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
Brazil's accession to the OECD a_{22}	8.13	7.88	7.34	7.84	7.03	7.69	7.04	7.23	6.68
Σ	1.94	2.20	2.30	2.29	2.28	2.12	2.24	2.37	2.44
CV	0.24	0.28	0.31	0.29	0.32	0.28	0.32	0.33	0.37
IQR	3.00	2.50	3.00	3.00	3.00	2.00	3.00	3.50	3.50

require long-term efforts, there is a potential for technology lock-in to occur (Haelg et al., 2018), thus preventing optimal paths for the transition.

Another concern highlighted by the panelists is the potential for cost growth. This element is crucial to the energy transition and is particularly challenging for a developing country like Brazil (Engelhorn and Müsgens, 2021; Li et al., 2021). The fourth most prominent risk is the political one, directly impacting foreign direct investment (Jiang and Martek, 2021), followed by investment capacity. Collectively, these five risks represent nearly 60% of the mentions provided by the specialists.

While many of the risks listed by panelists commonly appear in the literature, their combination is unique for each country, as are their corresponding mitigation strategies. However, specific tools and approaches are well-established and recognized, such as effective communication, diversification, accurate forecasts, and a favorable investment environment (Ali and Sabir, 2022). In Brazil, nearly all risks are influenced to some degree by the prospective accession to the OECD.

5. Conclusions and policy implications

The application of the Delphi method represents a valuable tool for acquiring more profound insights into relevant topics and structuring decision-making problems. In this work, a two-round Delphi method was employed to gather information and identify, within the 3Ds framework, the critical drivers that will shape the Brazilian electricity sector by 2050.

A substantial number of experts were invited to contribute with their perceptions. In the first round, 294 experts participated, and 102

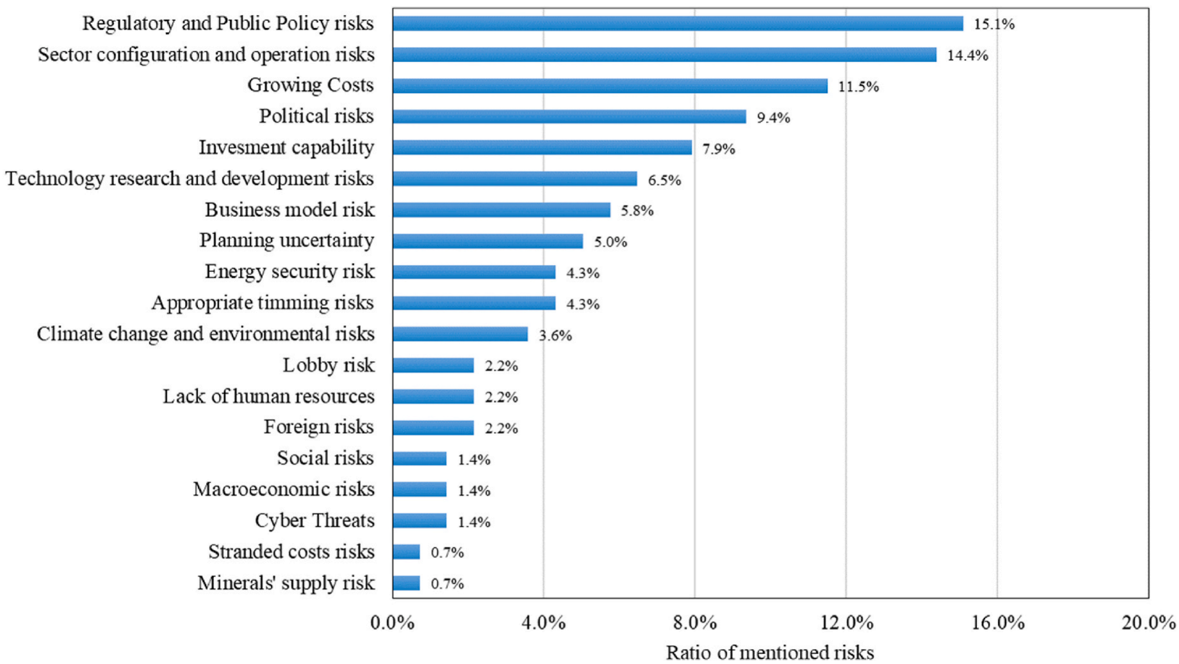

Fig. 12. Brazil's energy transition risks, according to the Delphi panel.

continued in the second round. These experts were divided into four categories: government, regulated companies, service providers, and academia. The number of participants, dropout rates, and levels of consensus and stability adhered to the accepted parameters derived from the literature.

The results obtained from the Delphi rounds validated the list of 21 critical drivers initially gathered through a meta-synthesis of the literature. The agreement of the experts with the evidence obtained from the literature serves as a reciprocal verification parameter. Furthermore, the drivers were directly ordered by the experts in terms of relevance as follows: evolution of storage technologies, penetration of solar and wind sources, distributed energy resources, electric vehicles, smart grids, energy efficiency, new business models, demand-side management and demand response, consumer behavior, hydrogen, artificial intelligence, cybersecurity, the role of hydroelectricity, information & communication technologies, greenhouse-gas emissions, the role of natural gas, big data, biofuels, electrification, carbon capture, use, and storage, and international integration. The experts also suggested that the critical drivers are followed by nuclear energy and transmission systems.

These findings can potentially strengthen the policymaking process by highlighting the most pressing issues that require attention. This helps policymakers focus on a more stable vision of the future and the difficulties that may arise and resist undue lobbying for peripheral issues.

Moreover, the impacts of the energy transition in the Brazilian electricity sector are expected to be significant, particularly in the coming decades. Since these impacts are predominantly considered positive, they present opportunities. Evidence suggests that Brazil will continue to follow the path of sustainability concerning electricity due to the expected significant role of wind and solar sources and storage technologies. However, the pressure to reduce emissions is not as relevant as in other countries since it is found among the less impactful drivers, according to the experts. These insights from experts can help identify gaps and lessons in the policy environment that need to be addressed in the coming decades.

The main drivers of the Brazilian transition are also in the ongoing debate in other parts of the world, especially in the EU and the United States. However, their interaction and relative importance reflect the specific context of Brazil and its unique energy mix. Furthermore, the study collected information regarding influences and risks, with notable attention to China's growing influence. The main risk identified involves policymakers and regulators, who are this prospective study's primary users. In this case, it is worth highlighting as a strength of this work the contribution to a better understanding of the Brazilian energy transition and the promotion of the debate on the subject, which can directly contribute to mitigating this risk to some extent.

As for the OECD, the evidence suggests that Brazil's prospective accession will significantly impact the electricity sector, comparable to some critical drivers. For instance, public policies and regulations are among the OECD's key focus areas, and it operates through disseminating best practices. The accession may also foster foreign direct investment and international trade, accelerating economic growth and promoting sector expansion. Identifying the specific nature and magnitude of this influence deserves further research.

Finally, the Delphi method also assisted in eliciting parameters for applying an ELECTRE-TRI MCDA. The selected criteria and each drive's performance, as well as the weights and different thresholds, were identified and quantified with the help of the experts, resulting in a performance matrix suitable for a future MCDA application.

We acknowledge that expert participation is among the limitations of this study. While the final group of experts was still representative for our purpose and methodology, there is room for expanding the expert pool and improving access to information, which would allow for gathering even more diverse perspectives and enhancing the robustness of the results. The absence of similar studies also limited the ability to make comparisons and benchmarks. Additionally, using written questionnaires to convey several and sometimes complex questions posed challenges in communicating with the experts.

Future research may apply an MCDA method to sort the identified critical drivers and effectively incorporate the accession to the OECD. It may also explore some of the aspects evidenced in this study (e.g., sources of influence, risks) and eventually gather perspectives from other related sectors, such as the oil and gas sector, which operates relatively independently from the electricity sector in Brazil and is regulated by a specific agency.

The results may be broadly utilized to calibrate the energy transition groundwork and implementation efforts, especially in the public policy and regulatory fields. The results obtained, especially from the rounds of the Delphi method, are valuable in illustrating the thinking of the professional categories involved in this work. While this group of experts offers a static view, it anticipates preferences and perceptions about the Brazilian electricity sector in the next three decades, allowing time to conceive strategic actions and even follow changes in the collective perceptions over time.

The results go beyond a vision for the socioeconomic endogenous development. Expert opinions have been systematically collected and synthesized, as in a public participation process. This gives policymakers access to the full range of advice from the most qualified people. Rather than relying on a single perspective, officials gained a more rounded understanding based on expert insights. Enriching the findings of the study with more stakeholder engagement can support better-informed policy decisions.

From a regulatory perspective, the findings can help prioritize items on the regulatory policy agenda and anticipate the evolution of the regulated sector. Given the expected magnitude of the impacts associated with the energy transition and the diverse array of drivers identified as critical, innovations need to be addressed in an appropriate and timely manner, reinforcing the importance of adopting a more adaptive regulatory framework to address the emerging challenges.

In summary, this information may assist the decision-making process in the public policy and regulatory environments and provide valuable insights to prioritize core elements, better preparing Brazil for its international role in sustainability.

CRediT authorship contribution statement

Alex Sandro Feil: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Carlos Henggeler Antunes:** Writing – review & editing, Supervision, Formal analysis, Methodology. **Patrícia Pereira da Silva:** Writing – review & editing, Supervision, Formal analysis, Methodology. **Nivalde de Castro:** Writing – review & editing, Supervision, Formal analysis, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alex Sandro Feil reports a relationship with National Electric Energy Agency that includes: employment.

Data availability

Data will be made available on request.

Acknowledgments

This work was partially supported by the Erasmus+ Programme of the European Union, by national funds through the Portuguese Foundation for Science and Technology, I. P., through Projects UID/MULTI/00308/2020 (DOI 10.54499/UIDB/00308/2020) and UIDB/05037/2020 (DOI 10.54499/UIDB/05037/2020), and by the Energy for Sustainability Initiative of the University of Coimbra. The authors are grateful to all experts who collaborated on this study by responding to the Delphi questionnaires.

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