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UK Hydrogen Roadmap: Financial and Strategic Insights into Oil and Gas Industry's Transition

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Abstract: Inspired by the announcement of the new Hydrogen Strategy for the UK in 2021, this study aimed to determine how the oil and gas industry responds and adapts to the changes. This paper analyses qualitative and quantitative data from the companies' annual and energy reports. Four oil and gas companies involved in hydrogen projects in the UK were selected as case studies. The responses from the companies were collected using the content analysis research strategy in 2019–2021. A steady increase was observed based on the code frequency, reflecting the increasing discussions and actions the companies took regarding this hydrogen pathway. Although only one company appears to be at the forefront of this transition progress, with a score of almost 90% based on the strategy management analysis, other companies continue to demonstrate their commitment to supporting the national target.

Keywords: hydrogen strategy; transition; oil and gas; sustainability; content analysis

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1. Introduction

The oil and gas industry has been at the forefront of the world's eye in converting energy into valuable products, such as fuels, for transportation since 1949 [1,2]. The increasing demand for global business shows a parallel growth in oil and gas exploration to meet the production needs of the industry [3]. However, the continuation of 'business as usual' for oil and gas companies is at odds with the global goal of achieving net-zero emissions [4]. The impact of fossil fuels is the leading cause of air pollution [5]. Fossil fuel dependence has led to significant carbon emissions and caused a continuous increase in the Earth's temperature since 1880 [6].

Renewable energy is globally recognized as a future solution to meet human needs sustainably and in the long term [7]. The oil and gas industry must shift to renewable energy projects to avoid becoming irrelevant in the future [8]. Achieving the net-zero target by 2050 to address climate change is a long journey that needs to start now. Hydrogen is a potential enabler for addressing challenges and can be used in various industries [9]. A low-carbon hydrogen solution can replace existing carbon-rich fuels and drive carbon emission reductions.

Developed and developing countries are working to ensure a smooth transition to hydrogen technology deployment. In 2021, the UK government unveiled the UK Hydrogen Strategy document, which sets out the strategies for implementing the hydrogen roadmap towards a net-zero country [4,10]. In line with the collective agreement described in [11],

limiting global temperatures to well below 2 °C as part of the Paris Agreement became the basis for creating the strategy document to make the country cleaner and greener.

A successful transition to this sustainable future requires an assessment of the current progress [12]. The document's introduction will directly affect many industries, and the current status and participation in hydrogen projects need to be analyzed. The oil and gas sector is among the key industries that underpin the country's economy [13] and needs to proactively implement the hydrogen strategy as part of its strategic business plan. In the long term, companies planning this transition to renewable energy early on will be in a better position compared to competitors. This will positively impact the country and can contribute to becoming the reference and world leader in hydrogen technology.

Hydrogen, as one of the renewable energy sources, can provide electricity and offer cooling and heating to the end users. Several studies have been conducted to assess the potential growth of hydrogen in the UK, for example, in the domestic sector using fuel cells [14,15] and in the transportation sector using hydrogen buses [16,17]. To understand the hydrogen potential in this industry, a review of the current state of hydrogen development in the oil and gas sector is required to drive decarbonization initiatives for the country [15].

Oil and gas companies have been working on the transition to renewable energy for several years. According to the Oil and Gas Climate Initiatives [18], its members, comprised of significant oil and gas companies, have developed their roadmap for net-zero ambitions [18]. However, an overview of this progress, particularly in hydrogen technology and development in the UK, is lacking.

To support the implementation of the net-zero target, the UK Hydrogen Strategy document, published in 2021, has identified several aspects and targets to guide the industry. This research paper, therefore, aims to review the current progress of oil and gas companies in setting the right direction based on the newly introduced strategy document [4]. This study will analyze to what extent the organizations have addressed the targets set by the government.

This study aims to contribute to the adoption of hydrogen technology by examining the transformation of oil and gas companies in the UK through the hydrogen strategy roadmap. The roadmap is intended not as a prediction but as a guideline integrating future expectations, aspirations, and commitments for hydrogen adoption [19]. Specifically, this study measures the readiness of oil and gas companies to pursue hydrogen technology in their mainstream business operations and offers recommendations for best practices to facilitate long-term business success in hydrogen transition.

The UK Hydrogen Strategy document, published in 2021, outlines several aspects of hydrogen technology and aims to guide the industry to support the UK's net-zero target. This research critically reviews the progress of oil and gas companies in implementing the hydrogen strategy, assessing the extent to which companies have addressed the targets set by the government. This study also identifies gaps in hydrogen adoption and suggests areas for improvement. By reviewing the strategy roadmap, this paper evaluates how effectively companies align their practices with the government's hydrogen goals, contributing to the body of knowledge on energy transformation and policy implementation within sustainable energy systems.

This paper is organized as follows: Section 2 critically examines the existing body of literature on this topic, Section 3 illustrates the data and research methodology, Section 4 presents the findings and discussion, and Section 5 summarizes the conclusions.

2. Literature Review

2.1. Role of Hydrogen

2.1.1. Production, Storage, and Distribution of Hydrogen

Hydrogen is not a direct energy source like wind or solar and is usually coupled with another element in nature. It has to be processed to be retrieved as a single element with high purity before it can be used in various applications. The different processing procedures determine the different color codes for hydrogen, which still need to be standardized as a single guideline for global reference [9]. Some authors classify five different colors of hydrogen [9,20,21], while others have broader categories with more than six color codes for hydrogen [22]. Due to this inconsistency, most authors define the production type in their articles. While the focus of this research paper is grey, blue, and green hydrogen, other new processes, such as orange hydrogen, are interesting as well.

Hydrogen produced from fossil fuels is referred to as "grey hydrogen", with carbon emissions from this process being the highest among all processes [21,23]. As hydrogen production is the most practical when using this process, according to [24], the negative impacts are usually mitigated with carbon capture storage (CCS) technology to secure carbon emissions, which makes this route known as "blue hydrogen". "Green hydrogen" is the most sustainable approach as it converts renewable energy from wind and solar into hydrogen through electrolysis; it is usually called the power-to-gas (P2G) approach by practitioners [25,26]. Based on the different types of hydrogen, "blue hydrogen" and "green hydrogen" have been found to be the main focus in most countries to support the global target of a low-carbon hydrogen economy [9].

Alternative routes have the potential to grow, such as "brown hydrogen" from coal gasification and "turquoise hydrogen" from methane pyrolysis, with the most promising one being "orange hydrogen", based on the geological reaction of iron minerals in the Earth's crust with water by oxidation–reduction reactions to produce hydrogen [27]. Teams of researchers such as those at CNRS-INSU have devised ways to speed up this natural production process, an interesting opportunity to help drive the energy transition since iron is found in about 5% of the Earth's crust [28]. However, some of these alternative methods are still needed at the pilot scale, as reported in [21], which has led to less discussion in the academic literature. Figure 1 below shows a summary of the different color codes for hydrogen.

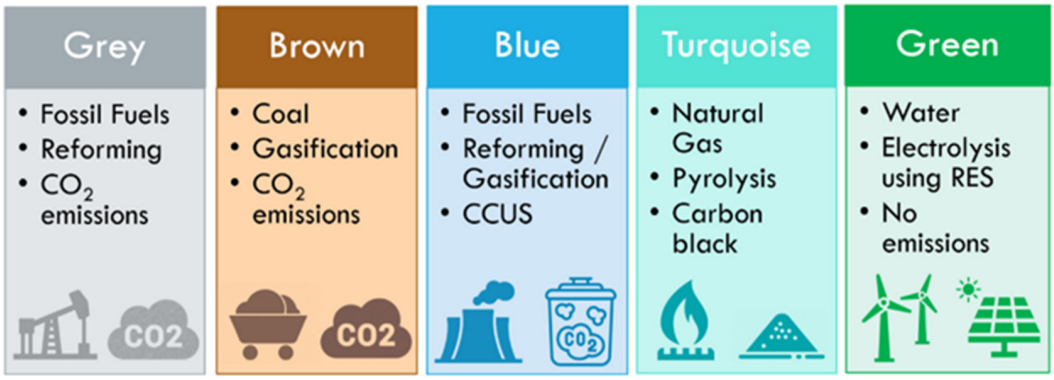


Figure 1. Colors of hydrogen production are based on different pathways. Source: [21].

2.1.2. Hydrogen Economy Concept

The future of hydrogen is linked to the hydrogen economy concept [29]. As early as 1970, John Bockris taught the nation the potential of hydrogen in the future as a substitute for non-renewable energy sources [28,30]. The ideal hydrogen economy encompasses the entire value chain from hydrogen production, storage, and transportation infrastructure to delivery to the end user [15].

The validity of implementing a hydrogen economy cannot be considered a clean solution for the world as there are potential side effects that can also harm the environment [31]. However, as research in this area has increased, awareness about implementing the right holistic approach has also increased. Several successful cases have been recorded, making the role of hydrogen even more significant in the move towards a cleaner and more sustainable system [32]. As many factors contribute to the development of the hydrogen economy, ref. [33] emphasized that innovative strategies help to make the right choice for the structure of the new market.

2.2. Hydrogen Roadmap: UK and Others

The positive impact of adopting hydrogen as an energy carrier aligns with the global need for a carbon-free energy supply. As derived from [34], four documents need to be produced to ensure that the integration of the new strategy into the existing system in the country goes smoothly. It starts with the research and development (R&D) program, the vision document, and the roadmap and ends with the strategy document. The transition from one initiative to the next is crucial to ensure that the long-term target of technological adoption is mature and covers all aspects [19]. In addition, ref. [35] pointed out the role of the government in guiding the country's policies to promote all hydrogen development projects in the country.

The rapid increase in global awareness has led countries to gradually introduce national strategies and policies that specifically address the hydrogen economy [36,37]. Most countries are making progress in addressing global climate change. Japan, for example, is the frontrunner, as the country launched its strategy in December 2017 and updated it in 2019 [9]. South Korea is following in the footsteps of the pioneer by developing and adopting a national strategy in 2018 before other countries begin to develop their national strategies [38]. The momentum for adopting such strategies has been increasing since 2020. The most recent countries that have just published their strategies include the Czech Republic, Colombia, Hungary, Norway, and the United Kingdom [20]. Figure 2 shows the annual progress of all countries in developing national hydrogen strategies as of 2021.

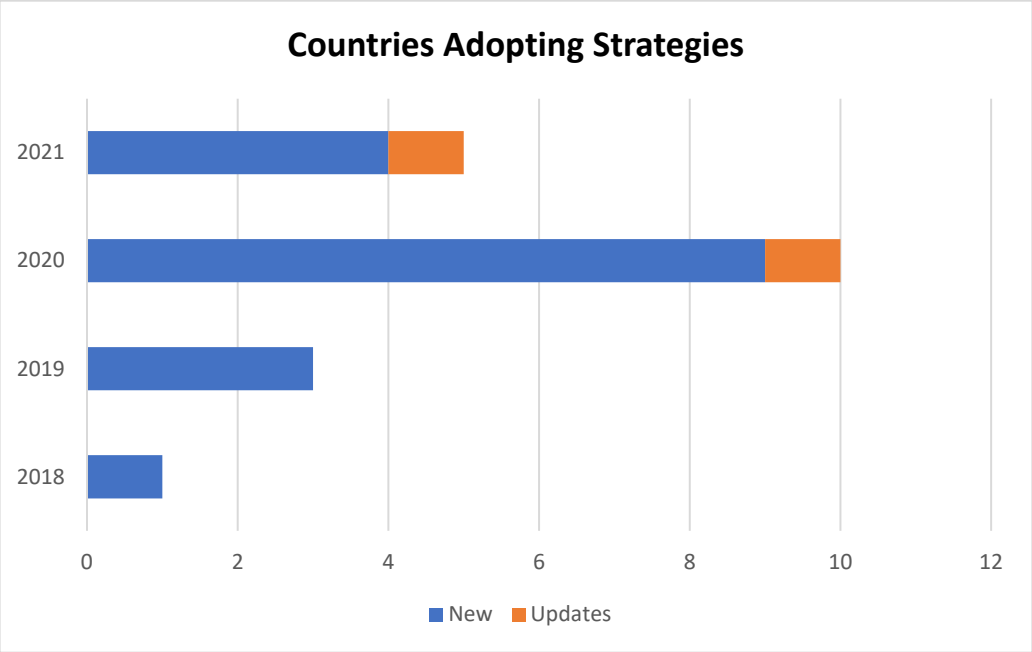


Figure 2. Annual announcements of government hydrogen strategies. Source: [20].

Transition targets, such as hydrogen production volumes, vary widely from country to country. Several factors influence the decision-making process, such as resource availability, demand, and R&D activities, which depend highly on the existing national system [39]. Some researchers [21] found that companies' strategies and objectives differ by region. For example, it was found that European countries focus on increasing the production of green hydrogen while importing other requirements, whereas Asian countries such as Japan and South Korea are expanding their capabilities to become significant importers of hydrogen [40,41]. Table 1 summarizes national hydrogen strategies, goals, and target capacities by country.

Table 1. Comparison of national hydrogen strategies.

Country	Hydrogen	Strategy, Goals, and Capacity
South Korea	Domestic; Import	• Produce Steam Methane Reforming (SMR) hydrogen until 2030. • Supply Fuel Cell Electric Vehicle (FCEV) and fuel cells. • Decarbonize domestic sectors. • Production goals. ▪ 17 Mtly of hydrogen demand by 2050. ▪ 3.7 Mtly of hydrogen produced from SMR and electrolysis by 2022. ▪ 3.5 GW fuel cell power generation capacity by 2030.
Japan	Domestic; Import	• Develop international supply chains. • Develop technologies for hydrogen production and transport. • Reduce hydrogen cost to 30/Nm^3 by 2030 and 20/Nm^3 after 2030. • Import 5–10 Mtly of hydrogen.
Australia	Domestic; Export	• Attract international investors and build bilateral market partnerships. • Top 3 hydrogen exporters to the Asian market in 2030. • Reduce hydrogen cost to D^2/kg.
France	Domestic	• Export hydrogen technology. • Achieve 10% green hydrogen by 2023.
Germany	Domestic; Import	• Make hydrogen competitive for energy and industry. • Build domestic infrastructure.
Netherlands	Domestic	• Act as an energy hub. • Support research and development (R&D).
Norway	Domestic	• Support R&D.
Finland	Domestic	• Increase industrial use by lowering costs.
Portugal	Domestic; Export	• Produce 1.75–2 GW by 2030 and 5 GW by 2050 through electrolysis.
Spain	Domestic; Export	• Support R&D
Chile	Domestic; Export	• Produce cheapest green hydrogen by 2030 (less than $ 1.5/kg).
USA	Domestic	• Produce hydrogen from diverse domestic sources. • Support hydrogen-based innovation and R&D.

Source: [21].

Hydrogen Strategy in the United Kingdom

In 2020, the UK recorded a 49.7% reduction in overall greenhouse gas emissions since 1990 [42]. Part of this result is the reduced use of fossil fuels in power stations. This aligns with the ambitious target to reduce emissions to zero by 2050.

In 2010, the Electricity Market Reform (EMR) was introduced to address the issue related to power supply [15,43,44]. Another step was the introduction of Carbon Budgets by the Committee on Climate Change (CCC) to monitor and assess emissions closely every five years until 2050 as part of the long-term goal [45]. More recently, a new strategy, called the 'UK Hydrogen Strategy', was published in 2021, aiming to increase low-carbon hydrogen

production to 5 GW nationwide by 2030 [10]. This was followed by an announcement to double the target production to 10 GW to maximize green hydrogen in the supply of energy across the country [46,47]. This series of initiatives has shown that the government has taken the necessary steps to shape the country's direction towards the target. Table 2 shows the timeline for various key policies and reports of change in the country.

Table 2. Summary of various changes in energy policies and reports in the UK.

No	Year	Policy or Report	Descriptions
1	2010	Electricity Market Reform (EMR)	To improve efficiency and reduce prices for electricity consumers.
2	2017	Clean Growth Strategy	A comprehensive set of policies and proposals that aim to accelerate the pace of 'clean growth', i.e., deliver increased economic growth and decreased emissions.
3	2017	Cost of Energy Review	An independent review into the cost of energy led by Professor Dieter Helm.
4	2018	Trilemma Speech	Speech by Business Secretary Greg Clark on the future of the energy market in response to the Helm review.
5	2018	Committee on Climate Change (CCC)	An independent statutory body to advise the UK and entrusted governments on emissions targets and to report to Parliament on the progress made thus far.
6	2019	Energy White Paper	Key policies comprising consumers, power, energy systems, buildings, industrial energy, and oil and gas.
7	2019	HM Treasury's Net Zero interim report	To inform the next steps in the UK's transition to net zero by 2050.
8	2020	Ten Point Plan for a Green Industrial Revolution 9	The approach the government will take to build back better, support green jobs, and accelerate our path to net-zero emissions.
9	2021	UK Hydrogen Strategy	To develop a successful low-carbon hydrogen sector in the UK to meet the increased ambition for 10 GW of low-carbon hydrogen production capacity by 2030.

Source: [42].

The UK Hydrogen Strategy document builds upon point 2 of the Ten Point Plan [10]. Its aim is to provide industries and regulators with details of how the hydrogen strategy will be integrated into current business operations. The period from 2020 to 2023 is the critical phase before the final policy decision, which requires the proper foundation and basis for the growth of this renewable energy. The main contents of the UK Hydrogen Strategy document are listed in Table 3.

Before the document was written, the costs of hydrogen incentives were the lowest compared to other technologies [48]. In contrast, the UK government has committed to allocating £1 billion specifically for hydrogen technologies to provide additional funding to help companies and industries share their technology [10]. Increasing job opportunities is also part of the government's goal, which aligns with promoting clean energy by creating green jobs, as mentioned in [39]. This proves that this technology has a continuous growth potential on national and international levels.

With hydrogen projects and plans expanding across the country (see Figure 3), various parties should consider adequate support from the government to ensure smooth project implementation. The government estimates that hydrogen-based energy consumption in the UK will account for 20% to 35% of total energy consumption by 2050 [47]. However, no studies have aimed to analyze the strategy document so far.

Table 3. Summary of the UK Hydrogen Strategy.

Chapter	Topics	Main Highlights
1	The case for low-carbon hydrogen	• 2030 vision for the UK as a global leader for hydrogen with six guiding principles. • Six strategic challenges from the overall hydrogen value chain. • Nine key outcomes by 2030 as a benchmark for success.
2	Scaling up the hydrogen economy	• 2020's Hydrogen Economy roadmap covering 10 supporting policies and activities. • Key commitments by the government in the hydrogen value chain, i.e., hydrogen production, networks, storage and use of hydrogen, and market for hydrogen.
3	Realizing economicbenefits for the UK	• Key commitments and action plans to support job opportunities and research and innovation activities. • Hydrogen investment plan and hydrogen trade (exporting).
4	Demonstrating international leadership	• Collaboration with key institutions and other leading hydrogen nations for hydrogen innovation, policy, and standards to meet global targets.
5	Tracking our progress	• Hydrogen strategy outcomes through key indicators for progress monitoring.

Source: [10].

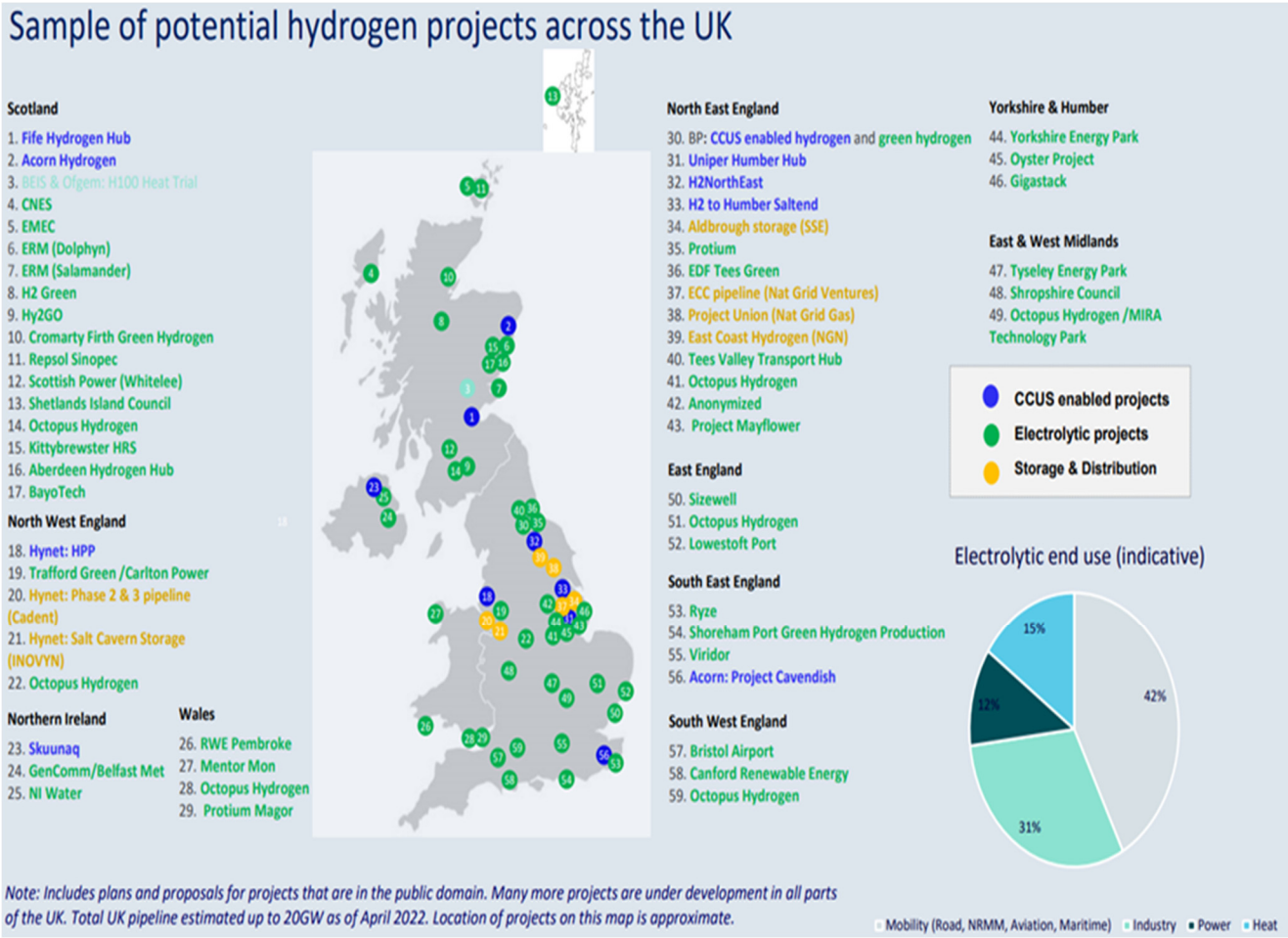


Figure 3. Planned and proposed hydrogen projects in the UK. Source: [41].

2.3. Hydrogen Market Outlook for Business Opportunities

The development of hydrogen technologies is increasing rapidly nowadays [15]. According to a study [49], demand is expected to increase by four to five percent annually. As shown in Figure 4, there is a higher demand for hydrogen produced by electrolysis. Although electrolysis costs are relatively high, they can be reduced significantly over time once the technology and infrastructure for deployment are stable and widely spread [28,50]. The intangible costs of this process include the generation of harmless water, the slowing of ice melt and rise in sea levels, and human health protection over the long term [51]. These benefits have a significant impact on climate change recovery.

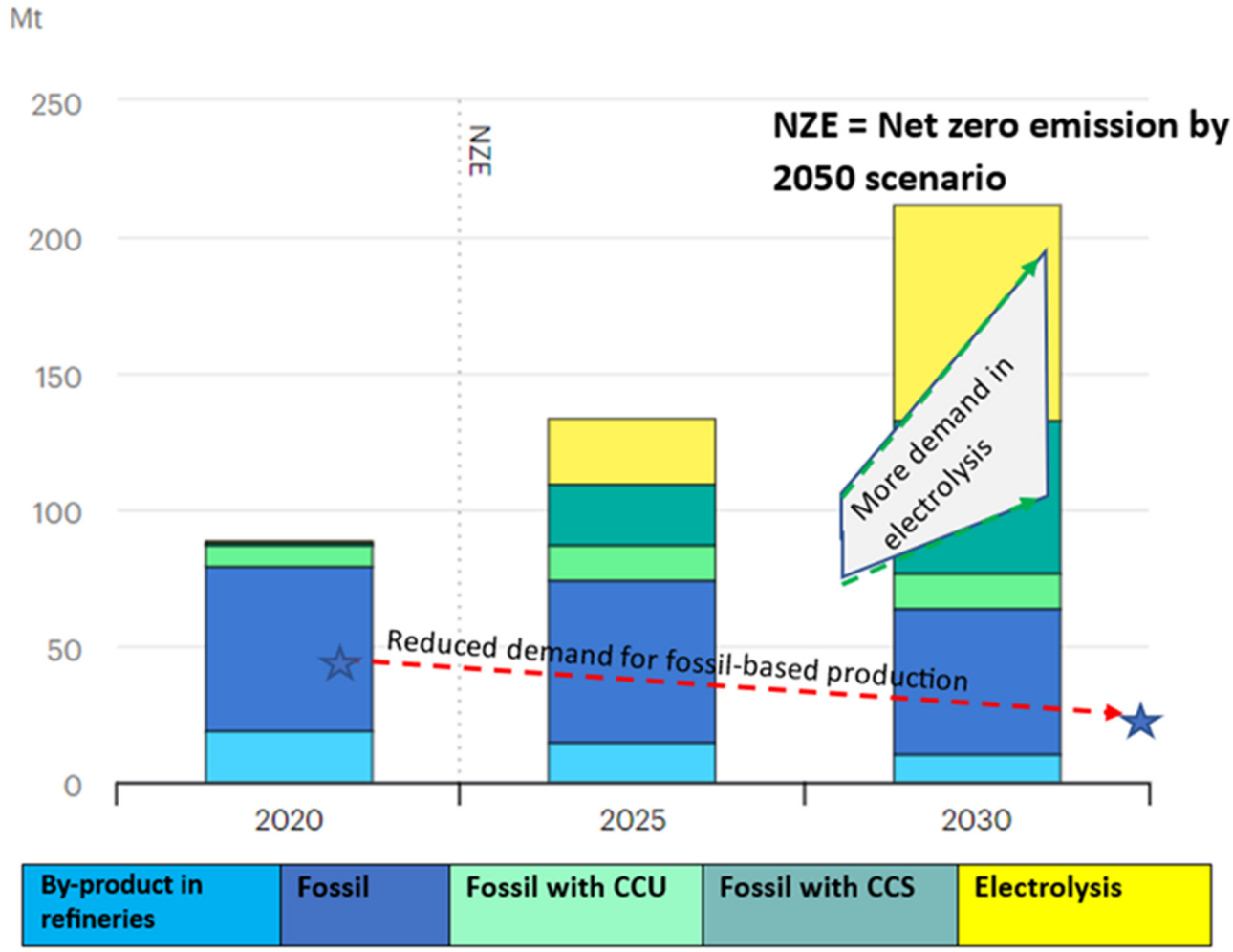


Figure 4. Global hydrogen demand in net-zero scenario. Source: [20].

2.4. Oil and Gas Transition Towards Renewable Energy

This industry is crucial as the leading supplier of energy demand and contributes to improving the country's economy. The authors of [13] have shown that an amount of £31.1 billion of Gross Value Added (GVA) has been allocated to support activities in various sectors in the UK. This industry will continue to contribute significantly to the country's economy, but the new energy transition brings various challenges and opportunities for sustainable business operations.

With the new Hydrogen Strategy document, the next critical milestone will be for the industry to adapt, embrace, and integrate the strategy. To achieve the strategy, the authors of [52] agree that this regulatory framework will help ensure the feasibility of the technology as well as its cost and economic viability; another study [53] highlighted the significance

of renewable energy investments on economic transition. Meanwhile, the authors of [54] claim that the oil and gas industry's progress on climate change needs to be monitored more closely to ensure that improvements can be identified and adjusted accordingly.

Oil and gas companies have begun to invest strategically and financially in this hydrogen roadmap [7]. However, the progress of these companies has not yet been evaluated, and more work is needed to address this transition issue, especially when the new hydrogen strategy document is available to support this process. A list of criteria for how a roadmap can support transition management, such as credibility, desirability, utility, and adaptability has been provided in the document [19]. Based on the strategy document and other research, a study on the current state of oil and gas companies in this phase will be helpful.

3. Data and Research Methodology

3.1. Research Strategy: Content Analysis

The strategy follows the steps of content analysis by identifying themes from the overall data. Content analysis is one of the fastest-growing strategies in the research field and is defined by [55] as a set of procedures for drawing valid inferences from texts. The systematic and objective technique can characterize messages [56]. Researchers can recognize the patterns of descriptions or written documents that can quickly go unnoticed due to the large amount of verbal text.

Three Phases of Content Analysis

As outlined in [57], there are three primary phases in conducting content analysis research: the preparation phase, the organization phase, and the reporting phase. Each of these phases includes essential steps that must be carried out to guide the data collection and analysis process.

To further support the data analysis, an additional measure, i.e., strategic business analysis, will be conducted to reflect the transition of the companies to the hydrogen technology business. The indicators are categorized using themes that are similar to that of the coding process. This is one of the advantages of content analysis, which allows a variety of themes to be explored, from organizational perceptions to strategy formulation, to address concerns raised by the CEO and higher management [58]. The basis of the questions for the indicators will mainly come from the UK Hydrogen Strategy document and supporting articles, which are listed in Figure 5. The steps described below are for the content analysis approach.

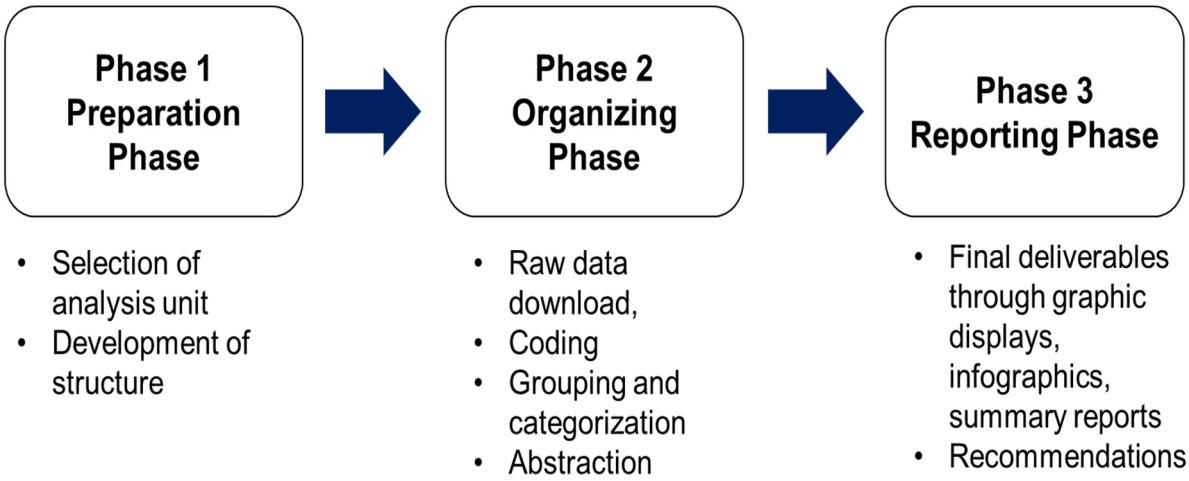


Figure 5. Content analysis phase. Source: [56].

3.2. Data Collection

3.2.1. Case Study: Oil and Gas Companies and Hydrogen Projects

These four companies were selected for two reasons. First, the hydrogen projects they work on are recognized and listed in the Hydrogen Investor Roadmap [46]. The second reason is the demographics of the projects, which are part of the most significant industry clusters in the country [48]. General information about each company and the location of hydrogen projects in the UK can be found in Table 4 and Figure 6.

Table 4. General information on selected oil and gas companies.

Companies	BP	ExxonMobil	Shell	Equinor
Headquarter Office	London, United Kingdom	Texas, United States	The Hague, Netherlands	Stavanger, Norway
Number of Employees (2021)	64,000	63,000	82,000	21,126
Hydrogen Projects in the UK	H2 Teesside and HyGreen Teesside	Southampton Hydrogen Hub	Acorn	H2 to Humber Saltend
Latitude and Longitude	54.57623° N, −1.23483° W	50.9105° N, 1.4049° W	34.6528° N, 120.4932° W	53.7465° N, 0.2388° W

Source: [59–62].

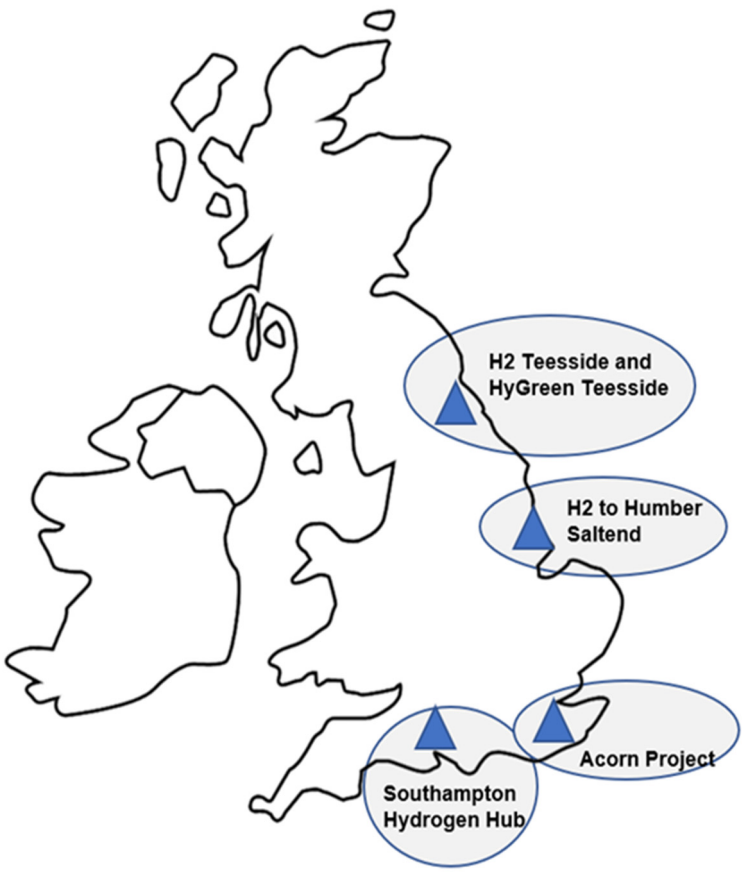


Figure 6. Location of identified hydrogen projects in the UK. Source: Authors.

3.2.2. Data Collection Instruments

The two types of publications that were collected from companies are annual and energy-related reports. As described in [63], annual reports serve as the primary communication tool for stakeholders, and they comprise the company's vision and directions that

are relevant to readers. However, additional information was used for analysis as most companies have also published other reports to support their vision, depending on the area they cover. Therefore, to support the data analysis specifically on hydrogen technology, the energy-related reports were used as a second reference source, providing more detailed information on the transition to hydrogen.

The types of data collected for each company are presented in Table 5. The reports cover three years, from 2019 to 2021, and all companies have published annual reports and energy reports each year, except Shell, which only launched its energy report in 2021; the energy-related progress in each year is explained in the sustainability report as part of the main content of the publications.

Table 5. Publications from companies used to obtain data for this study.

Document Type	Availability of Publications											
	BP			ExxonMobil			Shell			Equinor		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Annual Report	/	/	/	/	/	/	/	/	/	/	/	/
Energy Report	/	/	/	/	/	/			/	/	/	/
Sustainability Report							/	/				

Source: Authors.

3.2.3. Coding and Themes

A total of 19 principal codes were examined for this study, supported by 13 sub-category codes for the coding analysis process. Some terms were excluded from use as they led to irrelevant data. For example, the word 'sustainable' was removed after it was found to be associated with financial risk. Five themes were compiled from the list to organize the codes to fit the appropriate category: hydrogen-related policy, research and development, cost of hydrogen production, resources, and ease of business. Table 6 shows the keywords examined for this study.

Theme was described in [64] as a combination of a few topics that share commonalities. In the following, we examine the themes evaluated from the extracted data.

i. The hydrogen-related policy examines the companies' progress towards the 2030 and 2050 targets [47]. It also reflects an understanding of the company's direction toward achieving the goal through countable and non-countable targets.
ii. Research and development (R&D) focuses on identifying the collaboration and partnership of the company in working towards the decarbonization strategy [65]. Having a good R&D within the company will enable the company to increase its knowledge and expertise in solving climate issues.
iii. Cost of hydrogen—As cost is one of the challenges in hydrogen technology adoption [17,29], this theme looks for initiatives that the company is taking to reduce the production costs of adopting the technology. This includes the government's funding initiative, as announced in the UK Hydrogen Strategy document.
iv. Resources—a reliable facility and sufficient workforce are essential for the company to adopt the technology smoothly. This theme can be used to assess the readiness of resources within the company to achieve its objective.
v. Ease of business—assessing the acceptability of the transition through an awareness program to adapt to the current needs of the hydrogen business strategy conversion.

To quantify the results of the coding process, the frequencies of the principal and sub-category codes are counted and divided by the total word count of the annual report to normalize the results [66]. The frequencies show how often the words are mentioned in the company's official documents with respect to the abovementioned themes.

Table 6. Keywords identified for content analysis.

No	Main Codes	Sub-Category Codes	Themes
1	Carbon emission	CO_2 emission	Hydrogen-related Policy
2	Decarbon	Decarbonization	
3	Energy transition	Energy demand	
4	Hydrogen target	Hydrogen/hydrogen goal/hydrogen strategy/hydrogen policy	
5	Net zero	Zero net	
6	Climate	Climate change	
7	Low carbon	CO_2 emissions	
8	Collaboration	Partnership	Research and Development
9	Research and development		
10	Electrolysis	Electrolyzer	
11	Fossil fuel	CCS/CCUS	
12	Patent		
13	Hydrogen fund	Hydrogen funding	Cost of Hydrogen Production
14	Hydrogen production	Production of hydrogen	
15	Hydrogen capacity	Capacity of hydrogen	Resources
16	Hydrogen distribution	Hydrogen distributed	
17	Green job	Green talent	
18	Adapt		Ease of Business
19	Awareness		

Source: Authors.

The formula for calculating the frequency of terms is explained below.

$$X\% = ((\sum y)/n) \times 100$$

where:

X = Frequency of occurrence of codes in the report, in %.

y = Number of occurrences.

n = Total number of words counted in the annual report.

3.2.4. Strategy Management Analysis

Both themes and sub-themes are presented in a tabular form to better illustrate the relationship between the themes and indicators. The data evaluated in this analysis are oil and gas companies' annual and energy-related reports. Numerical scoring was performed as follows:

'1' was given to the company that discloses the information for each indicator.

'0' was awarded if no evidence or statements can be found in the report for the year. This includes the possibility that the company excludes the information for continuous progress that started in the previous year.

The analysis was based on the data collected and quantitative and qualitative results. The analysis was conducted through comparisons and contrasts between the companies and other related sources to ensure that the reasoning is appropriate and consistent with the supporting literature and this study's objective.

The indicators for the themes are listed in Table 7.

Table 7. Indicators based on themes and sub-themes for analysis.

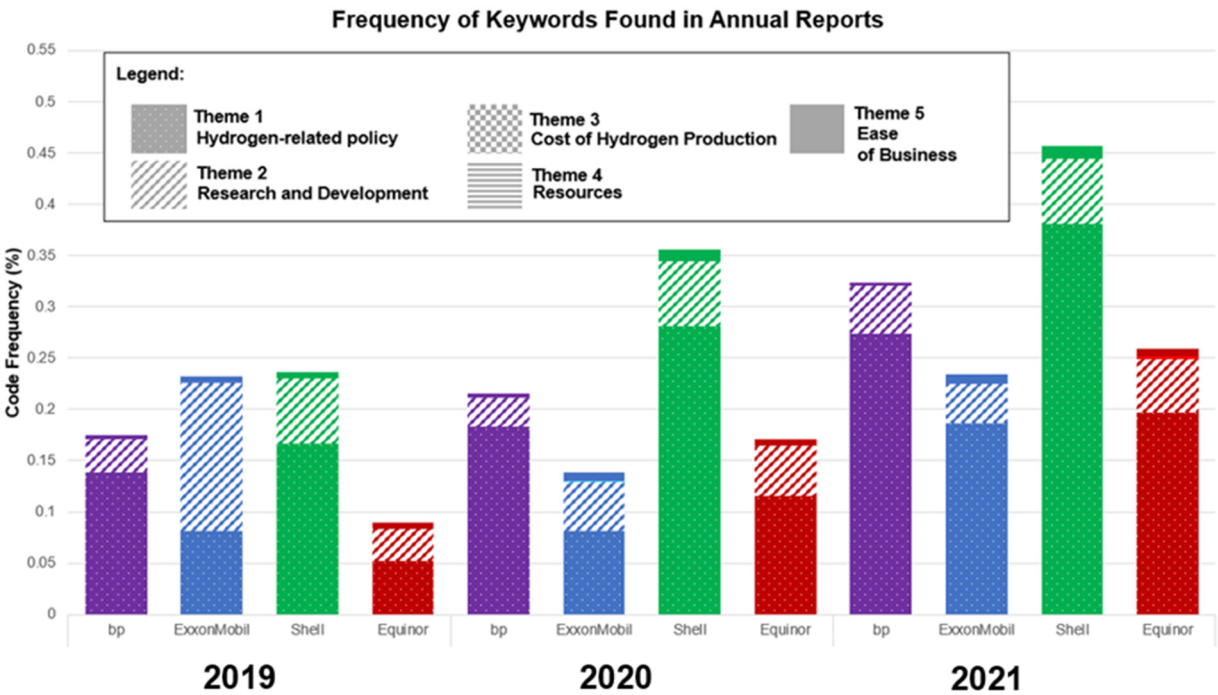
Themes	Sub-Themes	Indicators	Reference
Hydrogen Strategy policy	Progress towards 2030 goal	Does the company have a specific hydrogen target in its corporate objectives or strategic goals?	[10,52–54,67]
		Has the company announced the target for the hydrogen volume produced to support the national target?	
	Evidence-based policymaking	Does the company disclose any engagement with stakeholders and experts?	
	Climate change	Does the company affirm the need to shift towards a lower-carbon energy system to mitigate climate change?	
		Has the company announced that introducing hydrogen technology has reduced its CO_2 emissions?	
Research and Development	Decarbonization of the existing UK hydrogen economy	Has the company disclosed the remaining volume of hydrogen produced with fossil fuels?	[10,68]
	Breakdown of technology	Has the company provided the list of breakdown technologies? For example, is it an electrolysis approach or a fossil fuels approach?	
	Collaboration	Has the company collaborated with third parties, e.g., other companies or universities?	
	Patent	Has the company shared its research progress or patent for hydrogen technology?	
Cost of Hydrogen Production	Lower cost	Has the company disclosed the costs for hydrogen production?	[3,10,50,52]
		Has the company shared any initiatives or plans to reduce hydrogen production costs?	
Resources	Asset	Does the company provide information on the installed capacity for low-carbon hydrogen?	[8,10,39]
	End-to-end hydrogen system with a diverse range of users	Does the company have a target for hydrogen distribution to users?	
	Promote UK economic growth and opportunities	Has the company provided information on creating more 'green' jobs in the industry?	
Ease of Business	Increased awareness	Has the company illustrated initiatives to improve awareness about the transition?	[10,69,70]
	The readiness of the company to support the country's new plan	Has the company disclosed the ability to support the government?	

Source: Authors.

4. Results and Discussion

4.1. Findings from Code Frequency

Figure 7 shows the results for the code frequency of 19 principal codes with the sub-category codes that appeared in all the companies' annual reports from 2019 to 2021.



	2019				2020				2021			
Theme 1	0.14	0.08	0.17	0.05	0.18	0.08	0.28	0.12	0.27	0.19	0.38	0.20
Theme 2	0.03	0.14	0.06	0.03	0.03	0.05	0.06	0.05	0.05	0.04	0.06	0.05
Theme 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Theme 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Theme 5	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01

Figure 7. Frequency of keywords found in the annual report. Source: Authors.

From Figure 7, it can be seen that most companies show an increasing trend over the three years. The category 'hydrogen-related policy' is the most prominent of all five themes, followed by the group 'research and development'. This illustrates the companies' increasing focus on energy transition related to hydrogen policy and on improving their competencies in research in the technology sector. However, the companies could have scored better for Theme 4, i.e., the 'resources' category. This is probably because most projects are in the early phase and have yet to be commissioned as of the end of 2021. Therefore, companies tend to focus on highlighting the progress made in the initial phase rather than on the future of the operation of the installed hydrogen technology.

BP shows a steady increase over the study period, particularly in 2021, in the category of 'hydrogen-related policy', as shown in Figure 8. Some of the most common keywords in the reports that increased throughout the study period include 'hydrogen' (a massive increase from 2 to 76 mentions), 'net zero' (69 to 130), and 'low carbon' (82 to 213). This trend can also be seen in the highlighted messages in the Chief Executive Officer (CEO)'s letters. In 2020, the CEO, Bernard Looney, mentioned the reorientation from the Integrated Oil Company (IOC) to the Integrated Energy Company (IEC) in the future [71]. Furthermore, the company aims to use this new business model to reach net zero by 2050 or earlier, which aligns with the global climate target [61]. In 2020, the term 'green hydrogen' appeared, referring to the new project for green hydrogen production from renewable sources. It is predicted that it will be emphasized more in the following years as the company is only starting to venture into this opportunity in the country.

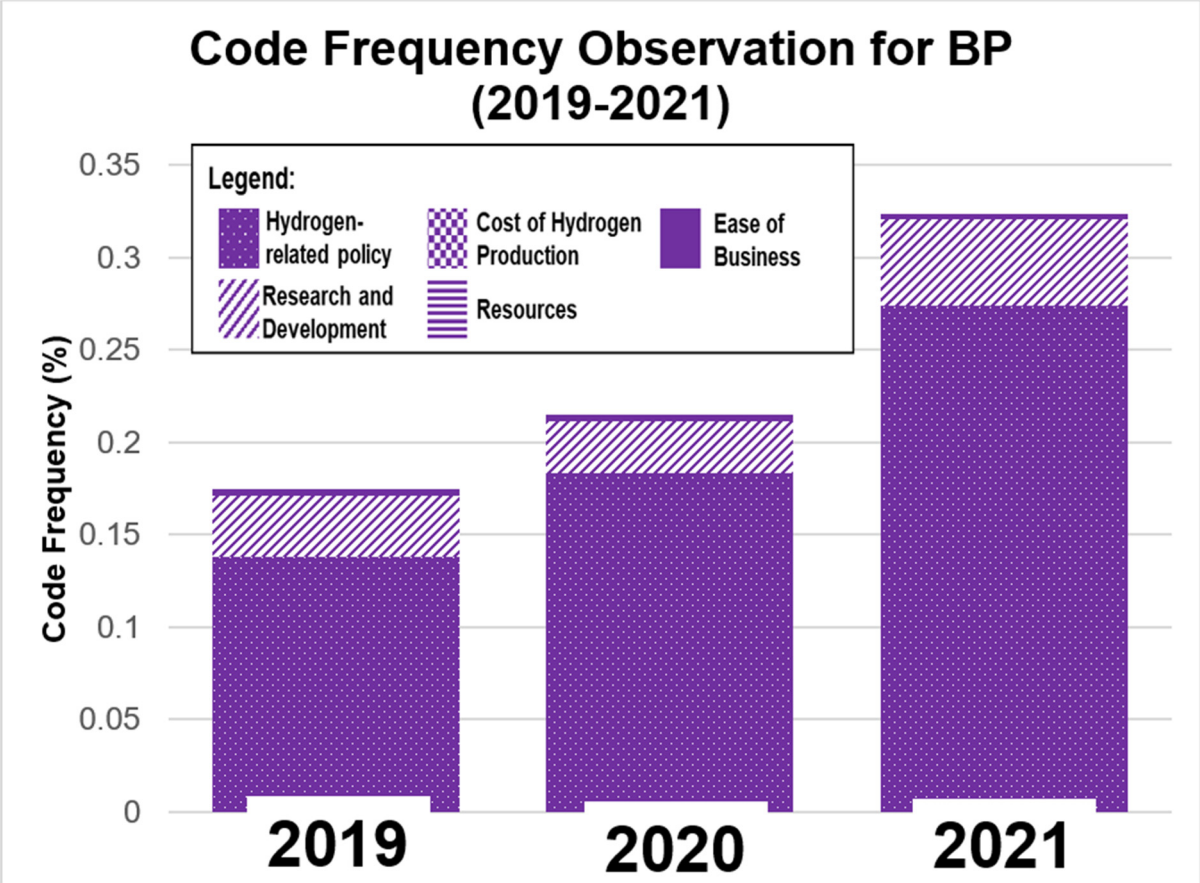


Figure 8. Observation of code frequency for BP. Source: Authors.

However, there was a slight drop in Theme 2 in 2020 as the company needed to disclose more about the 'collaboration' or 'partnership', leading to a low score in this category. This could be due to the long-term partnership mentioned in the previous year (2019) but not repeated the following year.

In contrast to BP, ExxonMobil (see Figure 9), considering its published annual report for 2019 and previous years, has only recently made the summary of its annual reports available to the public. This could affect the final code frequency calculations due to the simplified format of the 2019 report. However, from 2020 onwards, the company published a full format of the annual report on its official website, as did the other companies. The sudden drop in the overall score in 2020 resulted from the introduction of the new format of the full report. Moreover, the company gradually improved when more updates on the 'hydrogen-related policy' theme were discussed the following year, doubling the score (52 to 117 mentions). Like BP and other companies, a low frequency was noted for the topics 'cost of production' and 'resources', showing the company's lack of attention to these topics.

The results for Shell show high consistency compared to the other companies (see Figure 10). The company's goal of achieving net-zero energy has become an area of greater focus. The term 'energy transition' has become part of the company's main agenda. While ExxonMobil mentioned the term 'energy transition' only 51 times throughout the study period, Shell used it 163 times in 2019 alone, doubling it to 335 times in 2021. In 2019, the Chairman, Chad Holliday, pledged to promote hydrogen adoption in the company and the world, showing a high level of confidence and ambition from the company to continue working in the hydrogen technology field [72]. The missing points regarding the 'cost of hydrogen production' and 'resources' themes over the years remain a concern for the company.

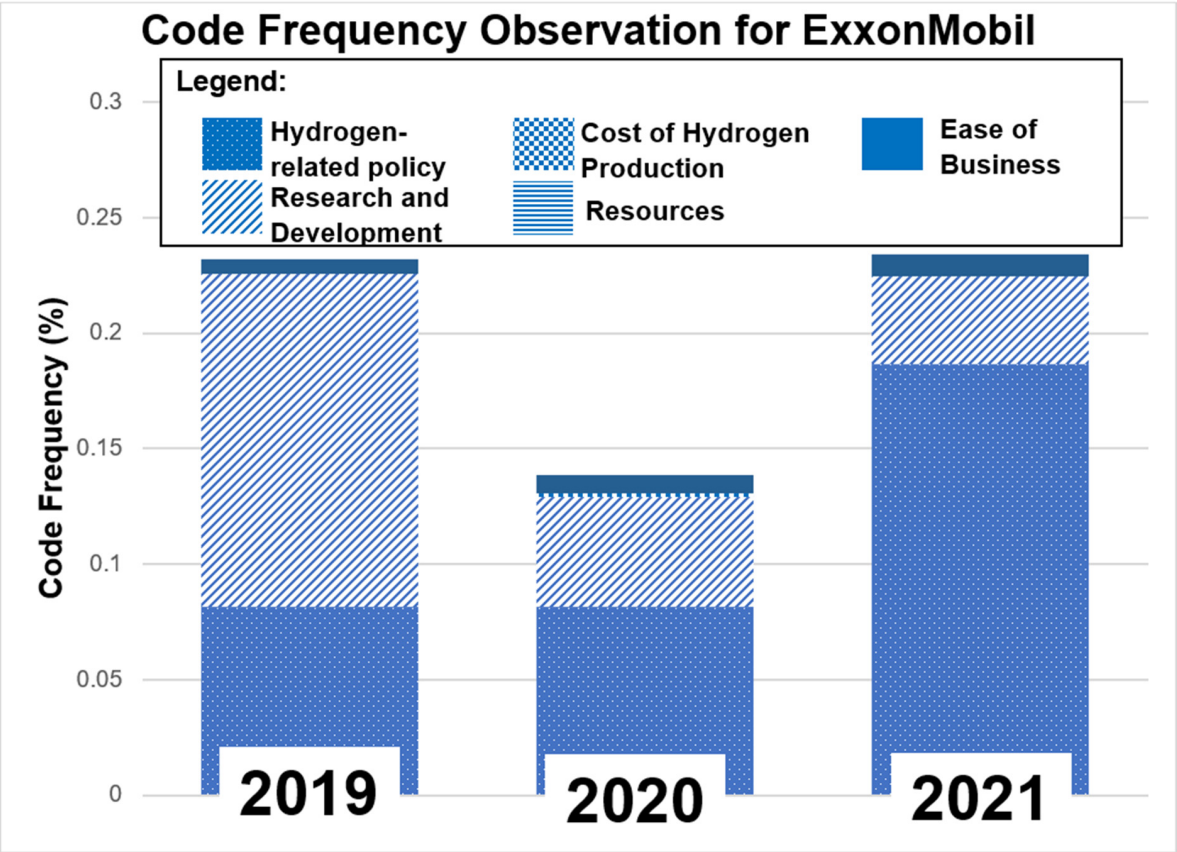


Figure 9. Observation of code frequency for ExxonMobil. Source: Authors.

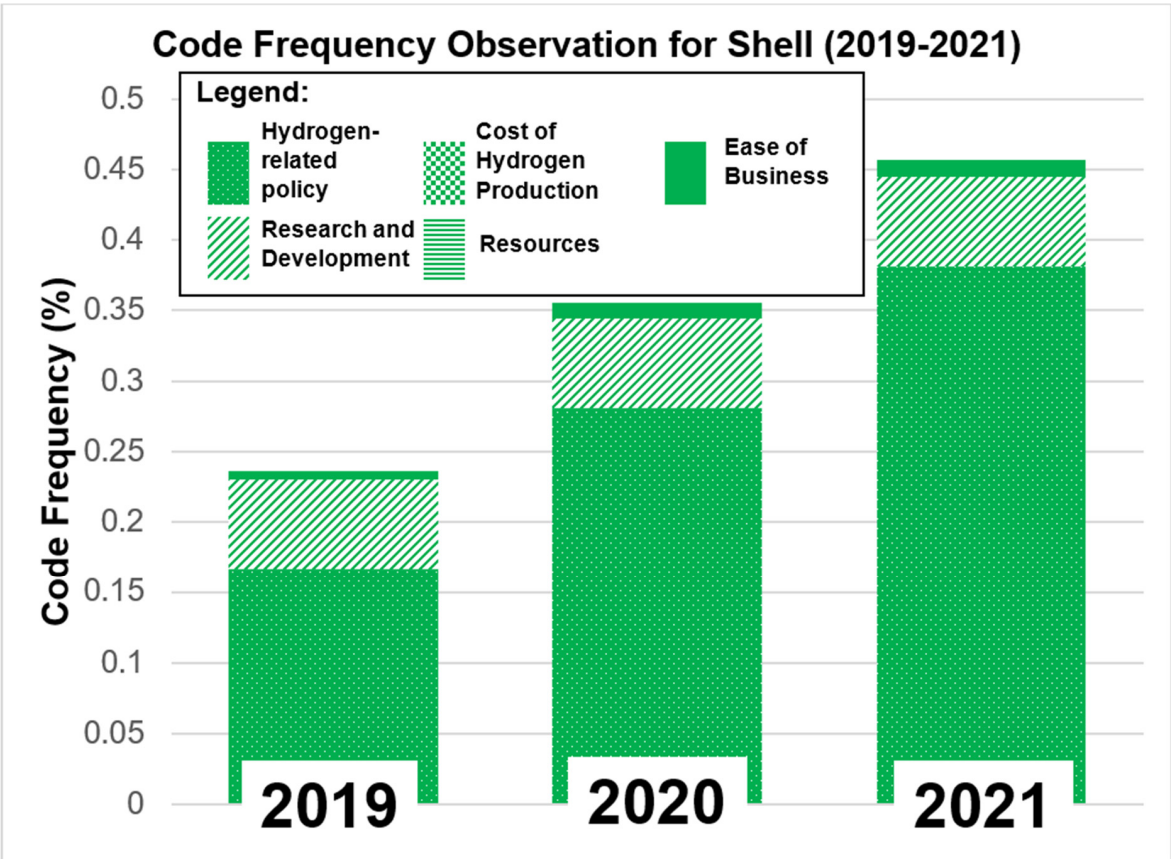


Figure 10. Observation of code frequency for Shell. Source: Authors.

As shown in Figure 11, the interpretation of Equinor's performance is interesting given that the company has the smallest number of employees compared to the other three major companies [61]. The company's transition to hydrogen was slow at first, with the appearance of one occurrence of 'net zero' in the entire 2019 annual report. From 2020 onwards, a clear trend emerged as the total frequency of codes related to the hydrogen roadmap increased steadily, resulting in a higher total number of code frequencies than ExxonMobil in 2021. The content of Theme 1, 'hydrogen-related policy', increased threefold, reflecting increased discussions and actions to implement and review the company's business strategy for this objective.

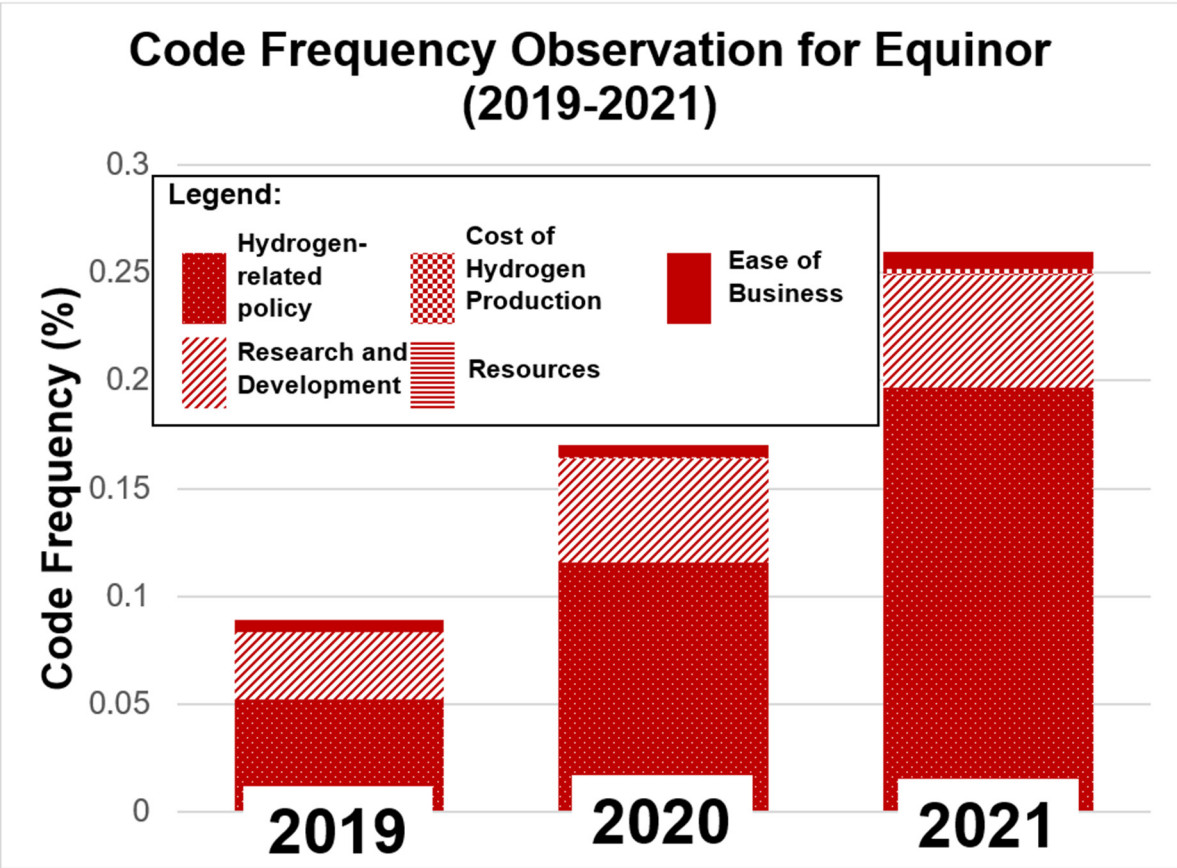


Figure 11. Observation of code frequency for Equinor. Source: Authors.

4.2. Findings from Strategy Management Analysis

Based on the code frequency analysis, this study assessed the progress of oil and gas companies in terms of their company's strategy management based on the indicators identified in the previous section in terms of achieving the hydrogen target in line with the country's vision. In total, 16 indicators were used to measure the progress of each company. Figure 12 shows the results based on a review of the annual and energy reports.

Based on the abovementioned strategic management analysis, there needs to be more discussion for all companies, with an average score of 4.75 for 2019. In the following years, there was a jump in the awareness of hydrogen technology as all companies significantly increased their contributions by discussing the transition in their official publications. This resulted in an average score of 9.50 for all companies in 2021. To discuss the results, each theme was examined individually across all companies to determine differences and similarities within the same topic.

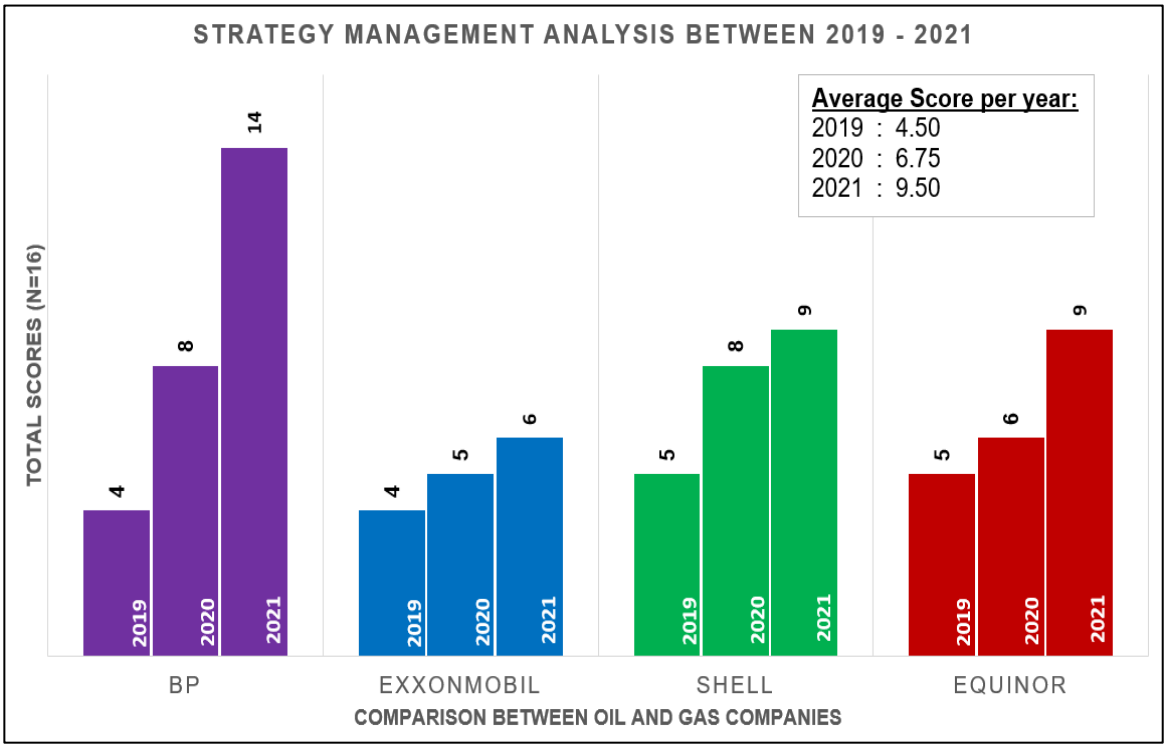


Figure 12. Results of the strategic management analysis for 2019–2021. Source: Authors.

4.2.1. Hydrogen-Related Policy

Table 8 shows the overall performance of Theme 1 throughout the study period. Five indicators of this theme were used to assess the companies' progress toward 2030 targets, including collaboration with relevant parties and their understanding of the need to tackle climate change.

Table 8. Scores for the theme 'hydrogen-related policy'.

Theme 1: Hydrogen-Related Policy			
Company	**2019**	**2020**	**2021**
BP	★★☆☆☆	★★★☆☆	★★★★★
ExxonMobil	★★☆☆☆	★★☆☆☆	★★★☆☆
Shell	★★☆☆☆	★★☆☆☆	★★★☆☆
Equinor	★★☆☆☆	★★★☆☆	★★★☆☆

Note: A black star indicates a score of "1" for each question. Source: Authors.

Achieving a low-carbon hydrogen production capacity of 10 GW by 2030 is the UK's national target [10]. This statement is not mentioned in any document on the target set by the UK government, except BP, which can only be found in the 2021 annual report. BP mentioned that the '30% of the UK's low-carbon hydrogen production' target will be achieved by 2030, a specific target the company wants to achieve for the country [61]. In the meantime, Equinor has announced an overall renewable energy production target that includes hydrogen and other clean energy sources.

Dialogue with key stakeholders is critical to present the ongoing project and understand the community's needs, particularly regarding hydrogen technology needs and policies. In Australia, development was halted as the project could not gain public confidence due to negative perceptions [73]. When reviewing all the reports, it was found that all the companies played their role in engaging stakeholders and experts in the field. For example, Shell became part of the Hydrogen Council to provide input on the role of hydrogen in energy transition [74]. In addition, all four companies are part of the Oil and Gas Climate Initiative [18], a pioneering group that leads discussions about climate change issues and solutions [75]. Membership in this group will enable all the companies to pursue a common goal of achieving net-zero emissions.

Setting a business target is essential for any organization [76]. The transition requires a change in the company's benchmarks. Based on the commitments of all companies to transition to a low-carbon energy system, there is strong evidence that a new business model plays a vital role in their primary strategy. ExxonMobil, for example, has introduced a new business structure of 'low-carbon solutions', which emphasizes the role of hydrogen as part of the company's focus [59]. Shell even advocated urgent action to tackle climate change for a better future [74].

Few companies disclosed calculations about carbon dioxide (CO_2) emissions reductions, one of the requirements of the UK Hydrogen Strategy document. As the projects are still under development, only emission reduction projections are included in the reports. Equinor has calculated that its blue hydrogen project can capture 90% of CO_2 emissions, while BP estimates a higher capture rate of CO_2 emissions (93–98%) with the same approach [62,77]. Recognizing the benefits of using hydrogen technology to reduce carbon emissions ensures that the project aligns with the national target.

Therefore, by analyzing the hydrogen-related policies and activities of the four big oil and gas companies, namely BP, Equinor, Shell, and ExxonMobil, the following can be learned about their respective advantages and prospects for developing and utilizing hydrogen:

BP: BP is committed to supplying 30% of the UK's production of low-carbon hydrogen by 2030. This sets a clear target date and quantity for that date, and regarding UK national hydrogen strategy targets, it is by far the most detailed. Advanced capabilities are further expressed in the field of carbon capture, with BP predicting to capture 93–98% CO_2 emissions in its blue hydrogen projects, hence making it the forerunner in meeting decarbonization targets.

Equinor: While Equinor has set wider renewable energy targets, the company has accomplished a considerable amount of work on hydrogen development, such as projecting the capture of 90% CO_2 emissions in its blue hydrogen projects. The approach taken by this company considers scalability and innovation; thus, there is a good chance for long-term leadership in hydrogen utilization if the company further builds on its renewable energy portfolio.

Shell: Shell's active participation in every large-scale global initiative has significantly demonstrated the company's interest in collaboration and innovation along value chains in the hydrogen sector. Thus, proactive action by Shell to tackle urgent climate change issues by taking additional steps to integrate hydrogen into the key Energy Transition Strategy places it in a competitive position within the global hydrogen energy landscape.

ExxonMobil: ExxonMobil has established a "low-carbon solutions" business unit, representing a focused move toward the transition to hydrogen, among other clean energy technologies. However, its specific contributions to hydrogen development in the UK appear less detailed compared to BP and Equinor, which may limit its near-term competitive advantage in this market.

It follows, however, that, with all the evidence considered, so far, the ambitions seem to be clearer for BP, and the goals are more ambitious when compared based on the UK Hydrogen Strategy. Nonetheless, Equinor fares better in the long term due to its general focus and scalability around renewable energy projects. Shell has a greater advantage regarding global partnership deals and advocacy, potentially making it a key player in framing hydrogen politics and technologies. Indeed, ExxonMobil proceeds with far-reaching structural changes but probably needs focused measures that would allow it to obtain the level of strategic clarity of both BP and Shell in the UK context.

4.2.2. Research and Development

Table 9 shows the company's performance under the research and development (R&D) theme. Four indicators in this category cover decarbonization initiatives, hydrogen technology breakdown, collaboration with others, and research and patent progress within three years.

Table 9. Scores for the theme 'research and development'.

Theme 2: Research and Development			
Company	**2019**	**2020**	**2021**
BP	★★☆☆☆	★★☆☆☆	★★★★★
ExxonMobil	★★☆☆☆	★★☆☆☆	★★☆☆☆
Shell	★★☆☆☆	★★★☆☆	★★★☆☆
Equinor	★★☆☆☆	★★☆☆☆	★★★★★

Note: A black star indicates a score of "1" for each question. Source: Authors.

Continuous research is essential for technological advancement. A combination of research and government policy can overcome all technological barriers, especially in larger-scale production [78]. Since 2019, all major companies have achieved similar scores, where improving collaboration and research activities are part of the company's focus on low-carbon solutions. This has been evident across all publications throughout the study period and reflects the need for continuous R&D to grow in the hydrogen business.

In 2020, Shell was the only company that disclosed the remaining hydrogen produced from the fossil fuels approach [79]. The 55% reduction from current operations equates to 45 million tons per annum (MTPA) instead of 100 MTPA, demonstrating the company's clear focus on a cleaner alternative to hydrogen production. In 2021, BP and Equinor met all the requirements under this theme, surpassing the other companies.

Based on the breakdown of technology and projections by both BP and Equinor, green hydrogen will be under significant production by 2050 [61,62,80]. This is aligned with the most sustainable approach mentioned in the literature [25,26,80]. Hence, all companies should have the same target by prioritizing green hydrogen production by 2050 [47].

This development also evidences how the R&D efforts of both BP and Equinor align with the goal of the UK Hydrogen Strategy, i.e., 10 GW of low-carbon hydrogen capacity by 2030, and demonstrates their commitment to decarbonizing both the UK and the world economy.

Despite notable advances, formidable barriers feature high production costs of green hydrogen and extensive and strong infrastructure development, which demands further investment and innovation. These R&D activities have great carbon emissions reduction

potential, but at the same time, they create an avenue for companies like BP and Equinor to seize market opportunities currently unfolding from renewable energy exports and sustainable technologies.

4.2.3. Cost of Hydrogen Production

This section involves the analysis and discussion of the third theme, i.e., the cost of hydrogen production, as shown in Table 10. The indicators listed in this category include the need for the company to contribute to the production costs and the plan to reduce future costs once the project has started.

Table 10. Scores for the theme 'cost of hydrogen production'.

Theme 3: Cost of Hydrogen Production			
Company	**2019**	**2020**	**2021**
BP	☆☆	★☆	★☆
ExxonMobil	☆☆	☆☆	☆☆
Shell	☆☆	☆☆	☆☆
Equinor	☆☆	☆☆	★☆

Note: A black star indicates a score of "1" for each question. Source: Authors.

Concern about the higher cost of using renewable energy, mainly green hydrogen, compared to traditional fossil fuels was cited as one of the biggest challenges for producers [80,81]. This limitation was also confirmed by the fact that most reports provided little information on the production costs of this technology. In contrast, BP sees the potential for hydrogen to be more competitive against other fuels from 2030 onwards once production has been optimized in conjunction with more stringent policies [62].

The government has taken several initiatives to support hydrogen projects at the commercial level. This is evidenced by Equinor's ability to share success stories about its hydrogen projects that have been accepted for funding through the Industrial Strategy Challenge Fund (IS) policymaker, who is aware of the financial challenges and has initiated these support measures to assist the industry in the smooth implementation of hydrogen transition [62].

Hydrogen production cost is one of the most critical challenges, especially for green hydrogen, which currently is more expensive than conventional fossil fuel. This concern is underlined by the variable scores of companies on cost management and future planning, as shown in Table 10. Green hydrogen can compete with conventional fuels in the long run, once its production scales up and policies become tighter, which was also emphasized in the BP's projections for greater competitiveness in 2030.

Overcoming financial barriers requires governmental support. Innovative initiatives like the Industrial Strategy Challenge Fund have granted financial opportunities to companies such as Equinor to fund hydrogen projects that have been delivered successfully. These initiatives set examples of how cooperation between industry and policymakers contributes toward cost reduction and the transition to low-carbon energy.

Most companies' reports did not provide detailed information on the cost of hydrogen production; this gap is an indication of the need for improvement in transparency and consistency. More disclosure about this topic would enhance the level of understanding

and accountability for the steps that companies are taking to ensure cost reduction in the production of hydrogen.

4.2.4. Resources

The fourth theme covers the capacity of the hydrogen project, the hydrogen distribution plan, and support for employment opportunities in the UK. Table 11 illustrates the results of these three indicators for all companies from 2019 to 2021.

Table 11. Scores for theme 'resources'.

Theme 4: Resources			
Company	**2019**	**2020**	**2021**
BP	★☆☆	★★☆	★★☆
ExxonMobil	☆☆☆	☆☆☆	☆☆☆
Shell	☆☆☆	★★☆	★★☆
Equinor	★☆☆	☆☆☆	☆☆☆

Note: A black star indicates a score of "1" for each question. Source: Authors.

This theme plays a role in understanding the resource readiness of all companies. The government has specified that low-carbon hydrogen capacity must be measured as a strategy metric [10]. However, this measure has yet to be reported by all companies, mainly due to the project's progress, which is still under development.

Regarding the projection of potential users, BP, Shell, and Equinor have targeted the transport industry as the primary hydrogen users once the projects are operational [78,82,83]. In addition, the second user of focus is the construction industry. As shown in [38], both transportation and building heating can benefit from hydrogen technology.

In addition, the country's economic growth is linked to the opportunities it provides by creating jobs. The 'green job' indicator is highlighted in the Hydrogen Strategy document to ensure that companies can benefit from highly skilled workers in the hydrogen energy field. However, these keywords and priorities are not mentioned in any document. This shows that the requirement to employ more talent in this field has yet to be met in the first years of implementation of the hydrogen project.

The theme also describes how hydrogen can contribute to the economy through jobs created in the UK, especially high-skill "green jobs". While this is expected to create jobs since the beginning of its implementation, it is not explicitly indicated in any of the company reports. Therefore, this gap points to the need for increased industry focus on workforce development in ways that align with the national strategy to ensure that hydrogen projects contribute fully toward economic growth and talent development.

4.2.5. Ease of Business

The final theme measures the ease of business in achieving awareness about the transition and willingness to support the company's new plan. Table 12 summarizes the results for two indicators in this category.

Table 12. Scores for theme 'ease of business'.

Theme 5: Ease of Business			
Company	**2019**	**2020**	**2021**
BP	☆☆	☆☆	★★
ExxonMobil	☆☆	★☆	★☆
Shell	★☆	★☆	★☆
Equinor	☆☆	★☆	★☆

Note: A black star indicates a score of "1" for each question. Source: Authors.

Community acceptance is one of the most essential measures to ensure smooth project implementation. There is a strong link between awareness and practice, especially in this new field of renewable energy [83]. Most awareness initiatives have been reported, but the topics covered vary widely in other areas. For example, cybersecurity and diversity are conducted by Shell as part of its annual activities [74]. On the other hand, Equinor has undertaken initiatives through a dedicated group called Exploration and Production International (EPI) to promote environmental awareness in society [83–86]. Through internal and external awareness programs, these companies can encourage people to adopt hydrogen energy so that the country can reap the associated benefits.

Regarding readiness to support the country's new strategic plan, Shell was the first to inform the UK government of its commitment to address carbon emissions in its reports [74], followed by other companies in 2020 and 2021.

More substantial adoption of this technology is supported by the activities that align with the decision. Smooth implementation in hydrogen projects largely depends on public buy-in. In this respect, community buy-in bridges the awareness and practice gap in renewable energy. Companies have tried different ways to build community awareness, as follows:

- Shell incorporates other topics, such as cybersecurity and diversity, into its annual activities.
- Equinor uses the EPI group to increase ecological awareness within society.

These efforts have been put in place to prepare the public and create a mindset that will help introduce hydrogen technologies, thus promoting the transition to renewable energy.

Shell led a written commitment to address carbon emissions in its corporate reports in 2019, followed by other companies in 2020 and 2021. Written commitment, if combined with consistent activities, shows preparedness for supporting the UK strategic hydrogen plan. These initiatives not only enhance the credibility of the company but also pave the way for multi-stakeholder collaboration at all levels, namely, company, government, and citizen.

4.3. Summary of Overall Outcome

To summarize the progress of oil and gas companies in the transition to the hydrogen roadmap in the UK, Figure 13 illustrates the companies' performance against the indicators used in this study.

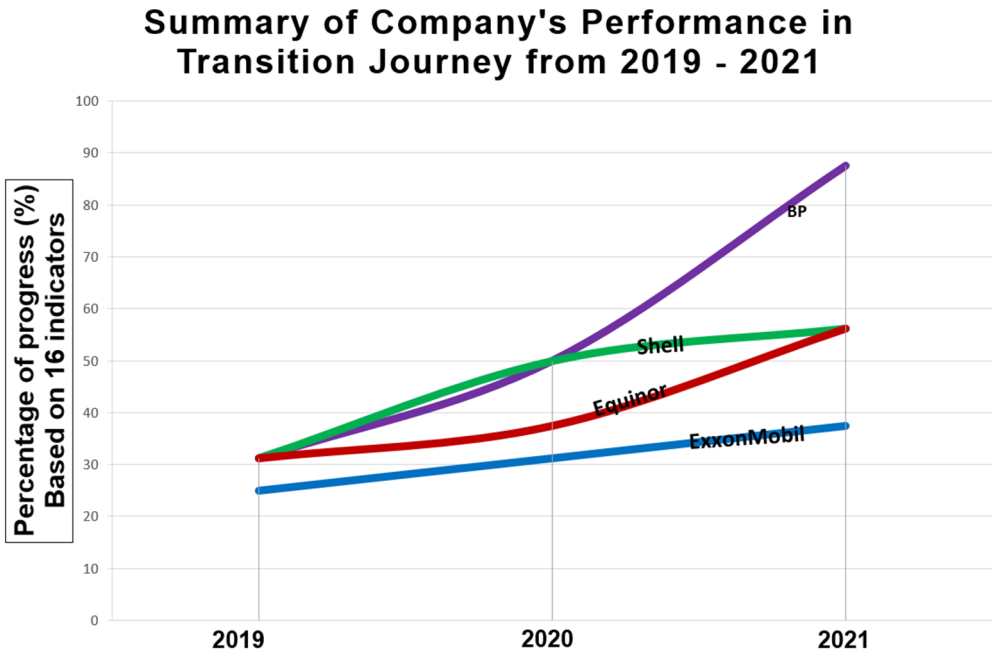


Figure 13. Summary of companies' performance in the transition (2019–2021). Source: Authors.

The results show significant growth for all indicators over the study period. BP is the most competitive company in the UK hydrogen market among the four oil and gas giants. The company achieved a high growth rate, boosting strategic indicator compliance from 30% to nearly 90% and making targeted promises such as producing 30% of the UK's low-carbon hydrogen output by 2030. Shell was in second place, with high consistency in delivery and a broad focus on energy transition. Despite being the smallest of the four companies, Equinor has been progressing at a fast pace, outpacing ExxonMobil by 2021 in overall hydrogen efforts. ExxonMobil, in particular, has made less progress and needs strategic direction and more transparent reporting.

Although the report reflects the company's attention and actions on this energy transition, there is still room for improvement, particularly regarding the theme of 'cost of hydrogen production' and 'resources'. The overall percentage is still low, which might be attributed to the early phase or introduction of the new hydrogen strategy document. All five themes need equal attention and resolution to ensure that the overall aspects can be met for the transition to smooth implementation of all UK hydrogen projects in the future. All companies have highlighted their readiness and commitment towards the global goal of net-zero emissions by 2050 [46].

4.3.1. Relevance for Practitioners

This study equips practitioners within the oil and gas sector with actionable insights to strategically align with the UK Hydrogen Strategy and wade through the complex dynamics of the energy transition. This research proves that early adoption secures a competitive advantage in hydrogen technologies by analyzing best practices such as the commitment by BP to 30% of the UK's low-carbon hydrogen by 2030. These findings will help the practitioners review their strategies based on policy objectives and reduce the risks of regulatory non-compliance. The emphasis on stakeholder engagement also underlines the need to develop collaborative networks, which will expedite project implementation and attract public and governmental support.

Operationally, this also provides a pragmatic framework through which the major barriers to the adoption of hydrogen cost and infrastructure can be overcome. The deep analysis of cost reduction strategies through the utilization of government incentives and

scalable models of production provides practitioners with a route toward the financial viability of investments in hydrogen. Resource readiness, from training a workforce to infrastructure capacity, is underlined as another important enabler for the successful execution of such projects. Ultimately, it is only the alignment of internal capabilities in the direction of the hydrogen roadmap that ensures much smoother transitions, with added capitalization from evolving market opportunities.

This transition also presents an opportunity for practitioners to redefine their competitive positioning in the low-carbon economy. Based on some key findings, such as Equinor's proactive decarbonization strategy and Shell's leading international collaboration, firms can enhance their strategic focus and operational preparedness related to hydrogen technologies. These demonstrate how the integration of hydrogen technologies into core business priorities, from market leadership to long-term sustainability, is of the utmost importance. Consequently, this study not only helps companies comply with national and global climate targets but also catalyzes innovation and resilience, and thus, their relevance in an energy landscape that is seeing a transformation at unprecedented speed.

4.3.2. Theoretical Contributions

This paper, through critical content examination combined with relevant strategic management indicators of this progress, offers a strong theoretical approach to the assessment of corporate progress regarding the adoption of hydrogen technology. The segmentation of key performance indicators relates to themes such as policies that relate to hydrogen R&D, cost, resource availability, and ease of business, in which research provides a replicable model regarding the assessment of alignments prevalent in the corporation strategies versus national priorities regarding decarbonization. Whereas most earlier approaches focused only on policy objectives or on corporate disclosures, this integrated framework allows a comprehensive assessment of industry readiness. Because the model has wide applicability across sectors and geographies, it would serve as a useful tool for researchers in the areas of policy, strategy, and sustainability, which will further the theoretical understanding of energy transitions.

Empirically, this study underlines how the oil and gas sector aligns with government-mandated hydrogen strategies, which is a significant gap in the literature. Although prior studies have addressed hydrogen adoption in various ways, they have focused on technical, economic, or policy dimensions without strategic responses at the corporate level. The latter, therefore, presents a variety of firm actions in terms of ambitiousness and implementation, thereby reflecting different organizational capabilities and levels of risk tolerance. This nuanced understanding will bridge the gap in policy design and corporate execution, adding to the greater discourse of organizational adaptation within energy transitions and their regulatory pressures.

This research finally advances the theoretical discourse on the integration of policy and strategy by illustrating how regulatory frameworks can drive corporate innovation and competitiveness. This study demonstrates how policies serve as both drivers and constraints in the course of sustainability through an analysis of corporate disclosures with regard to UK Hydrogen Strategy targets; for example, BP is leading the way in green hydrogen production, while Equinor has high CO_2 capture rates. This dynamic interplay between policy and corporate action underlines the importance of aligning regulatory expectations with organizational capabilities and provides a basis for future research on policy-driven industrial transformations. The results of this study contribute to an improved understanding of how national and corporate strategies can be aligned in view of accelerated progress toward global climate goals.

4.3.3. Relevance of Hydrogen Transition for Supply Chains and Practice

The transition to hydrogen provisionally challenges and simultaneously creates new opportunities that demand ingenious frameworks for supply chain management [87,88]. Hydrogen supply chains are intrinsically complex, considering the diversity resulting from the various production methods applied, the storage requirements, the transportation modes, and many other variables influenced by the variation in technological maturity and location [87,88]. For example, although decentralized hydrogen production by renewable sources of energy, such as solar or wind, may reduce transport costs, small-scale operations result in higher investment costs per unit. On the other hand, centralized production, which can be combined with a large facility like a hydropower plant, benefits from economies of scale but requires more complex logistics for long-distance distribution. It thus draws on a duality that exists in dynamic supply chain strategies to make those trade-offs while considering operational efficiencies and sustainability optimization.

For practitioners, in particular, this adds complexity to storage and distribution, noting that hydrogen plays a dual role, i.e., as a fuel and an energy carrier [87,88]. The low density of hydrogen allows for hydrogen storage technologies like liquid hydrogen tanks, compressed gas pipelines, and cryogenic systems, but they all have different costs and scalability [87,88]. Hydrogen storage systems, when integrated into renewable generation resources, can potentially offer a route to provide surplus electricity during periods of low demand; while there is a lower need to curtail renewable resources, this could be used to enhance grid reliability [87]. Nevertheless, there are some hurdles associated with such options, e.g., energy losses throughout storage and transportation, major capital investment, etc. These are trade-offs that practitioners must carefully consider in order to find scalable and cost-effective solutions that meet operational goals and contribute to broader sustainability objectives [87,88].

The transition to hydrogen also underlines the crucial interplay between supply chain practices and regulatory frameworks, where firms have to adapt to dynamic policy landscapes [87,88]. Hydrogen strategies, such as the European Union's Hydrogen Roadmap, call for strict adherence to green hydrogen certification standards, regulations on cross-border trade, and infrastructure development. These demands place the supply chain professional at the center of navigating policy complexity while cultivating collaborative ecosystems to drive innovation and adoption [87,88]. Hydrogen thus has immense potential to transform industrial decarbonization across its applications: transport, heavy manufacturing, and chemicals [89,90]. Companies who proactively invest in its infrastructure and align their business with policy directions set their businesses up for leadership status in the emerging low-carbon economy and strike a balance between hard environmental imperatives and economic opportunities.

5. Conclusions

This study sheds light on the progress made by oil and gas companies in the transition towards hydrogen energy under the UK's ambitious hydrogen program. From our examination of corporate reporting and strategic initiatives in 2019–2021, we have observed a few significant trends:

First, we have seen a notable ramping up of company involvement in hydrogen technology, with considerable variance in strategy and progress. The leader is BP, which has achieved complete strategic alignment by growing their indicator compliance from 30% to nearly 90% over the study period. They are directly committed to generating 30% of the UK's low-carbon hydrogen by 2030. This is an advantage compared to competitors and could indicate that early leadership in hydrogen will bring competitive advantages as the market matures.

Second, the report exposes critical information gaps in industry reporting and strategy, especially regarding production costs and resource management. As this is a common issue across all the companies studied, this suggests it is not a reporting oversight. Still, it probably indicates fundamental strategic uncertainty around cost models and resource needs in this industry. This calls for more apparent industry and government support in these fields to ease the transition.

Third, greater attention has been paid to hydrogen policies and R&D. The different levels of engagement and investment indicate different risk tolerances and strategic stances toward the energy transition. Shell's steady but slow pace contrasts with Equinor's fast lead and demonstrates the various ways companies are positioning themselves in the new hydrogen economy.

These findings are relevant to policymakers and the industry:

1. The government might need to offer more focused direction and guidance on cost structures and resource planning to enable companies to fill such gaps in their transition planning.
2. Leaders in the industry could adopt more open reporting on hydrogen projects, following BP's comprehensive approach as a potential model.
3. Enterprises behind the hydrogen development curve may have to ramp up their transition efforts to stay ahead as the market evolves.

This study also suggests several areas that need further research:

- In-depth examination of the commercial potential of different forms of hydrogen production in the UK.
- Evaluation of skills and workforce development requirements for hydrogen transition.
- Exploration of supply chain readiness and infrastructure requirements.

While the UK's oil and gas sector has taken a promising step in hydrogen adoption, much more work is needed to meet the government's 10 GW target by 2030. This disparate pace and commitment of key players suggest that the industry is only in the early phases of this process. There is room for companies to reinforce their leadership by planning and reporting hydrogen projects in more detail.

While annual and energy reports are a good source of data for the analysis of the performance of companies, they cannot represent the full spectrum of the company's activities, especially in the energy field. Companies usually do not disclose all information in these reports due to competitive reasons or confidentiality or because the data are considered non-material or are not required by regulations. As such, these reports may not provide a comprehensive view of the company's energy-related operations, especially those outside financial performance or regulatory compliance. To gain a complete understanding of this, a lot of those data require complementary internal documents, interviews with company personnel, specialized reports, or access to industry databases, which are considered a challenge in the current study. This information can provide more detail about the data available in annual and energy reports. In other words, although annual and energy reports are relevant and valid sources, they may not be comprehensive enough to fully encompass all the energy-related activities a company engages in. Consequently, such restricted data may lead to an incomplete research scope and limit the results.

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