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Research article

Emerging hydrogen spot indices: Price taker or maker?

Chaewon Kim [a,*], Scott M.R. Mahadeo [b], Keiron P. Roberts [c], Christopher R. Jones [d]

[a] School of Accounting, Economics and Finance, University of Portsmouth, UK
[b] Department of Economics, University of Reading, UK
[c] School of Civil Engineering and Surveying, University of Portsmouth, UK
[d] School of Psychology, Sport and Health Sciences, University of Portsmouth, UK

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ABSTRACT

Hydrogen is critical for decarbonisation in energy and hard-to-abate industries, such as refining, steel, and chemical production. The hydrogen energy transition requires systemic changes, including market and trade developments. Academic research has largely overlooked the hydrogen spot trading market and pricing mechanisms, despite their crucial role in mitigating price volatility, managing supply risks, optimising resource allocation, and promoting investments to accelerate the low-carbon hydrogen transition. We critically evaluate commonalities and differences of the key hydrogen spot indices and investigate whether they are market demand-driven, self-regulating, transparent, reliable, and consistent. We apply thematic content analysis to examine the hydrogen spot pricing methodology guides of two major price reporting agencies: Argus and S&P Global. We find that both hydrogen spot indices adopt a cost-based pricing mechanism and method, which are not market demand-driven and fail to capture customer demand and willingness-to-pay. Both indices rely on *ex ante* static features of cost structures, which are not self-regulating but are influenced by policy and subsidy. These pricing mechanisms and methods lack transparency, reliability, and consistency. We provide a novel framework for understanding key features, similarities, and differences of major hydrogen spot price indices, which serve as a departure point for future research directions.

1. Introduction

Amid increasing demand for decarbonisation, hydrogen has become a key element for reducing emissions from hard-to-abate industries like oil refining, steel manufacturing, aviation, shipping, and chemical production (IEA, 2024). Hydrogen can act as an energy vector, produced from both fossil fuels and renewable sources and then converted into power, heat, or other energy carriers, thereby playing a crucial role in future energy system integration (Sharma et al., 2023). According to the International Energy Agency's Net Zero Emissions scenario, global hydrogen demand is projected to rise from 100 Mtpa (million tonnes per annum) in 2024 to 150 Mtpa by 2030. However, the production of low-emission hydrogen - generated from renewable sources or fossil fuels equipped with carbon capture, utilisation, and storage (CCUS) - remained below 1 Mtpa in 2023. This is far from the 65 Mtpa needed by 2030 to achieve net-zero targets (IEA, 2024). To bridge the wide gap between current demand and future requirements, especially for low-emission hydrogen, creating a well-functioning spot trading market is essential. Spot trading can promote efficient resource allocation, attract investment and innovation, support hedging and risk management, stimulate international trade, and reduce reliance on government subsidies, while also strengthening risk management and improving the design of contracts (Geman, 2005). In addition, it can foster the transition to a low-carbon energy system as a substitute for fossil fuels and play a crucial role in enabling the commercial use of hydrogen to ensure access to clean, affordable energy, in line with the United Nations' Sustainable Development Goal 7[1] (United Nations, 2025 and Sharma et al., 2023). Indeed, hydrogen trading has the potential to play a pivotal role in the sustainable, secure, and affordable energy transition (IEA, 2024). A well-functioning trading system is vital for the hydrogen sector to prosper based on a market demand-driven system, rather than being reliant on policy and subsidy (Kantamaneni and Asi, 2023). Creating a competitive and efficient self-regulating hydrogen market will deliver Levelised Cost of Hydrogen (LCOH) reduction, stimulating the

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* Corresponding author. information. School of Accounting, Economics and Finance, Portsmouth Business School, University of Portsmouth, Portland Building, Portland Street, Portsmouth PO1 3AH T, UK.

E-mail addresses: chaewon.kim@myport.ac.uk, up2289777@myport.ac.uk (C. Kim).

[1] See https://sdgs.un.org/goals/goal7.

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substitution of fossil fuel-based hydrogen with green hydrogen (He et al., 2025), and achieving economies of scale, and various stakeholder participation, such as investors, producers, and end-users. A transparent, reliable, and consistent spot pricing mechanism is a precursor for establishing a well-functioning spot trading market, particularly for emerging and immature markets like hydrogen. In addition, the hydrogen energy transition requires systemic changes not only in technology, infrastructure, institutions, supply chains, industry structure, policy, but also market and trading schemes, as it is a long-term socio-technical transition (McDowall, 2012).

In the absence of a *transparent* spot pricing mechanism, defined as ‘openness and clarity of information and price discovery processes’, market participants could fail to make the optimal decisions in association with production, storage, and consumption (Geman, 2005). It could also lead to pricing information asymmetry between incumbents and newcomers, hindering the creation of adequate spot liquidity. A lack of *reliability* in the spot pricing mechanism, defined as ‘accuracy and dependability of the pricing mechanism’, could result in price manipulation or market distortion, which do not reflect real-market supply and demand dynamics (Pirrong, 2017). A lack of reliability could undermine investor confidence, and reduce capital investment and technology innovation (Horobet, 2024). A failure to have a *consistent* spot pricing system, defined as ‘uniformity and predictability of pricing’, prevents producers and end-users from comprehending price movement and predicting future prices, which hampers hedging and risk management against price volatility and uncertainties. High-quality information from key indicators promotes trust among investors and in risk management (Kirithiga et al., 2018). Roll (1978) highlights that different benchmarks can yield different rankings of “skill” in the stock market (i.e., making profits and mitigating risks), which can be applied to commodity spot prices. A poorly constructed and inappropriately represented benchmark could lead to incorrect pricing signals, misinterpretation of market dynamics, and misleading decisions.

Despite the critical importance of the transparent, reliable, and consistent spot pricing mechanism, especially in the emerging hydrogen spot trading market, little academic and empirical research has been conducted into the concept so far. While the dynamics of electricity market pricing have been analysed (Pal et al., 2010), and the importance of a robust spot trading system as a driver of market-based demand has been emphasised (Kantamaneni and Asi, 2023), these were without detailed attention to specific commodity pricing mechanisms. Furthermore, limited research has examined the role of Price Reporting Agencies (PRAs), which report benchmark price assessments for physical and some derivatives markets at distinct points in time (International Organization of Securities Commissions, 2012). These benchmarks are widely used in spot market transactions and long-term contracts, and they significantly influence the pricing of futures and forwards (ICE, n.d.). In this regard, in 2011, the Group of 20 (G20) assigned the International Organization of Securities Commissions (IOSCO) to prepare PRA reporting principles to address selective reporting, opacity, and variations in assessment methodologies of oil benchmark prices by mid-2012 (IOSCO, 2012). Despite certain PRAs going through IOSCO-assured auditing regularly since then, the detailed pricing mechanisms and methods remain in a grey area with limited academic attention, even more than a decade later.

Recognizing the key features of energy and commodity spot pricing mechanisms, and understanding the similarities and differences among various PRAs, is essential. Spot prices in these markets have cascading effects on energy security and affordability, extending far beyond their role in market creation. It is especially true for the emerging spot trading market, such as liquefied natural gas and hydrogen. For example, the global natural gas market shifted from a long-term bilateral contractual market towards a spot trading market driven by the US Shale Gas revolution (mid-2000s), raising spot liquidities, and COVID-19 (2020) and the Russia-Ukraine war (2022), which spurred spot LNG demand amid disrupted pipeline gas supplies. During the energy crisis, when the spot LNG prices hit a historic high in March 2022 (Bloomberg, 2022), several trading firms diverted cargoes to more profitable countries based on the higher spot prices, instead of their original destination. As a result, a country like Pakistan resulted in energy poverty due to the cancelled LNG shipments, which were made via long-term contracts at lower price in the past (Bloomberg, 2023). The experience of the LNG spot market showcases the importance of monitoring energy and commodities spot pricing mechanisms and methods to prevent inefficient resource allocations. Given the overlapping supply chains and the infancy of such markets, hydrogen spot trading could potentially take a similar trajectory as the LNG market showcased over the last few decades. Hence, our study seeks to deliver timely insights into the critical evaluation of hydrogen spot pricing mechanisms and methods. In particular, our analysis can help regulators, producers, traders, and consumers better understand and assess the transparency, reliability, and consistency of hydrogen spot pricing dynamics. This understanding is crucial to prevent under-representation, manipulation, and information asymmetry, which can hamper the effective creation and uptake of low-carbon hydrogen markets.

In this study, we aim to comprehensively evaluate and compare the key features of major hydrogen spot price indices. In doing so, we explore the similarities and differences, and the competitive advantages of these hydrogen spot pricing mechanisms. We ultimately seek to provide a fundamental understanding of hydrogen spot pricing via the systematic classification and analysis of these indices. Specifically, we address the following research questions.

RQ1. What are the key features of major hydrogen spot price indices?
RQ2. In what ways are hydrogen spot price indices similar, and how do they differ?

To answer these questions, we employ thematic content analysis of the hydrogen spot pricing methodologies used by two major PRAs: Argus and S&P Global Platts. Through a three-phase coding process that examines the granular features of each index, this study provides new insights into the mechanisms and methods of hydrogen spot pricing.

2. Literature review

There is limited literature that directly addresses our research questions. However, we identify three strands of literature based on a narrative review of the relevant literature: hydrogen markets, commodity pricing, and benchmarking and indices.

Many studies have explored the hydrogen market, focusing on Levelised Cost of Hydrogen (LCOH) perspectives. For instance, Shafiee and Schrag (2024) conduct LCOH calculations incorporating storage and distribution costs. They found that even if production costs reduce to US $2/kg hydrogen equivalent, high storage and distribution costs will prevent hydrogen from becoming widespread. Furthermore, George et al. (2022) addressed the limited opportunities of green hydrogen with LCOH analysis. However, they highlighted the necessity of government support, as the production of green hydrogen remains more expensive than blue hydrogen, even assuming low electricity and high gas prices. Additionally, le Duigou et al. (2013) concluded that hydrogen production costs from large-scale Steam Methane Reforming (SMR) are lower than low-emission hydrogen generation via large- and small-scale electrolysis.

In the literature on commodity pricing, a large amount is around the financialization of commodities, driven by growing investment by finance professionals or speculators (Cheng and Xiong, 2014). Most literature on commodity pricing focused on volatility, correlation, and price shock, with few studies investigating spot commodity pricing mechanisms and methods, which are within the scope of the current study. Existing literature on pricing mechanisms and methods offers a range of perspectives, though few directly address specific commodity spot pricing. While the dynamics of electricity market pricing under market power have been analysed (Pal et al., 2010), the focus was not extended to commodity markets. Sun et al. (2025) explored how carbon pricing mechanisms affect the cost, supply, and investment in lithium, nickel, and cobalt and alerted that uncertain and volatile pricing can hinder cost forecasting and long-term investment, although they did not study spot hydrogen pricing mechanisms. The importance of a robust spot trading system as a driver of market-based demand, rather than policy or subsidy dependency, has been emphasised (Kantamaneni and Asi, 2023), but without detailed attention to pricing mechanisms. Dynamic pricing, where prices adjust according to supply, demand, seasonality, and volatility, has been briefly outlined in Gibson (2024), though not specifically in relation to commodities. Broader pricing methods have also been summarised, including overviews of general goods pricing (Jain, 2021), market skimming and penetration strategies (Spann et al., 2015), and cost-plus pricing (Dholakia, 2016, 2018; Vohra, 1992; Hanson, 1992). In addition, the general concepts of various pricing methods, such as block pricing (Miyawaki et al., 2016), bundling pricing (Kopczewski et al., 2018), and continuous double auction (Cason and Friedman, 1996), were studied.

While the extant literature has focused more on general market pricing, it sheds light on the theoretical and conceptual frameworks underpinning pricing mechanisms and methods, which are used as cornerstones for the current study. Research on commodity indices, particularly their sub-themes of indexation, benchmarking, and the role of price reporting agencies, remains limited. While some studies have explored profitable commodity investment models (Blocher et al., 2018) and the influence of financialization and indexation on return correlations and price co-movements (Tang and Xiong, 2012), the specific role of spot benchmarks has received less direct attention. Price reporting agencies, such as S&P Global Platts and Argus Media, play a crucial role in publishing benchmark prices used in physical transactions across the energy and commodities markets (IOSCO, 2021). To improve the availability and accuracy of market-driven spot prices, it is imperative to understand the transparency, reliability, and consistency of various benchmarks published by the price reporting agencies. Concerns about the integrity of pricing mechanisms have been raised, particularly where a lack of transparency could open the door to manipulation or distortions, which do not reflect supply and demand dynamics (Pirrong, 2017). Although statistical reporting agencies have been evaluated for data accuracy and policymaker relevance (Swanson and van Dijk, 2006), such studies do not directly address the specific functions of commodity price reporting in energy markets.

3. Conceptual framework

To understand how commodity prices are formed and traded, we examine the structure of spot markets and the role of benchmark pricing in shaping transactions. As such, the following sections outline the key mechanisms and methods through which spot prices are determined in practice.

3.1. Overview of spot commodities trading

Wholesale trades in physical commodities tend to take place via term or spot contracts. On one hand, term contracts - or offtake agreements - are contracts in which sellers and buyers agree to deliver specific quantities of commodities at certain dates in the future (Distadio and Ferguson, 2022). On the other hand, the spot contracts are for delivery of specific quantities, in certain locations as soon as operationally available, often within a few days. Spot commodity trading markets include energy-related commodities, such as oil, coal, electricity, and petrochemicals; agricultural commodities such as corn, wheat, soybeans, and coffee; metals and minerals such as gold, silver, steel, and iron ore (Soumaré, 2022).

Theories of storage (Kaldor, 1939; Working, 1949) and convenience yield (Telser, 1958) provide key theoretical frameworks for understanding the benefits of holding spot commodities. The former explains why economic agents hold physical inventories bearing storage costs, such as warehousing, insurance, and potential price increases when supply is uncertain. The latter highlights the convenience yield, non-monetary benefits from having immediate access to commodities, to prevent potential supply disruptions (Geman, 2005). These theories shed light on the importance of understanding spot commodities pricing mechanisms and methods, which are the key information for strategising spot commodities trading.

The spot price discovery for commodities trading markets is firmly rooted in the crude oil trade. Until the 1980s, most crude oil term contracts were based on the fixed prices set by the negotiation between producers and end-users (Downey, 2009). However, since then, spot contracts have proliferated, which accounts for around 40% as of now (ICE, 2025). The remaining 60% of the term contracts are also mostly linked to the spot benchmark prices, while constructing the term contracts with various formulae (ICE, 2025). This applies to many commodity markets. In addition, many forward and futures contracts are based on the spot benchmark prices (ICE, 2025), as Fig. 1 shows.

The spot benchmark prices are defined as “the value at which a standard, repeatable transaction for merchantable material takes place, or could take place, in the open market at arm's length” (S&P Global, 2024a, p. 12). The spot benchmark prices are critical in determining the spot price value of crude and other various commodities (ICE, 2025). Price Reporting Agencies are the entities that publish various commodities spot prices, which are widely used as benchmarks for physical transactions among producers, traders, brokers, and end-users. This includes S&P Global Platts, Argus Media, Dow Jones OPIS, and ICIS, among others. The Price Reporting Agencies monitor spot trading that occurs in the over-the-counter (OTC) market and publish daily and weekly assessments of each benchmark price. The spot price discovery for various commodities by the Price Reporting Agencies takes place throughout the day. However, some industry-dominant Price Reporting Agencies operate their own pricing windows, such as Market on Close (MOC) by S&P Global. The MOC runs during specific periods (e.g., 4 p.m. to 4:30 p.m. in Asia), collecting spot price indications, such as bids, offers, and trades from traders, brokers, producers, and end-users, depending on the specific market convention (Downey, 2009). In fact, several dominant Price Reporting Agencies and key participants – producers, trading firms, and end-users - have functioned as a Price Maker, who influences the spot prices with high volume of liquidity or market shares, etc., over the past few decades in the global spot commodities trading markets (Downey, 2009).

3.2. Pricing mechanisms and pricing methods for spot commodities trading

Pricing mechanism is a pricing rule that exhibits the broader framework or system that affects price determination. It can be classified into three categories, which align with the practical dynamics of the spot commodities market (Kienzler and Kowalkowski, 2017): discriminatory, competition-oriented, and cost-based. Pricing methods refer to the specific strategies or techniques used in price discovery (Hinterhuber, 2008). This research identifies the most widely used pricing methods employed by practitioners in the spot commodities trading markets. These include market skimming, market penetration, cost-plus pricing, marginal cost pricing, value-based pricing, block pricing, commodity bundling, continuous double auction, and bilateral pricing, as Table 1 shows.

Based on the key definitions and explanations above, we have developed the following conceptual framework mapping of spot commodity prices, as illustrated in Fig. 2.

4. Methodology & data collection

We conducted a thematic content analysis of two key price reporting

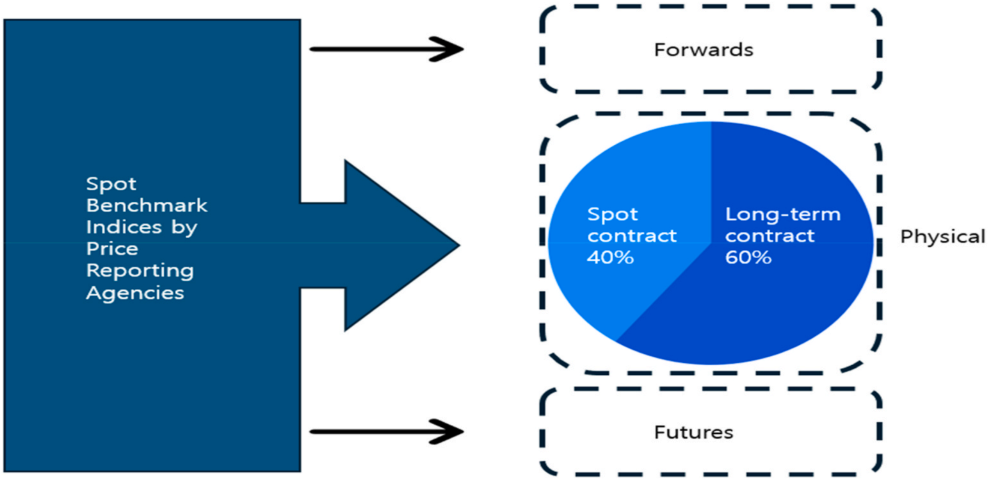

Fig. 1. Illustration of associations between spot benchmark indices and physical spot & long-term contracts, forwards, and futures.

agencies' spot hydrogen pricing methodology guides using NVivo, following six phases of reflexive thematic analysis methods presented by Braun and Clarke (Braun and Clarke, 2006; Byrne, 2022). We selected two major price reporting agencies, Argus and S&P Global's spot hydrogen pricing methodology guides as samples, which are available online and have dominant market shares and track records in many commodities and energy sectors, such as oil and natural gas. Firstly, we familiarised ourselves with the hydrogen spot indices provided by the two methodology guides and identified meaningful patterns, features, and characteristics. Secondly, we classified Argus's 99 indices and S&P Global's 404 indices into 13 prototypes and 21 prototypes, respectively, as Table 2 shows, based on comprehensive observation of parameters of each index. Then, we generated initial 47 codes based on the above observation and systemic classifications. Thirdly, we collated 47 codes into 4 broader initial themes, which deliver important patterns and meaning, such as cost, type of hydrogen, technology, and location. Fourth, we reviewed and defined the themes into relevant pricing methods and pricing mechanisms with reference to the conceptual framework that we generated as Fig. 2. When reviewing and redefining the codes, themes and the generic conceptual framework, we developed the customised conceptual framework, which applies to the hydrogen spot indices and trading market as Figs. 4 and 5 elaborate. Fifth, we grouped the 4 themes into relevant specific pricing methods (2nd coding phase) and pricing mechanisms (3rd coding phase), to clearly articulate the specific pricing methodologies by applying the conceptual frameworks for the hydrogen (Figs. 4 and 5). Sixth, we run the NVivo analysis to answer the two research questions of "What are the key features of major hydrogen spot price indices?" and "In what ways are hydrogen spot price indices similar, and how do they differ?" in Section 5. The Argus and S&P Global are two leading third-party IOSCO-assured price reporting agencies, which have launched the hydrogen assessments earlier than other PRAs in 2019 (S&P Global Platts, 2019) and 2021 (Argus Media, 2022), respectively, and their detailed spot hydrogen methodology guides are open to the public. Due to the spot hydrogen indexation being in its infancy, there is a limited number of methodologies available to the public. The G20 and the Financial Stability Board (FSB) mandated IOSCO to devise global standards for energy and commodity price benchmarks after the LIBOR and oil-price manipulation scandals in 2012 (Financial Stability Board, n.d.). The IOSCO PRA principles mandate transparent methodology, data management, and governance to prevent manipulation and information asymmetry. The IOSCO assurance is verified by third-party auditing firms (IOSCO, 2021). The S&P Global hydrogen methodology and specification guide provided 404 spot hydrogen indices as references (S&P Global, 2024b), while the Argus hydrogen and future fuels methodology guide provided 99 (Argus Media, 2024).

4.1. First coding phase under dominant themes – cost, type of hydrogen, technology, and location

After comprehensive observation and grouping with standard features, S&P Global's spot hydrogen 404 indices were classified into 21 prototypes, while Argus's 99 indices into 13, as Table 2 shows.

After classifying 503 hydrogen indices from both S&P Global and Argus into 34 prototypes, four key themes were identified, including *cost*, *type of hydrogen*, *technology*, and *location*, definitions for which are provided below. The cost theme consists of 5 codes, the type of hydrogen theme has 6 codes, the technology theme includes 9 codes, and the location theme has 27 codes, totalling 47 codes, as Fig. 3 displays. As a result, the 503 hydrogen index references were grouped into the 47 codes, based on the 34 prototypes with multiple selections. For example, the indices defined as 'SMR + CCS + Carbon + CAPEX' were coded into 'SMR + CCS' under the technology theme, into 'Blue under the type of hydrogen theme, 'Carbon' under the cost theme, 'CAPEX' under the cost theme, and the relevant 'country' under the location theme. The 503 references were coded into one code for each theme, except for the cost theme, which allows multiple choices.

4.1.1. Cost

The theme of 'cost' relates to any mention of financial cost or expenditure within the indices. Five codes were created under the cost theme: (1) Production; (2) Carbon; (3) Capital Expenditure (CAPEX); (4) Grid; and (5) Power Purchase Agreement (PPA). Since specific indices incorporated multiple cost elements, we coded references based on multiple selections. This resulted in the number of references under the cost themes being aggregated at 939, differing from other themes, which had 503 each.

4.1.2. Type of hydrogen

The theme of 'type of hydrogen' is explicitly related to the hydrogen production pathways and carbon abatement processes referenced (Incer-Valverde et al., 2023). This was defined mainly by the 'colour' of the hydrogen and consisted of 6 codes: (1) Green; (2) Yellow; (3) Blue; (4) Grey; (5) Brown; and (6) Black. For definitions of these hydrogen types, see Table 3.

4.1.3. Technology

Nine different codes were identified under the 'technology' theme: (1) Steam Methane Reforming (SMR) without Carbon Capture and Storage (CCS); (2) SMR with CCS; (3) Proton Exchange Membrane

Table 1
Pricing mechanisms and pricing methods for trading.

Pricing mechanisms		Pricing methods	
Discriminatory pricing mechanism	A framework in which prices are determined through sealed bids, offers, and matched price pairs (Paudel and Beng, 2018). Under this system, different buyers pay different prices based on their bid levels, rather than a uniform price applied to all buyers. In practice, premiums and discounts may be applied based on factors such as buyer characteristics, the origin of the spot commodities, the locations of loading and unloading ports, as well as the quality and quantity of the commodities.	*Market skimming pricing*	The market skimming pricing is a strategy that the company sets a relatively high price (Monroe, 1980), or high initial prices (Simon and Dolan, 1998) for differentiated products, which companies have brand reputation, distribution strength, breadth of product line, competitive intensity, and cumulative manufacturer sales. It tends to launch the new product 16% higher than the market price (Spann et al., 2015). For example, Australia-origin liquefied natural gas (LNG) has a premium over other origins for Asian customers, thanks to the distribution strength in proximity.
		Market penetration pricing	The market penetration pricing method is a strategy in which the company sets a relatively low price (Monroe, 1980), or low initial prices (Simon and Dolan, 1998) for less differentiated (Eliashberg and Jeuland, 1986) and more price sensitive (Krishnan et al., 1999) products. In addition, the market stage and late firm entry affect companies' adoption of penetration pricing methods (Spann et al., 2015). US-origin LNG, which entered the international market later than the Middle Eastern incumbents, offered at cheaper prices, could be one of the examples.
		Block pricing	The block pricing method is a nonlinear pricing system often applied to public utilities, such as water, gas, and electricity. Consumers under block pricing face several prices corresponding to the level of consumption (Miyawaki et al., 2016).
		Commodity bundling	The commodity bundling pricing method is a marketing technique of selling two or more products jointly at a discounted price (Kopczewski et al., 2018). For example, a refiner purchases crude oil from a producer under a commodity bundling contract, which allows them to take a discounted supply of refined petroleum products, such as naphtha, gasoline, and diesel, depending on market conditions.
Competition-oriented pricing mechanism	The competition-oriented pricing mechanism is a system in which competitors set the prices in the market (Jain, 2021). It is frequently used in the highly competitive market with similar grades or quality of goods, such as the spot commodities market.	*Continuous double auction*	The continuous double auction (CDA) pricing method is a real-time trading system, where traders freely announce bids and offers and may accept other traders' bids or offers as long as the market remains open (Cason and Friedman, 1996). This method is commonly used in spot commodity exchanges, such as crude oil or natural gas futures on the Intercontinental Exchange (Intercontinental Exchange, n.d.) and Chicago Mercantile Exchange (CME), or various commodities spot benchmark indices on the S&P Global Commodity Insight's MOC process.
		Bilateral pricing	Bilateral pricing is a method in which the price of a commodity is negotiated by counterparties, such as buyer and seller, directly without going through a centralised market platform or system, such as an auction, etc. The pricing could be based on a fixed or variable price, depending on the negotiation.
Cost-Based pricing mechanism	The cost-based pricing mechanism is a system in which the cost structures determine the pricing methods, regardless of market fundamentals, buyer characteristics, quantity, or quality (Guerreiro and Amaral, 2018).	*Cost-plus pricing*	The cost-plus pricing method is a strategy that sets the price by multiplying the average cost by the desired mark-up (Hess, 1991). This approach calculates the total fixed and variable costs and applies a mark-up percentage to determine the asking price (Dholakia, 2018). This method is one of the most used pricing methods in the commodities market, especially where the capital expenditure (CAPEX) is high. It is relatively fair and non-discriminatory to all customers; however, it may fail to capture customer demand and willingness to pay, resulting in pricing that is either too high or too low (Dholakia, 2018). For example, the LNG price from the new projects is typically based on the cost-plus pricing method.
		Marginal cost pricing	Marginal cost pricing is an economic strategy to match the marginal cost of production of additional units of a product. This ensures that the price reflects the cost to the firm of producing one more unit and is often considered an efficient way to allocate resources in competitive markets (Vohra, 1992). National gas utilities often take this approach to maximize customer welfare and efficiency by achieving Pareto optimality. (Davis and Muehlegger, 2010)

(PEM) Electrolysis; (4) Alkaline (ALK) Electrolysis; (5) Autothermal Reforming (ATR) with CCS; (6) Coal gasification; (7) Coal gasification with CCS; (8) Lignite gasification with CCS; and (9) Carbon Neutral Hydrogen.

4.1.4. Location

The 27 codes under the location theme were identified: Spain, Australia, Canada, US, Namibia, South Africa, Brazil, Chile, Trinidad, India, Indonesia, Vietnam, Russia, UK, Netherlands, Germany, France, UAE, Saudi Arabia, Qatar, Oman, South Korea, Japan, and China for country, while Far East Asia, Middle East, Northwest Europe for region. Regions were coded separately from countries, as it was unclear which specific countries were being considered within those regions in the methodology guides.

4.2. Second coding phase under pricing mechanisms

Given the first phase of coding with identifying four themes, and 47 codes from the granular data, the second phase of coding was conducted based on three pricing methods, and the third phase of coding was done based on two pricing mechanisms following the conceptual framework we created in the previous chapter 3. Only those pricing mechanisms and pricing methods applicable to the hydrogen market have been selected from the conceptual framework (Fig. 2). We first developed Table 1 and Fig. 2 to illustrate the pricing mechanisms and pricing methods commonly used in generic commodities trading. However, given the nascent stage of the hydrogen spot market, many of these mechanisms—particularly those under the competition-oriented pricing category such as Continuous Double Auction and Bilateral Pricing—are not yet applicable. Therefore, we constructed a customised conceptual framework for the hydrogen sector, as shown in Figs. 4 and 5, to better reflect the market's current characteristics and limitations. In addition, we developed a customized conceptual framework for hydrogen during the first phase of coding, which was based on 47 codes and four themes, grouping the four themes to respective pricing methods, then pricing mechanisms. Only the pricing methods and pricing mechanisms relevant to this initial coding phase were included. While the generic framework encompasses the full spectrum of pricing mechanisms and methods relevant to commodity markets, it should not be viewed as a prescriptive model for all markets. Instead, it serves as a reference structure from which market-specific adaptations can be derived. Our hydrogen-specific framework thus represents a tailored application of these general principles to a market that remains in its early developmental phase.

The codes under the *type of hydrogen and location* have been grouped into the market skimming pricing methods, as differentiated products, such as green hydrogen, and distribution strength, such as location, as well as regulatory changes, can affect the different pricing methods (Fig. 4). It is important to note that this classification operates at the level of the broader ‘type of hydrogen’ theme rather than individual codes; thus, the inclusion of yellow hydrogen reflects the role of relative differentiation across production pathways in emerging markets, not an assumption that yellow hydrogen inherently functions as a premium product. The codes under - *location, technology, and type of hydrogen* - have been classified as value-based pricing methods, as the price can vary based on the differentiated worth of hydrogen from different locations, technology, and type of hydrogen, which can appeal to a particular customer segment. The codes under - *technology and cost* - have been categorised into cost-plus pricing methods, as the hydrogen indices based on these two are mainly concerned with various industry average costs based on production pathways, source of electricity, grid, carbon, and capital expenditures (CAPEX), both fixed and variable costs.

4.3. *Third coding phase and applying the conceptual framework*

For the third phase of coding, market skimming pricing method and value-based pricing method were grouped into discriminatory pricing mechanisms, following the conceptual framework we discussed in section 3. The cost-plus pricing method was allocated to a cost-based pricing mechanism under the same logic. As a result, a new conceptual flowchart for the spot hydrogen indices has been developed, as illustrated in Figs. 4 and 5.

5. Findings

We will first present the combined findings in Section 5.1 to answer RQ1: *What are the key features of major hydrogen spot price indices?* - which applies to both Argus and S&P Global hydrogen spot indices. We then discuss *differences* between the price reporting agencies (Section 5.2) and similarities between the price reporting agencies (Section 5.3) to answer the RQ2 - *In what ways are hydrogen spot price indices similar, and how do they differ?*

The following Table 4 was extracted from NVivo results provide detailed information on the percentage of coded references across the three-phase coding process.

5.1. *Commonalities between indices*

As Table 4 shows, the discriminatory (64%) pricing mechanism and value-based (38%) pricing method were identified as predominant for both indices, followed by the cost-based (36%) pricing mechanism and cost-plus (36%) pricing method. Among the 4 themes, cost (38%) accounted for most of the largest proportion. Under the *cost* theme, 49%

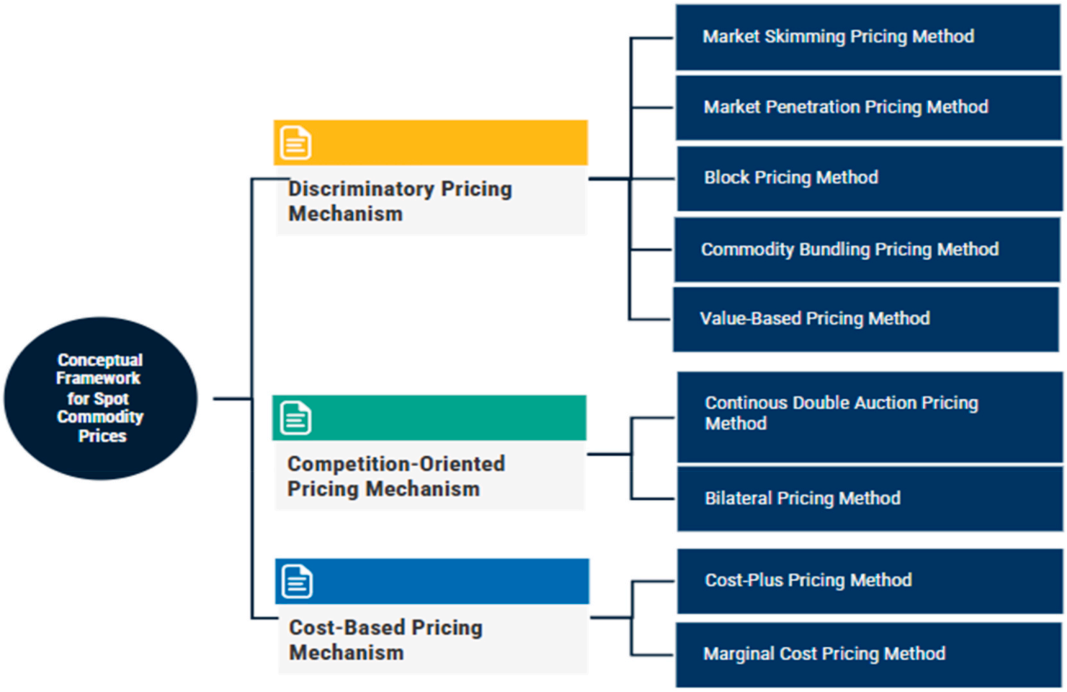

Fig. 2. Conceptual framework mapping of spot commodity prices
Notes: The above conceptual framework will serve as a cornerstone for both the coding and the conceptual framework of Spot Hydrogen Indices and Trading Market, as illustrated in Fig. 4.

Table 2
34 Prototypes of spot hydrogen indices – S&P Global vs Argus.

Indices	Definition
S&P Global	
ALK	Alkaline Electrolysis
ALK + CAPEX	Alkaline Electrolysis + Capital expenses
ALK + Grid only	Alkaline Electrolysis + Grid only
ALK + CAPEX + Grid only	Alkaline Electrolysis + Capital expenses + Grid only
PEM	Proton Exchange Membrane Electrolysis
PEM + CAPEX	Proton Exchange Membrane Electrolysis + Capital expenses
PEM + Grid only	Proton Exchange Membrane Electrolysis + Grid only
PEM + Grid only + CAPEX	Proton Exchange Membrane Electrolysis + Grid only + Capital expenses
SMR w/o CCS	Steam Methane Reforming without Carbon Capture and Sequestration
SMR w/o CCS + CAPEX	Steam Methane Reforming without Carbon Capture and Sequestration + Capital expenses.
SMR + CCS	Steam Methane Reforming with Carbon Capture and Sequestration
SMR + CCS + CAPEX	Steam Methane Reforming with Carbon Capture and Sequestration + Capital expenses
SMR + CCS + Carbon	Steam Methane Reforming with Carbon Capture and Sequestration + Carbon costs
SMR + CCS + Carbon + CAPEX	Steam Methane Reforming with Carbon Capture and Sequestration + Carbon costs + Capital expenses
ATR + CCS	Autothermal Reforming with Carbon Capture and Sequestration
ATR + CCS + CAPEX	Autothermal Reforming with Carbon Capture and Sequestration + Capital expenses
Coal + CCS	Coal Gasification with Carbon Capture and Sequestration
Coal + CCS + CAPEX	Coal Gasification with Carbon Capture and Sequestration + Capital expenses
Lignite + CCS	Lignite Gasification with Carbon Capture and Sequestration
Carbon Neutral	Carbon Neutral Hydrogen
Renewable PPA	Renewable Power Purchase Agreement
Argus	
baseline grid + ALK	Baseline grid + Alkaline Electrolysis
no-C grid + GOO + ALK	No carbon grid + Guarantee of Origin + Alkaline Electrolysis
baseline grid + PEM	Baseline grid + Proton Exchange Membrane Electrolysis
no-C diurnal + PEM	No carbon diurnal + Proton Exchange Membrane Electrolysis
no-C offshore wind + PEM	No carbon offshore wind electricity + Proton Exchange Membrane Electrolysis
baseline SMR	Baseline Steam Methane Reforming
BAT + SMR + CCS	Best Available Technology Steam Methane Reforming with Carbon Capture and Sequestration
*BAT + Coal*6000 NAR	Best Available Technology Coal Gasification with Net As Received Calorific Value of 6000 kcal/kg
*BAT + Coal*5500 NAR	Best Available Technology Coal Gasification with Net As Received Calorific Value of 5500 kcal/kg
*BAT + Coal*4800 NAR	Best Available Technology Coal Gasification with Net As Received Calorific Value of 4800 kcal/kg
*BAT + Coal*3800 NAR	Best Available Technology Coal Gasification with Net As Received Calorific Value of 3800 kcal/kg
BAT + Coal	Best Available Technology Coal Gasification
low-C ATR + CCS	Low Carbon Autothermal Reforming with Carbon Capture and Sequestration

of coded references (n = 939) were related to production, followed by CAPEX (30%). Under the *type of hydrogen* theme, 50% of the total references (n = 503) were related to yellow hydrogen, which is produced using grid electricity without any guarantee of origin (Argus Media, 2024), followed by blue hydrogen (19%), grey hydrogen (14%), and green hydrogen (14%). This interpretation again reflects our theme-level coding approach: yellow hydrogen is not treated as a premium product per se, but as part of a broader differentiation across production pathways that can influence pricing behaviour in immature markets. In terms of the *technology* theme, Proton Exchange Membrane (PEM, 30%) and Alkaline (ALK, 30%) Electrolysis received the most coded references (n = 503), followed by Steam Methane Reforming (SMR) without Carbon Capture and Storage (CCS, 14%), and SMR with CCS (11%). In terms of *location*, the US accounts for 28% of coded references (n = 503), followed by Australia (24%) and the Netherlands (10%). The Middle Eastern countries, Saudi Arabia, UAE, Qatar, and Oman, accounted for 3% each. Except for Japan, Asian countries accounted for a negligible share (less than 1-2%) of coded references. Among all aggregated 47 codes, Production under the *cost* theme accounts for 19% of all aggregated coded references (n = 2448), followed by CAPEX (Cost, 11%), and Yellow (Type of hydrogen, 10%).

5.2. Contrasts between indices

Hydrogen indices of S&P Global are more inclined to opt for the discriminatory (65%) pricing mechanism than Argus (57%), while those of Argus prioritised the cost-based (43%) pricing mechanism compared with S&P Global (35%), as Table 4 shows. Argus opted for the cost-plus pricing (43%) method the most, while S&P Global opted for the value-based pricing (39%) method. Both hydrogen indices prioritised the theme of *cost*; however, the Argus (48%) indices showcased comparatively more cost-related themes compared to S&P Global (35%), which showed similar patterns found from the pricing mechanisms and methods.

5.2.1. Codes under themes

Under the *Cost* theme, Argus equally prioritised Production (36%) and CAPEX (36%), while S&P Global emphasised Production (54%) over CAPEX (27%), as Fig. 6 shows.

Regarding the *type of hydrogen*, Argus relatively symmetrically reflected various types of hydrogen (Blue, Green, Yellow, and Grey) compared to S&P Global, which was asymmetrically distributed to Yellow and Blue, as Fig. 7 shows. The proportion of coded references to green hydrogen accounts for 26% in Argus, while 11% in S&P Global. By contrast, the yellow hydrogen accounts for 58% in S&P Global, while 18% in Argus.

Under the *technology* theme, Argus reflected PEM (30%), while S&P Global ALK (34%), as Fig. 8 shows. Both indices included green hydrogen-related technologies, such as ALK and PEM; however, they included SMR without CCS and SMR with CCS, which are relevant to fossil fuel-based technologies, with 30% (Argus) and 24% (S&P Global), respectively.

Considering *location*, Argus reflected the relatively symmetrical distribution of various countries and regions. At the same time, S&P Global hydrogen indices covered the US (32%), Australia (29%), and the Netherlands (10%) intensively, as Fig. 9 shows.

5.2.2. Codes - aggregated

Overall, Argus hydrogen indices included more cost and low-carbon related codes. In contrast, S&P Global for location and fossil fuel-based hydrogen, which showcased the relative importance of respective elements in each index—based on the aggregated 47 codes, Production (Cost theme) and CAPEX (Cost) accounted for 17% each, respectively, out of all coded references (n = 575) of Argus hydrogen indices, followed by Carbon (Cost, 10%), PEM (Technology, 5%), Blue (Type of Hydrogen, 5%), and Green (Type of Hydrogen, 5%). For S&P Global, Production (Cost theme) accounts for 19% of all coded references (n = 1873), followed by Yellow (Type of technology, 13%), CAPEX (Cost, 10%), ALK (Technology, 7%), US (Location, 7%), PEM (Technology, 6%), Australia (Location, 6%), and Carbon (Cost, 5%). Production was identified as a dominant code for both hydrogen indices; however, CAPEX was not as important in S&P Global (10%) as Argus (17%). Yellow hydrogen accounts for a substantial proportion in S&P Global (13%), while it was less dominant in Argus (3%). Carbon was the 3rd most important code in Argus (10%), while less important in S&P Global (5%). The codes related to location were not identified as significant in Argus, as S&P Global, as Fig. 10 shows.

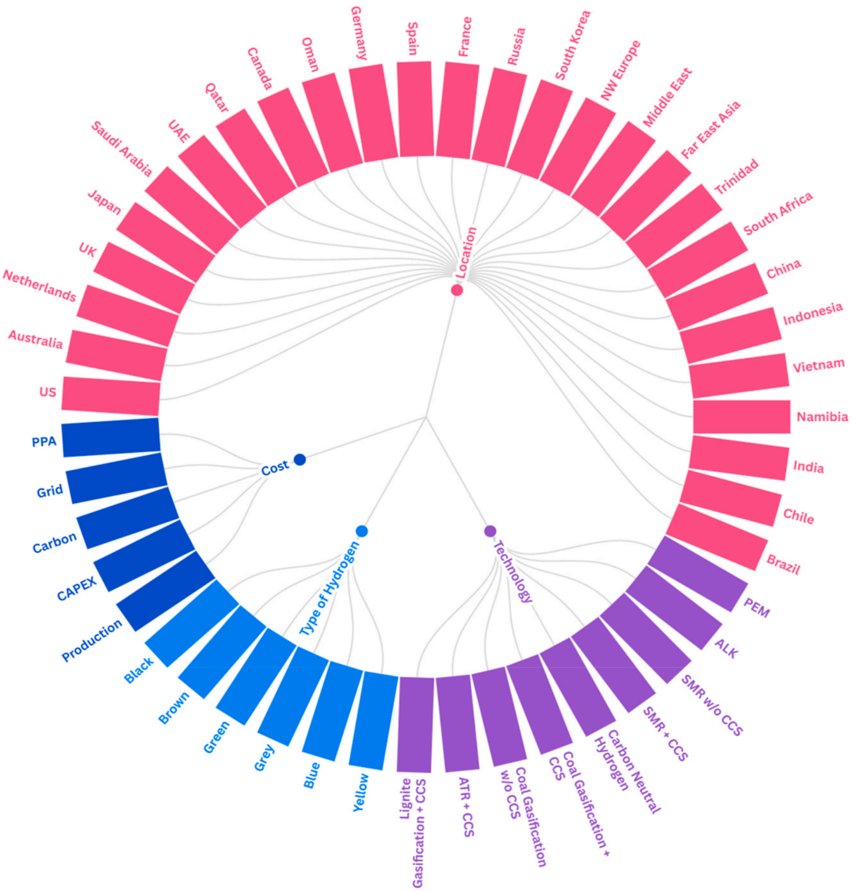

Fig. 3. Hierarchical mapping of the four themes (cost, location, technology, and type of hydrogen) and 47 codes.

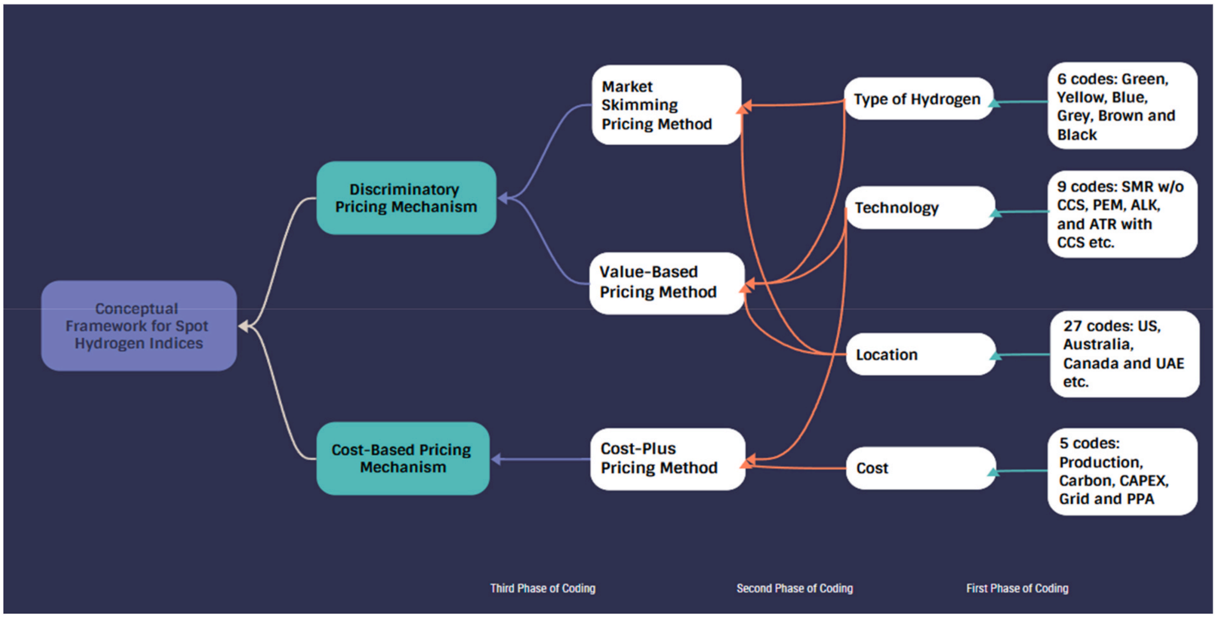

Fig. 4. 3 Phases of coding and conceptual framework for spot hydrogen indices and trading market.

5.3. *Similarity between the indices*

Based on the percentages of all coded references (Table 4), we analysed correlation coefficients of Argus and S&P Global hydrogen indices, using standard non-parametric correlations measures, as Table 5 shows. A correlation coefficient of 0.526 and 0.656 indicates a moderate positive relationship between the two variables, Argus and S&P Global. A significance level of less than 0.001 showcases that this relationship is statistically significant, suggesting that the relationship between the two hydrogen indices is statistically meaningful.

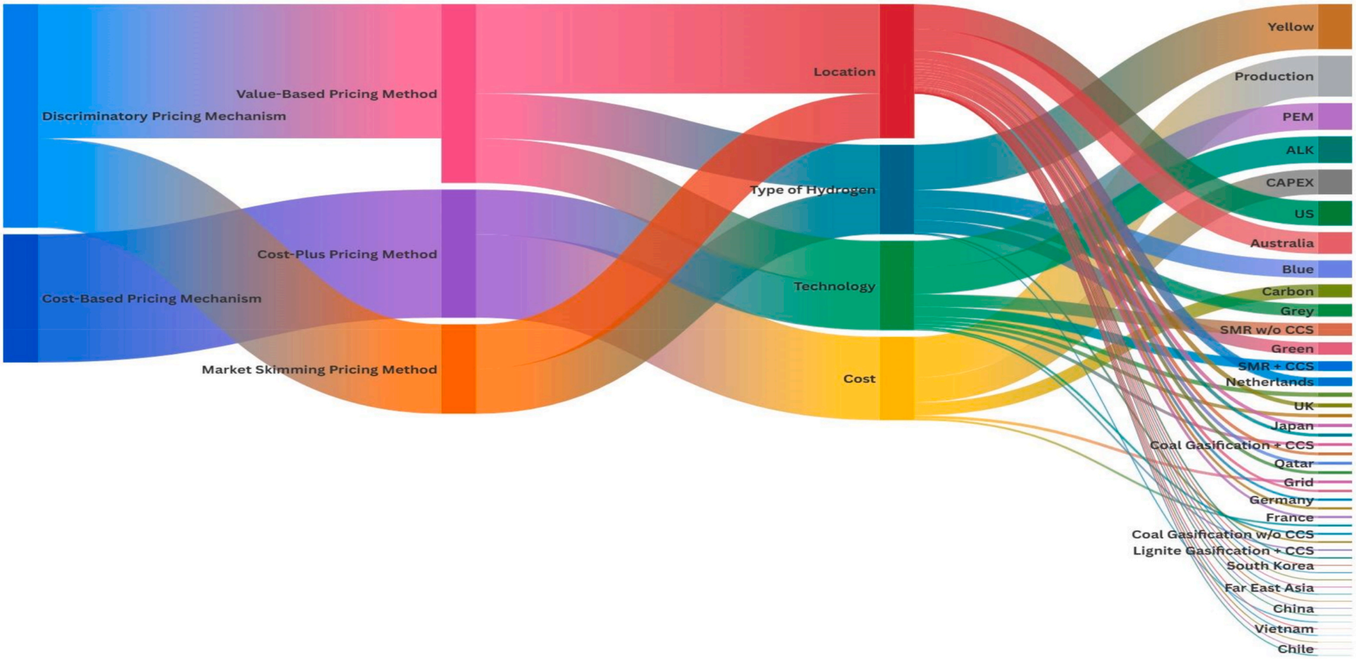

Fig. 5. Sankey flowchart of the conceptual framework's three phases of coding.

Table 3
Types of hydrogen.

Type of Hydrogen	Production	Key Energy Source
Green	Electrolysis (PEM, ALK, etc.)	Renewables (Solar, wind, and hydro, etc.)
Yellow	Electrolysis (PEM, ALK, etc.)	Grid electricity (mixed sources from fossil fuels, renewables, and nuclear)
Blue	Steam Methane Reforming (SMR) or Autothermal Reforming (ATR) with Carbon Capture and Sequestration (CCS)	Natural Gas
Grey	Steam Methane Reforming (SMR) or Autothermal Reforming (ATR)	Natural Gas
Brown	Coal Gasification	Lignite
Black	Coal Gasification	Bituminous

6. Discussion

In the following subsections, we assess the extent to which Argus and S&P Global hydrogen indices align with market-driven principles and theories, uphold transparency, reliability, and consistency, and contribute to the promotion of low-emission hydrogen. According to the Efficient Market Hypothesis (Fama, 1970), an ideal market is bolstered by accurate price signals, which reflect all available information fully, enabling efficient resource allocation. Grossman (1980) argued that, despite efficient markets being only possible in theory, transparent price discovery could enhance market efficiency. Several studies have emphasised that the lack of demand-responsive and transparent price signals could hinder efficient resource allocation and investment decisions (Newbery, 2005; Joskow, 2008). In this regard, we critically evaluated the findings from the following three perspectives. While the hydrogen sector exhibits several unique characteristics (such as its role as an energy carrier, dependence on emerging infrastructure, and a policy-intensive development pathway) these features do not negate the usefulness of traditional commodity-market theories as analytical benchmarks. Instead, they help explain why current hydrogen spot indices diverge from the core conditions required for efficient price discovery, including market-driven pricing, transparency, and consistency. Acknowledging these sector-specific constraints provides important context for understanding the limitations observed in existing indices, while still underscoring the need for pricing mechanisms that can evolve toward greater market efficiency as hydrogen markets mature.

6.1. *Less market demand-driven and self-regulating*

For the adoption of a low-emission hydrogen economy, the creation of a well-functioning hydrogen spot trading market is essential, which could increase liquidity and prompt lower prices (Slade and Thille, 2006). Given the Efficient Market Hypothesis (Fama, 1970), the well-functioning hydrogen market could be created by accurate price signals, which are market demand-driven (Newbery, 2005; Joskow, 2008) and self-regulating, which can facilitate market participation and investment via long-term scalability and cost-effectiveness (Kayikci et al., 2025). Although subsidies and policies are essential to make low-emission hydrogen cost-competitive in the near term (Ueckerdt et al., 2021), reliance on subsidies could erode the efficiency of the overall energy system and expose hydrogen projects to policy changes and regulatory uncertainties.

Despite both Argus and S&P Global's hydrogen spot indices predominantly incorporated discriminatory pricing mechanisms (64%) - the typical features of commodity spot trading markets, where buyer characteristics, quality, quantity, and location (i.e., the market demand drivers) determine the prices - both indices incorporated the cost-based pricing mechanisms (36%) substantially, which are non-market demand-driven factors. Especially, Argus (43%) indices were more inclined to adopt cost-based pricing mechanisms over S&P Global (35%). Neither index opted for a competition-oriented pricing mechanism, where prices are set by competitors, which is one of the market demand-driven factors. Regarding pricing methods, despite value-based pricing (38%) prevailing, which set a price based on the perceived differentiated worth of a product for a specific customer segment, as compared to competitors (Dholakia, 2016), which are market demand-driven factors, both indices substantially adopted cost-plus pricing (36%), which calculates the price by totalling fixed and variable costs and adding a mark-up. Argus prioritised cost-plus pricing (43%) over value-based (34%). This was reiterated in the aggregated codes, where production

Table 4
Percentage distribution of coded references over three coding phases.

	Combined	Argus	S&P Global
3rd coding **- pricing mechanism**			
Discriminatory	63.56%	56.78%	65.47%
Cost-Based	36.44%	43.22%	34.53%
Sub-total	100%	100%	100%
2nd coding **- pricing methods**			
Value-based pricing	38.13%	34.02%	39.29%
Cost-Plus Pricing	36.44%	43.22%	34.53%
Market Skimming	25.42%	22.76%	26.17%
Sub-total	100%	100%	100%
1st *coding* - themes			
Cost	38.36%	48.35%	35.29%
Type of Hydrogen	20.55%	17.22%	21.57%
Technology	20.55%	17.22%	21.57%
Location	20.55%	17.22%	21.57%
Sub-total	100%	100%	100%
1st *coding* - themes - cost			
Production	48.88%	35.61%	54.46%
CAPEX	29.82%	35.61%	27.38%
Carbon	15.76%	20.14%	13.92%
Grid	3.30%	8.27%	1.21%
PPA	2.24%	0.36%	3.03%
Sub-total	100%	100%	100%
1st *coding* - themes - *type of hydrogen*			
Yellow	50.50%	18.18%	58.42%
Blue	19.48%	30.30%	16.83%
Grey	14.12%	15.15%	13.86%
Green	13.92%	26.26%	10.89%
Brown	0.20%	1.01%	0.00%
Black	1.79%	9.09%	0.00%
Sub-total	100%	100%	100%
1st *coding* - themes - *technology*			
PEM	29.82%	30.30%	29.70%
ALK	29.82%	14.14%	33.66%
SMR w/o CCS	14.12%	15.15%	13.86%
SMR + CCS	10.93%	15.15%	9.90%
Carbon Neutral Hydrogen	4.77%	0.00%	5.94%
Coal Gasification + CCS	3.18%	0.00%	3.96%
Coal Gasification w/o CCS	1.99%	10.10%	0.00%
ATR + CCS	3.78%	15.15%	0.99%
Lignite Gasification + CCS	1.59%	0.00%	1.98%
Sub-total	100%	100%	100%
1st *coding* - themes - *location*			
US	27.63%	11.11%	31.68%
Australia	24.25%	6.06%	28.71%
Netherlands	9.54%	7.07%	10.15%
UK	4.57%	7.07%	3.96%
Japan	3.58%	6.06%	2.97%
Saudi Arabia	3.38%	1.01%	3.96%
UAE	3.18%	4.04%	2.97%
Qatar	3.18%	4.04%	2.97%
Canada	3.18%	4.04%	2.97%
Oman	2.58%	1.01%	2.97%
Germany	2.39%	7.07%	1.24%
Spain	2.39%	7.07%	1.24%
France	2.39%	7.07%	1.24%
Russia	1.39%	7.07%	0.00%
South Korea	0.80%	4.04%	0.00%
NW Europe	0.80%	0.00%	0.99%
Middle East	0.80%	0.00%	0.99%
Far East Asia	0.80%	0.00%	0.99%
Trinidad	0.60%	3.03%	0.00%
South Africa	0.60%	3.03%	0.00%
China	0.60%	3.03%	0.00%
Indonesia	0.40%	2.02%	0.00%
Vietnam	0.20%	1.01%	0.00%
Namibia	0.20%	1.01%	0.00%
India	0.20%	1.01%	0.00%
Chile	0.20%	1.01%	0.00%
Brazil	0.20%	1.01%	0.00%
Sub-total	100%	100%	100%
1st *coding* - aggregated			
Production	18.75%	17.22%	19.22%
CAPEX	11.44%	17.22%	9.66%
Yellow	10.38%	3.13%	12.60%
PEM	6.13%	5.22%	6.41%
ALK	6.13%	2.43%	7.26%
Carbon	6.05%	9.74%	4.91%
US	5.68%	1.91%	6.83%
Australia	4.98%	1.04%	6.19%
Blue	4.00%	5.22%	3.63%
Grey	2.90%	2.61%	2.99%
SMR w/o CCS	2.90%	2.61%	2.99%
Green	2.86%	4.52%	2.35%
SMR + CCS	2.25%	2.61%	2.14%
Netherlands	1.96%	1.22%	2.19%
Grid	1.27%	4.00%	0.43%
Carbon Neutral Hydrogen	0.98%	0.00%	1.28%
UK	0.94%	1.22%	0.85%
PPA	0.86%	0.17%	1.07%
ATR + CCS	0.78%	2.61%	0.21%
Japan	0.74%	1.04%	0.64%
Saudi Arabia	0.69%	0.17%	0.85%
Coal Gasification + CCS	0.65%	0.00%	0.85%
UAE	0.65%	0.70%	0.64%
Qatar	0.65%	0.70%	0.64%
Canada	0.65%	0.70%	0.64%
Oman	0.53%	0.17%	0.64%
Germany	0.49%	1.22%	0.27%
Spain	0.49%	1.22%	0.27%
France	0.49%	1.22%	0.27%
Coal Gasification w/o CCS	0.41%	1.74%	0.00%
Black	0.37%	1.57%	0.00%
Lignite Gasification + CCS	0.33%	0.00%	0.43%
Russia	0.29%	1.22%	0.00%
South Korea	0.16%	0.70%	0.00%
NW Europe	0.16%	0.00%	0.21%
Middle East	0.16%	0.00%	0.21%
Far East Asia	0.16%	0.00%	0.21%
Trinidad	0.12%	0.52%	0.00%
South Africa	0.12%	0.52%	0.00%
China	0.12%	0.52%	0.00%
Indonesia	0.08%	0.35%	0.00%
Brown	0.04%	0.17%	0.00%
Vietnam	0.04%	0.17%	0.00%
Namibia	0.04%	0.17%	0.00%
India	0.04%	0.17%	0.00%
Chile	0.04%	0.17%	0.00%
Brazil	0.04%	0.17%	0.00%
Sub-total	100%	100%	100%

Notes: These figures were based on the number of coded references in each phase of analysis, which is available in the appendix. All data are reported to two decimal places. The first coding dataset was presented in two parts: the percentage under four themes (cost, type of hydrogen, technology and location) and the total aggregated percentage.

(17%) and CAPEX (17%), both under the cost theme, were equally predominant. The cost-based pricing mechanism and cost-plus pricing method could fail to capture customer demand and willingness to pay (Dholakia, 2018), which are crucial for the low-carbon hydrogen market uptake by narrowing the wide gap between producers' and buyers' price indications.

Pricing mechanisms and methods driven by market demand tend to be self-regulating and less influenced by policy and subsidy interventions (Chen and Gallego, 2019). However, both indices put into practice cost-based pricing mechanisms, specifically, cost-plus pricing methods, rather than market demand-driven, which negated the above hypothesis. Both indices rely on *ex ante* static features of cost structures, such as production cost and CAPEX, which are not self-regulating - prompted by supply-demand dynamics in the market- but are more affected by subsidy and policy changes. Codes under the *location* theme also indicate that both indices failed to capture the potential hydrogen demand centres, such as East Asia and Europe, but focus more on supply centres, the US, Australia, and the Middle East. It also exhibits the regionally asymmetric development of the hydrogen market, which was caused by geographically varying policies and subsidies instead of a

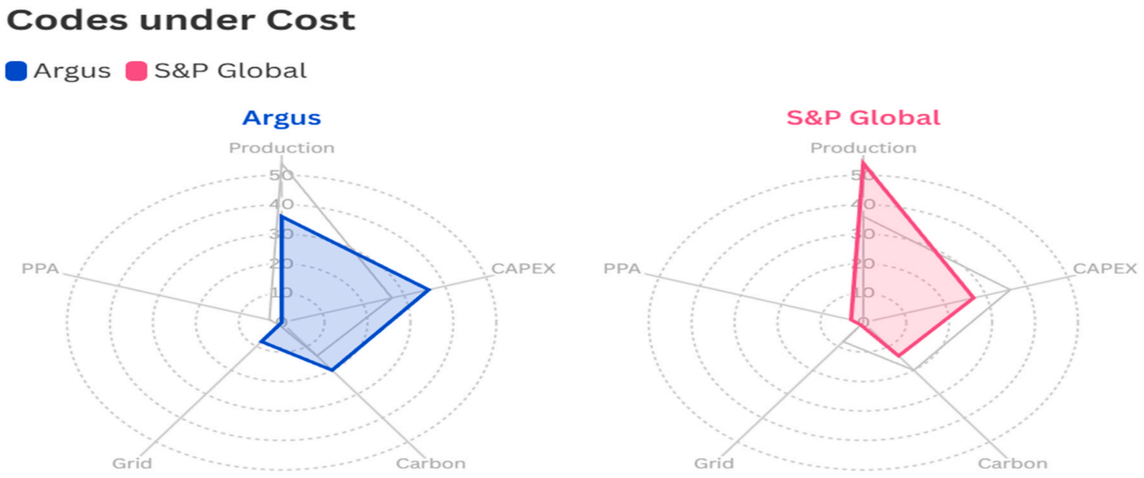

Fig. 6. Coded references under “Cost” – Argus vs S&P Global.

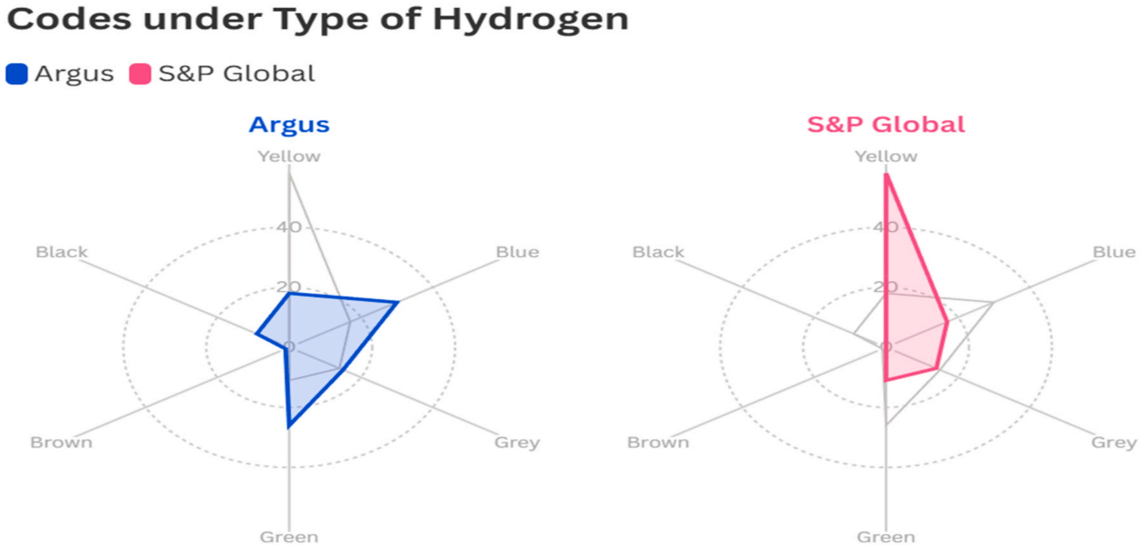

Fig. 7. Coded references under “Type of Hydrogen” – Argus vs S&P Global.

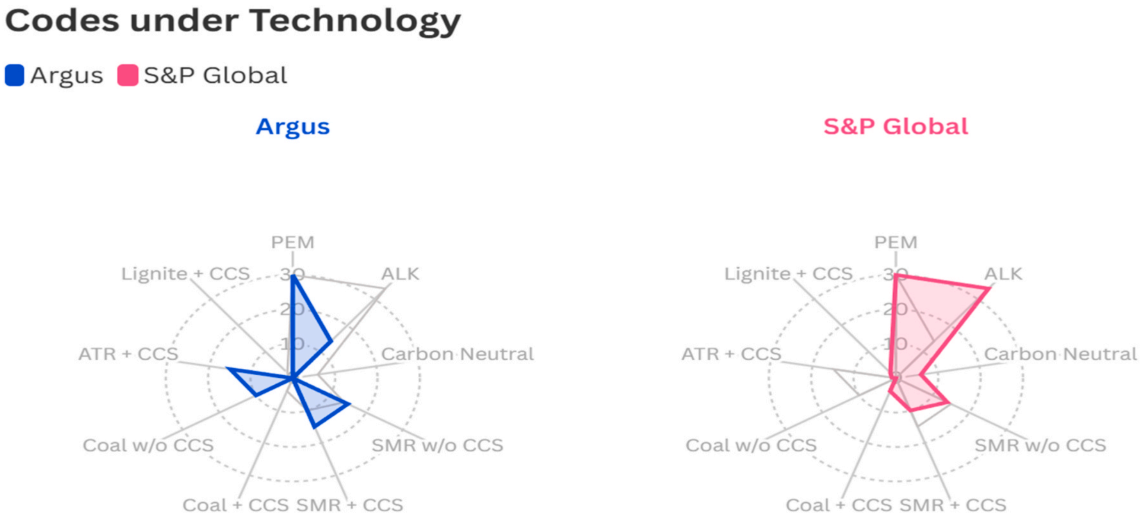

Fig. 8. Coded references under “Technology” – Argus vs S&P Global.

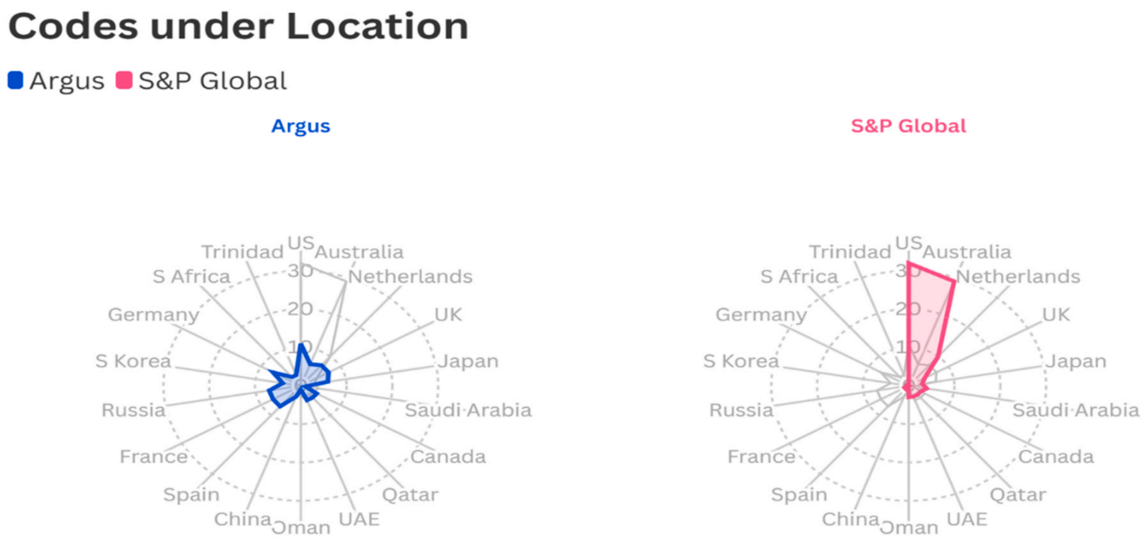

Fig. 9. Coded references under "Location" – Argus vs S&P Global.*Notes*: for a more concise illustration, the coded references below 2% for both Argus and S&P Global were not included.

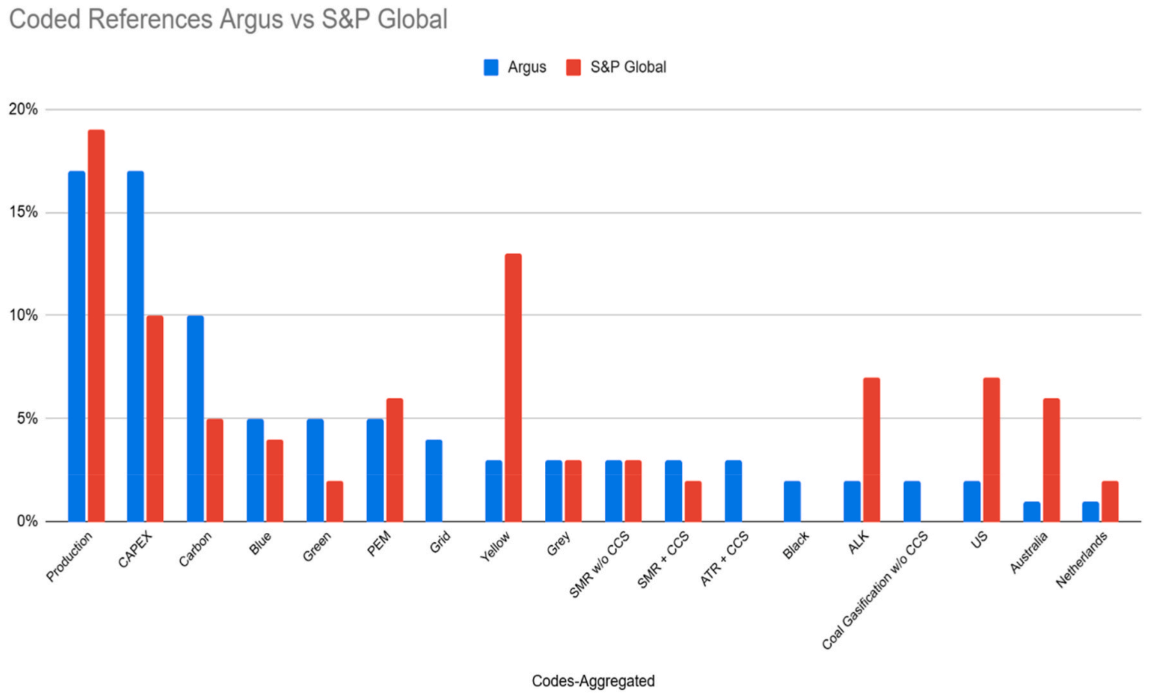

Fig. 10. Percentages of coded references by aggregated codes – Argus vs S&P Global.

geographically interconnected self-regulating system. Government policy played a central role in infrastructure transition and addressing barriers so far in the absence of a broader engagement of social, political, and economic aspects, such as market conditions, consumer behaviours, and cultural practices, etc (McDowall, 2012) in the hydrogen sector. The effectiveness, priorities, and strategies of policies vary depending on regions and countries (Kayikci et al., 2025). It was mirrored in the uneven regional distribution of both hydrogen spot indices, which concentrated on certain 'supply' countries (i.e., US, 28%; Australia, 24%) and 'trading' countries (i.e., Netherlands, 10%).

6.2. *Lack of transparency, reliability, and consistency*

A transparent, reliable, and consistent pricing mechanism is essential for efficient resource allocation and sound investment decisions (Newbery, 2005; Joskow, 2008), particularly in an emerging market such as low-emission hydrogen. However, both indices largely rely on cost-oriented pricing mechanisms that generate *ex ante* modelled price

Table 5
Correlation coefficient – percentages of all coded references of Argus and S&P Global.

Correlation measure	Index		Argus	S&P Global
Kendall's τ	Argus	Correlation coefficient	1.000	0.526**
		Sig. (2-tailed)	.	<0.001
		N	103	103
	S&P Global	Correlation coefficient	0.526**	1.000
		Sig. (2-tailed)	<0.001	.
		N	103	103
Spearman's ρ	Argus	Correlation coefficient	1.000	0.656**
		Sig. (2-tailed)	.	<0.001
		N	103	103
	S&P Global	Correlation coefficient	0.656**	1.000
		Sig. (2-tailed)	<0.001	.
		N	103	103

Notes: ** implies that the correlation coefficient is significant at the 0.01 level (2-tailed).

assessments (S&P Global, 2024). While such approaches reflect the early-stage nature of the market (where CAPEX accounts for 20–60% of the levelised cost of hydrogen - LCOH) they rely heavily on broad assumptions regarding production pathways, region-wide or sector-wide CAPEX averages, generalised PPA costs, and uniform carbon costs. These assumptions overlook substantial regional and technological variability, including differences in technological maturity, cost of capital (Choi and Kang, 2023), renewable electricity prices, and emissions trading system (ETS) pricing. Because these parameters fluctuate significantly across regions, countries, and industries, the use of static inputs weakens real-time price discovery and limits the indices' ability to reflect actual supply-demand conditions. As hydrogen systems evolve toward near-real-time coupling of renewable electricity and production (Ricks and Jenkins, 2023), such static assumptions will become increasingly misaligned with market realities.

Reliability is further compromised by the absence of storage, transport, and distribution costs, which are elements that constitute a substantial share of hydrogen's delivered cost structure. Hydrogen's low volumetric energy density requires specialised infrastructure, resulting in transport and storage costs of approximately \$2–5/kgH_2 depending on application (Shafiee and Schrag, 2024). Moreover, refuelling accounts for 26–28% of green hydrogen's LCOH, second only to production (54–61%), yet these components are omitted from both indices (Kayikci et al., 2025). Given that hydrogen is an energy carrier rather than a primary energy source, the omission of these midstream and downstream costs limits the indices' ability to represent the full commercial value chain. A more holistic approach—integrating production, storage, delivery, and end-use (He et al., 2025)—is therefore necessary for credible and reliable price assessments.

Finally, the treatment of “Yellow” hydrogen highlights the transparency challenge. Codes under the “type of hydrogen” theme show that yellow hydrogen accounts for the largest share of references (50%). Yellow hydrogen is produced via electrolysis using grid-connected electricity, where the mix may include both renewable and fossil-fuel-based generation. Because the emissions profile of grid electricity varies widely across regions, its carbon intensity cannot be inferred without disclosing the underlying electricity mix or providing a verifiable emissions calculation. This ambiguity makes it difficult for market participants to assess the environmental attributes of the product, which are attributes that are increasingly central to hydrogen contracting and policy frameworks. For instance, to qualify as low-carbon hydrogen in the EU, production must meet a threshold of 3.38 kgCO_2e/kgH_2 (Trüby et al., 2024), a determination that is impossible without clarity on the electricity source. When yellow hydrogen is featured prominently in an index without transparent disclosure of its electricity mix, the price signal becomes less informative and less reliable for users seeking to evaluate both economic and emissions performance. Consequently, the heavy use of yellow hydrogen in the S&P Global index weakens transparency and consistency by obscuring the underlying assumptions about its carbon footprint.

6.3. *Partially accelerates low-emission hydrogen*

The findings suggest partial support for low-emission hydrogen inclusion. According to the codes under the *type of hydrogen* theme, yellow accounted for 50% of both indices, which means that the indices endeavour to reflect low-emission hydrogen produced from electrolysis using grid electricity. However, this grid electricity includes renewables as well as fossil fuels and nuclear. Therefore, it failed to clarify the emission profiles. Green hydrogen assumes zero greenhouse gas footprint in the entire supply chain in most certification schemes globally (IEA, 2023). As such, it is crucial to articulate that electrolysis does not omit embodied emissions from power generation and consequential emissions from broader electricity systems (De Kleijne et al., 2024). However, yellow hydrogen produced from either PEM or ALK electrolysis does not specify the origin of electricity and, consequently, casts doubt on whether both indices endeavour to reflect low-emission hydrogen in price discovery. Given that the electricity costs account for the most significant proportion of the total costs of the green hydrogen supply chain (He et al., 2025), it is essential to address the origin of electricity in detail. Although Argus indices endorsed 26% of green hydrogen, blue hydrogen accounted for the majority (30%). Notably, a larger portion (86%) of both indices is based on non-green hydrogen, including blue (19%), grey (14%), and even brown (1% for Argus) and black (2%).

The codes under the *technology* theme also indicate that despite efforts to include PEM and ALK - major green hydrogen production pathways - SMR without CCS, which uses carbon-intensive natural gas without carbon abatement, amounted to a substantial proportion for both indices (14%, Argus 15%, and S&P Global 14%). By contrast, one of the emerging highly efficient green hydrogen production pathways, Solid Oxide Electrolysis (Wang et al., 2019), was not included within any of the indices. The codes under the *cost* theme also showcased that relatively little attention was given to low-emission hydrogen-relevant elements, such as carbon (16%), grid (3%), and PPA (2%). However, the *location* themes are asymmetrically concentrated on specific countries, such as the US (28%), Australia (24%), Saudi Arabia, UAE, Qatar, Oman, and Canada (3% each), which overlap key natural gas and coal exporting countries. However, they overlooked emerging low-carbon hydrogen-producing countries, such as Latin America (Khazaei et al., 2025). We could infer that existing hydrogen spot indices are primarily backed by non-renewable feedstock-based hydrogen rather than low-emission hydrogen. Different degrees of domestic technological capability could have affected the locational asymmetry. In addition, low-emission hydrogen adoption is contingent on governments' support, such as subsidies and funding, determined by regulation and political landscapes (Kayikci et al., 2025).

Pink hydrogen, which is produced through high-temperature steam electrolysis of heat and power by nuclear means and is regarded as low-emission hydrogen, was not present in either index. Pink hydrogen is actively discussed as an alternative to high-cost green hydrogen, as nuclear power is cheaper and more efficient than renewable power with continuous supply and recycling of waste reactor heat. For hydrogen to expand from industrial feedstocks to an energy transition strategy, it should be low carbon across the full life cycle, and Environmental, Social and Governance (ESG) consideration is paramount in hydrogen supply chain optimization (Khazaei et al., 2025). However, both Argus and S&P Global hydrogen spot indices endorsed limited low-emission hydrogen assessments, mirroring the infant hydrogen spot trading market status.

7. Conclusion

This study provides a comprehensive understanding and critical evaluation of two key price reporting agencies' hydrogen spot indices by thematic content analysis using NVivo. By grouping observed 503 indices from both S&P Global and Argus into 47 codes, four themes (cost, type of hydrogen, technology, and location), three pricing methods (market skimming, value-based, and cost-plus), and two pricing mechanisms (discriminatory and cost-based), we presented a novel framework for comprehending the emerging spot hydrogen indices. These evaluations provided vigorous insights into whether the indices are market demand-driving, self-regulating, transparent, reliable, and consistent, so that they can bolster low-emission hydrogen market creation and uptake, which has been delayed for more than a few decades.

We found that both hydrogen spot indices adopted a cost-based pricing mechanism and method substantially, which are not market demand-driven and fail to capture customer demand and willingness-to-pay. Both indices rely on *ex ante* static features of cost structures, which are not self-regulating but are influenced by policy and subsidy. These pricing mechanisms and methods lack transparency, reliability, and consistency. The implications of these findings are multifaceted. From a practical perspective, this research provides policymakers and regulators with a systematic evaluation of emerging hydrogen spot indices and other energy and commodities indices, utilizing our framework. Despite the IOSCO having launched a PRA principle in 2012, the critical evaluation of detailed pricing mechanisms and methods of the spot indices has mainly been superficial and remained in an uncovered area, with limited clarity and information asymmetry between internal stakeholders and external regulators. This study will fill the gap, enabling the development of optimal technology roadmaps and policies to promote an efficient and long-term hydrogen energy transition. The market participants, such as producers, traders, brokers, and end-users, who use the spot energy and commodities indices for their businesses, could refer to our frameworks to understand and critically evaluate the robustness of existing indices for better representation of the real market dynamics. The price reporting agencies could self-reflect on their current spot pricing methodologies and reinvigorate the market trust and impartiality. From a theoretical perspective, the application of our framework demonstrates whether the emerging hydrogen spot indices can bolster the market demand reflection and information symmetry, which are precursors for the efficient market and liquidity creation, which could be applied to various energy and commodity sectors.

Our research provides a starting point for the virtuous cycle: (1) exploring market demand-based, self-regulating pricing mechanisms and methods; (2) improving transparency, reliability, and consistency in pricing, so that it can support the development of low-emission hydrogen trading markets and uptake. Given the scope of thematic content analysis using NVivo and limited access to the hydrogen spot price data, which are available upon subscription to PRAs at hefty costs, the findings mainly explored the extrinsic characteristics based on methodology guides, rather than the empirical dynamics of hydrogen spot price discovery on real-world trading floors, which would demonstrate versatile intrinsic characteristics. Due to the limited accessibility of other price reporting agencies' methodology guides, this study focused on two major indices, which could constrain the depth and breadth of the findings. Future work could include all other indices and build on the analytical framework presented here to identify optimal pricing mechanisms and methods for hydrogen, including comparative analyses with more mature commodity markets, such as oil and natural gas. Key areas for further study include examining which features of hydrogen spot pricing mechanisms and methods can help expand and modernise hydrogen spot trading, enhance energy efficiency and resource allocation, prevent price manipulation and underrepresentation, so that it can encourage the broader adoption of low-carbon hydrogen.

CRediT authorship contribution statement

Chaewon Kim: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Scott M.R. Mahadeo:** Writing – review & editing, Supervision. **Keiron P. Roberts:** Writing – review & editing. **Christopher R. Jones:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129758.

Data availability

Data will be made available on request.

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