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Cities leading hydrogen energy development: the pledges and strategies of 39 Chinese cities

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Hydrogen energy from renewables has the potential to address climate challenges, and technological advancements are vital for driving this energy transition. Globally, an increasing number of cities are actively adopting hydrogen strategies. The literature on the urban sustainability transition primarily focuses on policy innovations for technology adoption, while the role of cities in enabling technological innovation is underexplored. Here, we address this gap by analyzing 122 policy documents from 39 Chinese cities with hydrogen plans by using qualitative content analysis methods. The findings reveal myriad and critical roles of cities in fostering technological innovations in an emergent hydrogen economy via targeted policy support and investment in desired technologies. By moving ahead of the national government, these early movers play a critical role in creating early momentum and laying the foundation for future scale transition. Our findings also point to a clear need for these bottom-up initiatives to be better guided and channeled toward clean hydrogen development, as the lack of upper-level policy guidance can lead to diversified priorities and outcomes. Our findings call for renewed research and policy attention to the proactive role of cities in technological innovation and the sustainability transition and they stress the importance of engaging cities in hydrogen economy development nationally and internationally.

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INTRODUCTION

Hydrogen energy from renewable resources has the potential to address climate challenges[1], but there are barriers to lowering costs on both the supply and demand sides, with technological advances being the key to success[2–5]. Many countries are racing to develop hydrogen energy[4,6–10], with the primary goal of taking the lead in hydrogen technology, as well as for additional environmental benefits and diversification of energy supply[11].

Globally, frontrunner cities are proactive in climate protection[12–14]. In recent decades, cities have risen to become a new power in battling climate change[15–19], with more than 1000 cities worldwide making net-zero pledges as of 2021[20]. In the emergent hydrogen-economy landscape, a few early-mover cities are actively developing and adopting hydrogen fuel for diverse purposes[21–23]. For example, the Kitakyushu Hydrogen Town in Japan was launched as a demonstration project included in smart community initiatives[22]. In Fukushima Prefecture, the local goals of hydrogen adoption are driven by a post-nuclear disaster transition strategy—to build a society powered by 100% renewables and hydrogen energy[23]. In addition, some pioneering cities in Europe expect the introduction of hydrogen fuel to help mitigate local air pollution and support economic growth[21]. Some frontrunner cities in China are actively introducing local hydrogen strategies to enable technological innovations and adoption.

In the literature, the focus of urban sustainability transition research is primarily on cities' innovation capacity in policy, community-led actions, or sociotechnical experiments[24–27]. These studies have explored a variety of innovative urban initiatives promoting the adoption of new technologies (e.g., smart city technologies, electric vehicles, solar and wind power, and sponge city demonstrations) to achieve their transition goals[28–33]. These studies emphasize the role of cities in applying and embedding sustainability technologies to meet reduction targets. However, despite some empirical evidence that a city may invest in sustainability technologies such as solar water heaters[26], the question of whether and how cities can play an active role in promoting R&D for sustainability has yet to be systematically explored. Investigating the willingness and efforts of municipal governments to facilitate technological innovations within their jurisdiction will deepen our understanding of cities' contribution to the sustainability transition. Such insight is of particular importance in hydrogen energy development, as technological advancement is vital in aiding this emergent transition.

Cities are regarded as the loci of knowledge production and technological innovation; they are where actors congregate and where capital and technical resources are concentrated[34]. The innovative capacity of cities is positively related to their size, and innovation cycles are running at an accelerating rate to maintain sustainable growth[35]. In addition, the creative capacity of cities is improved when activities are deeply embedded in intercity innovation networks, where inventor interactions can be enhanced[36,37]. Importantly, policy effort is needed to navigate cities' innovation potential toward the desired directions[38]. In an emergent landscape in which hydrogen is being adopted into energy systems, investigating the drivers, opportunities, barriers, and impacts of city-level hydrogen policies will provide timely new insights into cities' role in incubating technological innovations and will contribute toward accelerated hydrogen adoption.

Various experiments incubated in cities can be scaled up for broad transition[25,38–41]. The concept of urban sustainability experiments can be understood in two layers: first, a city as a whole can be considered a sustainability experiment when examining its role in enabling a national/international transition; second, cities can be seen as an incubator or lab for experimentation[42,43]. The sustainability experiments fostered by/in cities can inform upper-level policy-making or intercity learning[42,44]. Understanding the mechanisms to facilitate the

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upscaling process, such as the vertical and horizontal linkages between agents, is crucial for providing insights[38,45,46].

In this research, we took frontrunner cities from China as case studies to explore cities' potential role in enabling the transition toward hydrogen fuel. Since 2017, a growing number of Chinese cities have announced hydrogen strategies[47], even though China did not have a national-level hydrogen strategy as of the end of 2020. Moreover, some regions in China are ahead in hydrogen technology R&D and adoption[47–49], such as the Bohai Circle, Yangtze River Delta, and Pearl River Delta, which benefit from local policy support and industrial development. Frontrunner cities have made a vital contribution to the initial achievements of these regions[48].

Even in the absence of an explicit state strategy by 2021, intentions to develop hydrogen-related technologies were occasionally mentioned in several national policy documents in China. For example, in 2016, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) jointly issued an action plan for energy technological innovations (2016–2030), in which hydrogen energy and fuel cell technologies are listed as one of 15 key innovation tasks. In addition, another set of policies on hydrogen vehicles was gradually introduced over a period of years, including the Subsidy Policy for the Promotion and Application of New Energy Vehicles starting in 2015, the Development Plan for the New Energy Vehicle Industry (2021–2035) issued in 2020, and the Fuel Cell Vehicle Pilot City Policy launched in 2020. Notably, China's pledge to become carbon neutral by 2060, which was announced in 2020, is expected to promote or accelerate the adoption of hydrogen fuel[50].

In reality, there are institutional barriers to hydrogen production, storage, transport, and usage because in China, hydrogen was previously regulated as a hazardous chemical. Due to this regulation, the approval procedure for constructing a hydrogen refueling station was complex and time consuming, involving multiple government sectors[49]. Moreover, policies and standards for supporting hydrogen energy have not yet been established, which is a deficiency that creates confusion and difficulty for potential developers[51]. Since 2020, efforts have been made to address these policy barriers. For example, the Energy Law of the People's Republic of China (Exposure Draft) started to list hydrogen as an energy source. Subsequently, the National Bureau of Statistics of China added hydrogen to the list of annual energy statistics. These policy changes may indicate a promising role for hydrogen energy in China's sustainability transition.

The 2020 launch of the Fuel Cell Vehicle Pilot City Policy has encouraged more cities to join the hydrogen energy trend as they compete to be chosen for the pilot project. Unlike other programs, this policy encourages intercity collaboration by requiring cities to apply in teams instead of competing with each other in the hydrogen economy. This policy is the first national scheme for hydrogen adoption that specifically engages cities as key players.

This paper attempts to answer the questions – are cities active in enabling hydrogen technological R&D in an emergent hydrogen economy? If so, why and how? Specifically, we address four subquestions by examining the urban hydrogen policies of 39 frontrunner cities in China, i.e., (1) on what value chain segments are city-level policies focused? (2) What hydrogen production methods are prioritized by cities? (3) How do cities support R&D activities within their jurisdictions? (4) What motivates frontrunner cities to do so? For analysis, we conduct qualitative content analysis of policy documents.

RESULTS

Focus of urban strategies on hydrogen value-chain segments

The focus of city-level strategies on hydrogen value chain segments is presented in Fig. 1. Each bar represents the number of cities, and the color represents the policy intentions: blue bars are cities encouraging technological development; orange bars are those promoting hydrogen adoption. On the supply side (including hydrogen production, storage, and transport), more cities support technological innovation than encourage technology application. The opposite trend is observed in the fueling station segment. Almost all cities issued policies supporting an increase in refueling infrastructure; comparatively, only half supported technological innovation in this field through policy. On the demand side, hydrogen use in the urban transport sector has attracted the most policy attention, and policies equally support technological innovation and demonstration. Comparatively, fewer cities have policy plans to drive hydrogen use in the power, industry, and building sectors; in particular, there is little support for R&D. Notably, many cities stated their visions of building a hydrogen society in the future, indicating an ambition for a broad use of hydrogen in other urban sectors beyond transportation. However, they are not the immediate focus.

We further investigated the hydrogen production methods proposed by these cities, as shown in Fig. 2. Four methods are mentioned in the policy documents—hydrogen production from (1) fossil fuel, (2) fossil fuel with Carbon Capture and Storage (CCS), (3) grid electricity, and (4) renewables. This categorization is crucial for understanding whether city-level policies can potentially benefit sustainability development. Figure 2 presents the numbers of cities with near-term hydrogen production plans (by 2025). Most cities support hydrogen production from multiple sources; thus, a city can be counted multiple times under different

Fig. 1 City-level hydrogen technological development policies and technology application policies. Bar length represents the number of cities.

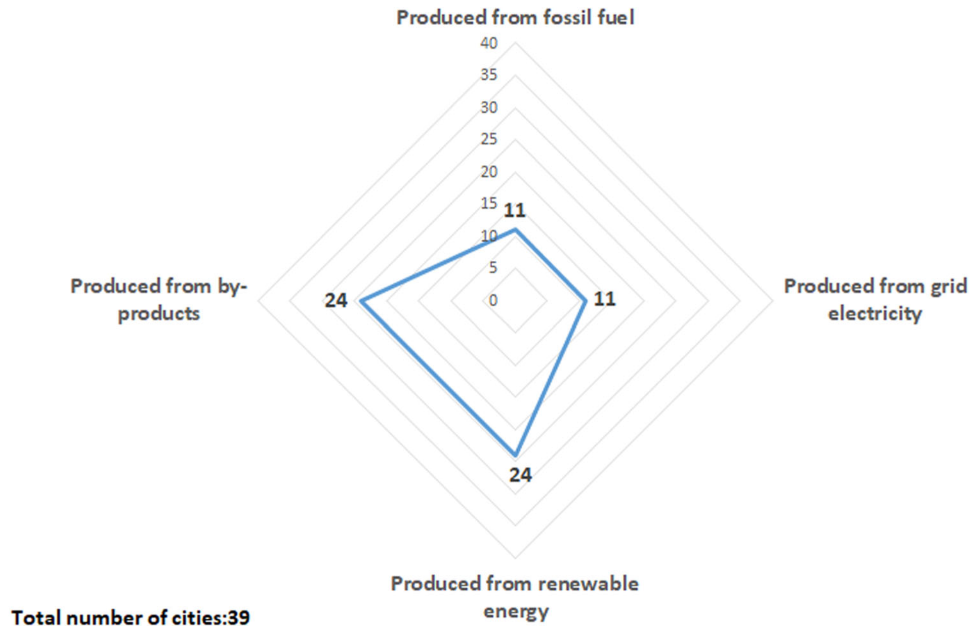

Fig. 2 Hydrogen production methods proposed in city-level policy plans by 2025. The position of data represents the number of cities.

categories. The results reveal that 24 out of the 39 cities expressed their intentions to encourage renewable hydrogen. Also, producing hydrogen from industrial by-products is another popular approach employed by cities (24 out of 39). The by-product approach has immediate benefits, such as using possibly wasted resources and providing hydrogen supply to meet near-term demand. The findings indicate that cities might adopt the most accessible methods in the initial stage (by 2025). For example, if they are close to renewable resources, they may prefer to advocate renewable hydrogen. If they have ample by-products from local industries, they may plan to prioritize these ready-to-use resources. If cities have established hydrogen industries from fossil fuels, they might follow this path in the near future before transitioning to green hydrogen. A study examining national strategies for hydrogen development worldwide also revealed a similar trend— most nations planned to 'scale first and clean later' to enable the proliferation of hydrogen energy in the immediate future[52]. Fossil fuels account for a large share in the composition of primary energy production in China, with coal and oil taking up 67.6% and 6.8%, respectively, in 2020, although the share of primary electricity, including renewables, has been increasing over the years, e.g. from 9.6% in 2011 to 19.6% in 2020[53]. Hydrogen production from renewables is expected to increase in the coming decade after the introduction of national strategy[54].

Moreover, thirty-two of the 39 cities had planned or introduced policies to encourage both hydrogen vehicle adoption and refueling station deployment, signifying a co-existence phenomenon in these two areas. This identified pattern may reveal an adoption strategy for governments—promoting hydrogen vehicles concurrently with refueling infrastructure. Meyer and Winebrake[55] argued that 'a coordinated policy approach that simultaneously encourages both the purchase of hydrogen vehicles and the building of hydrogen infrastructure is the most effective approach for rapid vehicle—infrastructure adoption.' Shin, et al.[56] also verified that expanding infrastructure is a cost-effective option for encouraging the purchase of hydrogen cars.

All thirty-nine cities indicated their preference to adopt fuel cell vehicles as heavy-duty or public-use vehicles in their immediate plans, such as in urban public transport (e.g., buses and delivery vehicles) and industrial vehicles (e.g., forklifts and heavy-duty trucks). A few cities planned to purchase hydrogen vehicles for their government fleets. Comparatively, fewer cities (19 out of 39) planned to encourage the use of hydrogen passenger vehicles in taxi, business, and rental cars in the short or mid-term.

In addition, as indicated in Fig. 1, policy support for technological development extends to all segments of the hydrogen value chain, indicating that cities not only are operational units for adopting hydrogen into their infrastructure but also are direct supporters of technological R&D. Globally, technological development is the key driver in the hydrogen energy transition[57]. In China, hydrogen production and fuel cell technologies are acknowledged as critical technical gaps in several national-level government documents. Such a global and domestic environment might encourage cities to invest more in technological development. In the next section, we will further explore the motivations of cities for doing so.

The horizontal axis of Fig. 1 shows the policy development progress in these cities. For example, in the hydrogen production segment, 34 cities set their policy goals to support technological R&D, and 27 cities made further roadmaps for meeting these goals. Some cities translated the plans into policy action: 29 cities announced policy measures to adopt in the future, while 24 cities had already implemented some policy tools. Overall, the number of cities gradually declines along the horizontal axis as they move from vision to action. Similar trends can be found in other segments.

We further examined and compared the policy progression of each city, as shown in Fig. 3. We identified 11 types of policy instruments employed by these cities for technological innovation and application (see details in Methods section). In Fig. 3, the orange bar represents the number of policy instrument types being implemented, while the blue bars represent the total number of all planned and implemented instrument types. As revealed in Fig. 3, cities varied in policy progression. For example, seven cities on the right side of the graph had only announced policy intentions and had not yet implemented any measures, while a few cities on the left side of the graph had already made progress. Cities differ in terms of their hydrogen industry base, industrial structure, financial capacity, and policy vision for sustainability. It seems that cities that are leading in hydrogen/fuel cell development may already have many policies in implementation, while cities in the early stages of hydrogen energy industries are more likely to be on the right side of the graph. This finding may indicate that these frontrunner cities have

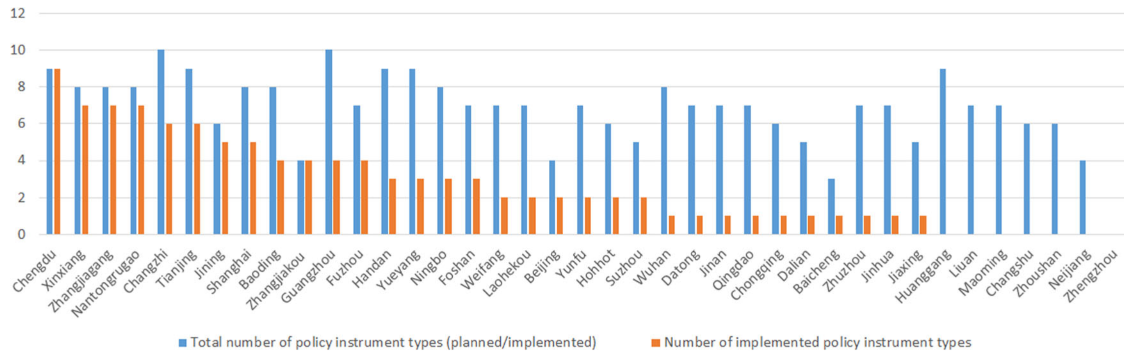

Fig. 3 Policy progression in each city. Bar length represents the number of policy instrument types.

invested in hydrogen plans with different levels of capacity and investment. Since these cities share the same policy environment in China, the heterogeneity in policy progression might be due to endogenous or regional factors. We will discuss this issue in the next section.

Policy instruments for technological R&D and application

We further investigated the policy instruments adopted by these cities and present their distribution patterns across value chain segments in Figs. 4 and 5. These instruments are organized into two categories based on policy intentions: (1) promoting technological development as presented in Fig. 4 and (2) encouraging technology application as presented in Fig. 5. Bars in blue represent policies in planning stages; bars in orange represent policies in implementation. The bar length shows the number of cities using each policy instrument.

Cities employed a suite of policy instruments to support technological development: enabling institutional arrangements, regulation, financing mechanisms for leveraging investment, demonstration projects, tax incentives, subsidies, pilot districts, industrial parks, and R&D funding. The policy support is comprehensive, including fiscal and nonfiscal measures. Two policy measures in particular—building a supportive institutional environment and providing financial incentives (e.g., tax incentives, subsidies, and R&D funding)—are used more frequently than the others. The policy instrument of industrial parks is also widely employed, especially in hydrogen supply segments and the urban transport sector. In terms of policy progress, three policy instruments—enabling institutional arrangements, subsidies, and R&D funding—appear more in implementation than in planning. The opposite trend is observed for financing mechanisms and industrial parks, where most cities have planned to adopt them but only a few have taken action.

To enable technology application, cities adopted another suite of policy instruments, including enabling institutional arrangements, regulation, financing mechanisms for leveraging investment, demonstration projects, government procurement, pilot districts, industrial parks, subsidies, and land-use policies. Some policy tools are specifically to enable technology adoption. For example, government procurement is planned/adopted by some cities for hydrogen vehicles. Land-use policies are used to support the construction of refueling stations and other demonstration projects. Compared with policies for technological development, demonstration projects receive more popular support from cities, especially in the segments of hydrogen production, fueling station growth, and applications in the urban transport, power, and building sectors. Half of the cities had planned or issued regulations for hydrogen refueling station construction and operation, and roughly a quarter of them had done so for hydrogen-fueled vehicle application. As noted previously, the institutional development for hydrogen energy is still ongoing at the national level in China. This finding may indicate that cities are proactively taking action to fill this gap to enable the adoption of hydrogen energy. Similar to R&D support policy, subsidies have been commonly adopted and implemented by these cities, while two policy tools—financing mechanisms and industrial parks—have mostly been planned rather than implemented.

Motivations of city-level hydrogen strategies

The first dedicated national-level hydrogen-relevant program—the Fuel Cell Vehicle Pilot City Policy—was introduced in 2020, and many cities responded by issuing local hydrogen or fuel cell vehicle development plans. However, among the 39 case cities, we identified 21 cities that had introduced the relevant policies before this national-level scheme, indicating that this national policy framework may not directly drive the policy development of these pioneers. We analyzed the motivations of these 21 pioneers as stated in their policy documents and summarized them in Fig. 6.

As shown in Fig. 6, the upper-level government is an influencing factor in enabling city-level strategies. Sixteen cities acknowledged that their hydrogen strategy decisions are influenced by various national plans. Nine cities stated that their hydrogen schemes are in response to provincial-level hydrogen frameworks. Research on urban climate governance has found that vertical links across levels of government can facilitate local-level actions[42,45]. We further investigated the provincial-city links in these cases. In some cities, provincial policies may play a critical role in stimulating city-level strategies and encouraging intercity collaboration. For example, in Shandong Province's hydrogen strategy, the targets for each city and the expectation for intercity collaboration are explicitly articulated. Later, four cities (Weifang, Jinan, Qingdao, and Jining) responded to this provincial strategy by issuing city-level plans. In other cases, provincial schemes might play a limited role in inspiring city-level policies, as pioneer cities were ahead of the province in declaring local strategies. For example, Zhangjiagang and Nantongrugao in Jiangsu Province disclosed their hydrogen strategies a year before the provincial framework was announced. Notably, in China, only a few provinces had issued hydrogen strategies[47]; therefore, many frontrunner cities included in this study planned their hydrogen strategies in the absence of provincial guidance, for instance, Zhuzhou and Yueyang in Hunan Province and Wuhan and Laohekou in Hubei Province.

Moreover, the global momentum to develop a hydrogen economy may impact these cities, as 12 cities described the worldwide trends in their policy documents. In addition, 19 cities expressed ambitions of taking the lead in this emerging field as national or global frontrunners. The expressed interest in joining the global trend of the hydrogen economy may signify that cities have identified future opportunities if they can act early. While the leadership role of cities in adopting sustainability technologies has

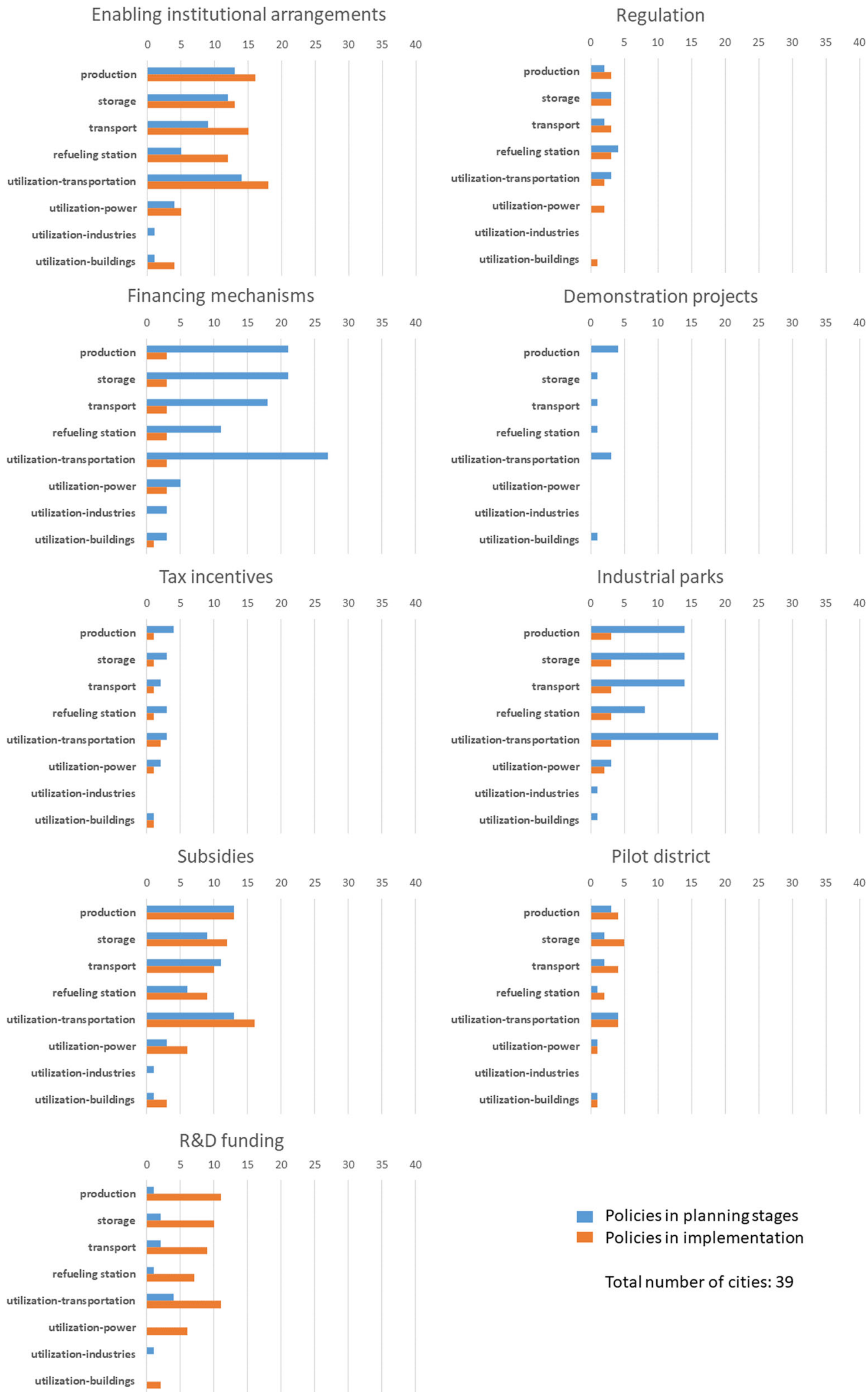

Fig. 4 Policy instruments employed by cities to promote hydrogen technological development. The bar length shows the number of cities using each policy instrument.

been recognized and discussed by academics and practitioners[38,58,59], cases where cities support technological development with the explicit goal of taking the lead in a new industry—as demonstrated by these cases—are not widely reported. This revealed motivation depicts the willingness of cities to embrace technological R&D opportunities for global sustainability.

Endogenous factors are also disclosed in these policy documents. Some cities acknowledged that their specific endowments

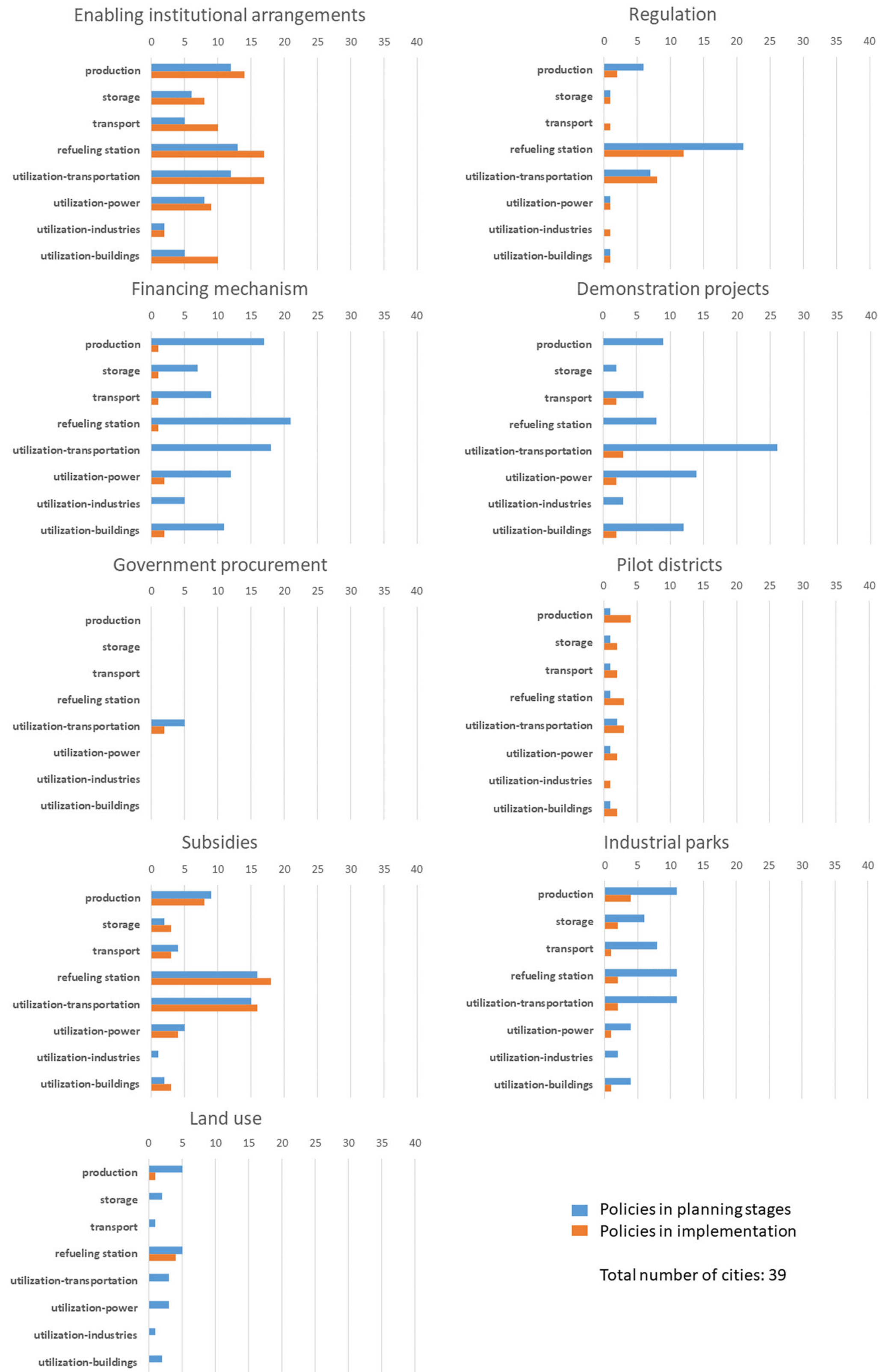

Fig. 5 Policy instruments employed by cities to promote hydrogen technology application. The bar length shows the number of cities using each policy instrument.

provided an advantage as pioneers in the future hydrogen economy. For example, some cities might be close to renewable energy sources or have ample industrial by-products for hydrogen production; some cities may have already established relevant industrial bases (e.g., motor industries) or achieved technical innovations in this field; and some may have identified emergent local market opportunities. Previous research has found that some endowments of cities may provide an opportunity to initiate

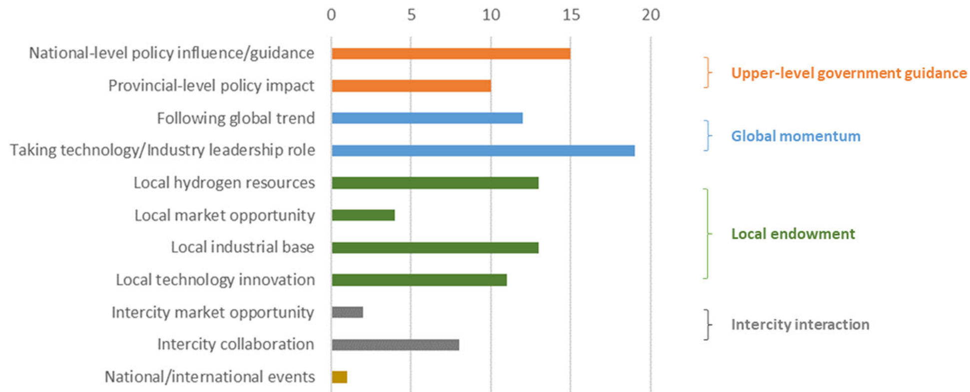

Fig. 6 Motivations of frontrunner cities to develop the hydrogen economy. Bar length represents the number of cities.

positive inertia that may potentially support urban sustainability practices in the long run[60]. In this study, we found that some case-study cities issued long-term technological innovation/renewable energy policy schemes before making hydrogen plans. To some extent, the hydrogen strategies that were planned later might have inherited policy support from prior policies as their extensions in specific areas such as hydrogen energy. For example, Guangzhou city introduced the 13th Science and Technology Innovation Five-Year Plan in 2016, in which the supporting list included hydrogen-related technologies. This established policy framework may have laid (and may continue to lay) the foundation for hydrogen strategies introduced later. Another example is Zhuzhou city. Its hydrogen strategy was announced in 2019 after an earlier renewable energy scheme in 2018, in which the synchronous development of multiple new energies, including solar, hydropower, wind, and hydrogen, was planned.

In addition, intercity connections are stated in these documents to be a motivation for cities to join in the trend, for example, potential markets in neighboring cities or opportunities for technical/economic collaboration. The role of intercity links in enabling policy learning (e.g., through networks or city-to-city proactive influencing) has been discussed in the literature[44,60], but other types of interactive approaches (such as some in-depth collaboration opportunities as identified in this study) need further investigation. Due to the limitations of the methodology, we cannot explore this topic further in this paper, but our findings suggest paying renewed attention to the role of intercity connections in enabling sustainability transition—from peer influencing/learning to peer collaboration on technology/market development.

Lastly, national/international events could be a driving factor. For example, Zhangjiakou was one of China's host cities for the 2022 Winter Olympic Games. It aimed to provide green energy and green transportation for this international event, which motivated the city to develop its hydrogen energy strategy in 2018.

From the above analysis, we conclude that pioneer cities might be motivated by the following factors to develop local hydrogen strategies: (1) the policy influence of upper-level governments; (2) anticipated economic benefits/technical advantages; (3) local resource, market, technology, and industry endowments; (4) the peer influence of other cities; and (5) national/international events.

DISCUSSION

First, cities have a critical part to play in enabling technological innovations in a hydrogen economy. Cities are regarded as engines of innovation. However, there are critiques against this city-centered innovation argument, contending that while cities may have advantages in providing market access and resources at the innovation distribution phase, similar degrees of firm-level innovation are found in both urban and remote areas[61]. In addition, although the geographic proximity of agents in cities may indeed create opportunities for information exchange and interactions among actors that are instrumental for learning and invention, innovation outcomes must also be supported and enhanced by other factors, such as social, organizational, cognitive, and institutional proximities[62]. Moreover, in recent decades, internet penetration may significantly impact innovation practices in cities and regions by restructuring communication networks[34,63], diminishing a city's advantage in terms of geographic proximity. In this regard, the connection between cities and innovation is neither an inevitability nor a natural bond. Therefore, cities must make efforts to improve and enhance their innovation capacity with the necessary policy support. Existing policy studies on the urban sustainability transition have focused on policy innovations that enable new technology adoption for the sustainability transition instead of explicitly enabling technological innovation and development[42,64]. Our study shows that frontrunner cities in the transition to hydrogen energy were actively and purposefully encouraging technological R&D through a range of supportive policies, suggesting a potential contribution of cities to technological advancement in the hydrogen economy, in addition to being adoption locations for new technologies.

Some research has found that cities are more proactive in facilitating the sustainability transition if they also anticipate the cobenefits of their actions, such as local economic growth or a reduction in air pollution[38,65,66]. Two frequently mentioned motivations in our study—following global trends and taking a leadership role in technology/industrial development—were expected cobenefits that the frontrunners identified. More importantly, as demonstrated by this study, if cities can identify such opportunities, they might be able to take action ahead of the national government. In contrast, if carbon reduction may negatively impact local economic interests, cities may face difficulties or challenges in developing and implementing local sustainability strategies[67].

We discovered from policy documents that some city-level hydrogen plans in China had inherited the policy support of previous/existing local technological innovation or renewable strategies as extensions of these policy schemes in specific areas such as hydrogen energy. In addition, there are diverse local endowments across cities motivating policy-making, as revealed in Fig. 6, indicating the heterogeneity in cities' innovation capacities due to these innate attributes. Some studies also found that innovation processes differed from one city to another, depending on various factors, such as their past innovation trajectories, the diversity or specialization of industrial structures, and human capital endowments[34,37,68]. In this regard, intercity collaboration, as revealed in our case study, may potentially benefit the transition by integrating the diversified strengths of collaborating cities.

The stated ambitions of Chinese cities to promote renewable hydrogen might signify a possible contribution of cities to the future sustainability transition. At the time of data collection, more cities had set short-term goals for renewable hydrogen than long-term goals. This finding might reveal the experimental nature of these early urban hydrogen policies—mainly attending to pilots or demonstration projects in three to five years. These local policy efforts may be able to create or have already incubated dispersed niche markets. The scaling process could possibly be accelerated after the introduction of China's national strategy in 2022, where the goal of producing hydrogen from renewables has been set, i.e., 100,000–200,000 tons per year by 2025. Similarly, the goals of adopting fuel cell vehicles in urban mass transit can open up opportunities for early hydrogen vehicle markets, potentially benefiting technological advancement and preparing for scale adoption in the long run.

Second, cities are playing an experimental role in the transition to hydrogen fuel. This study illustrates a bottom-up approach in the early years of hydrogen energy industry development in China—the frontrunners had introduced their hydrogen plans before a state policy scheme. The urban policies were driven by diverse factors and varied in policy progression. Later, these bottom-up experiments were met with top-down guidance that may play a coordinating role in strengthening collaboration and avoiding overcompetition across cities. For example, the national Fuel Cell Vehicle Pilot City Policy announced in 2020 required cities to proactively seek partners and apply as a team. Most cities teamed up within provinces, while exceptions exist—some cities from different provinces applied together, such as the pairing of Yulin in Shanxi Province (in Northern China) and the city team in Guangdong Province (in Southern China) for project cooperation.

Although the lack of upper-level guidance might result in diversified policy priorities, degrees of detail, and planned periods in the beginning phase, city-level endeavors have laid some primary groundwork for an emergent hydrogen economy, such as creating niche markets, incubating early technological innovations, and establishing industrial bases. The subsequent top-down guidance can build on these foundations and expedite development. Earlier research has identified a nested structure for innovation 'where a top-down design is met with bottom-up innovation and proactive adoption of enabling mechanism'[42]. This governance structure can facilitate policy learning across scales and cities. In our case study, although the initial policy effort came from the ground level, which is different from the designed policy schemes facilitated by the nested structure, it still demonstrates some critical characteristics of the nested structure, such as enabling sustainability experiments and learning.

Importantly, the integration of bottom-up and top-down efforts may also facilitate institutional development for hydrogen energy adoption. The hydrogen energy transition may occur in a systematic way, requiring the replacement of existing energy production, storage, distribution, and utilization systems or the integration of hydrogen into them[1,69]. Thus, the transition toward a hydrogen economy requires not only strong policy support, particularly in promoting infrastructure deployment and technological innovation, but also the growth and development of enabling institutions[70,71]. For example, research on integrating hydrogen into the existing gas supply infrastructure in the Netherlands shows that technical challenges are not the main bottlenecks. Instead, solutions to address institutional barriers are key, such as amending laws, regulations, and standards and integrating various actors in the strategy implementation process[72]. In China, hydrogen was previously regulated as a hazardous chemical[49]; therefore, a new set of regulations and institutions to support the adoption of hydrogen into the existing energy system is needed. Meanwhile, the development of a supportive institutional environment has been widely adopted and implemented by case cities for both technological R&D and application. In particular, some cities are actively developing regulations for refueling station construction and hydrogen vehicle adoption. An advantage of cities in joining the hydrogen energy transition may be their flexibility in making institutional adjustments to accommodate the changes and provide feedback for upper-level policy-making[42,73].

To summarize, our findings suggest that frontrunner cities can potentially play myriad and critical roles in fostering technological innovations in an emergent hydrogen economy by purposefully supporting and investing in desired technologies. However, our findings also point to a clear need for these bottom-up policies to be better guided and channeled toward clean hydrogen development, which in turn can render accelerated sustainability transition. Specifically, frontrunner cities are moving ahead of their national government, particularly when they have existing advantages in developing hydrogen energy or can identify opportunities for future technology leadership or economic potential. In practice, while 60% of them have a clear plan to include renewable energy for hydrogen production, many cities may prioritize hydrogen production methods and application fields that are the most accessible for them based on their diverse energy and technological endowments. This risks lock-in to the path of producing hydrogen from fossil fuels before transitioning to green hydrogen. More generally, the lack of early upper-level policy guidance may result in diversified policy priorities, details, scopes, implementation periods, etc., across cities. On the one hand, this bottom-up approach can stimulate momentum and lay the foundation for future scale transition; on the other hand, it may result in fragmented policy strategies leading to varied transition pathways instead of focusing on sustainability gains. Later, a national roadmap was announced—explicitly emphasizing the target for renewable hydrogen—which can better guide and coordinate these bottom-up initial efforts and accelerate the development of renewable hydrogen in cities. In addition, the bottom-up approach combined with later top-down support has the advantage of facilitating institutional building for accommodating hydrogen energy across levels, which is of particular importance in enabling hydrogen adoption. In this way, the nested structure of innovation, with a strong linkage between national and local governments, can incubate innovations and enable the transition toward sustainability.

The outcomes of such city-level strategies are yet to be seen. However, these strategies demonstrate the willingness and policy investments of cities to enable technological innovations for sustainability within their jurisdictions. The findings call for renewed attention to the proactive role of cities in facilitating technological R&D in the sustainability transition. Empirically, they also suggest the importance of engaging cities as key actors in hydrogen economy development at the national and international levels.

METHODS

We employed qualitative content analysis to explore publicly accessible policy documents that were collected online.

Qualitative content analysis of policy documents

Content analysis is a research method that adopts a series of procedures to interpret text data and draw conclusions from their meaning[74]. The goal is a structured organization of a large amount of text into a few categories to draw new insights or extend existing theories. Hsieh and Shannon[75] summarized three qualitative content analysis approaches: conventional, directed, and summative. The conventional analysis approach explores and derives coding categories directly from text data in an inductive way[75–77]. Directed analysis draws on existing theories and findings from the literature to define a preconceived coding framework that guides the coding process in a deductive manner[75–77]. Summative content analysis approaches text through quantification—counting and comparing the frequency of specific words or content—and then explaining and interpreting the underlying context based on those data[75,78].

Qualitative content analysis is widely used in social research[74], particularly in the nursing, medical and bioethics literatures[77,79]. Recently, this methodology has been introduced in policy research[78,80–83] to describe policy trends and attributes, to compare the use of policy instruments, and to examine policy implementation to inform policy adjustments.

Data collection

To determine the status quo of city-level hydrogen policies in China, we looked for potential case cities by searching several key areas online: news media, third-party reports, and public policy reports. The thirty-nine cities are included as case studies in this research. Each of these cities issued its dedicated hydrogen strategies or fuel cell vehicle development plans before February 2021.

Policy documents were used as secondary data sources. Most city-level policy documents are accessible online. For each city, we included the strategic policy scheme, traced back to the antecedent policies, and followed up with the subsequent policies at the implementation stage, if any. Policy documents were collected over 10 weeks from December 2020 to February 2021.

Defining a coding scheme

To address the research questions, five sets of information had to be extracted from the document data: (1) the policies targeting each segment of the hydrogen value chain, (2) the policy focuses on hydrogen production methods, (3) the policy progression in each city, (4) the employed policy instruments, and (5) the motivation of city-level hydrogen strategies. A combination of inductive and deductive approaches was applied to construct the coding schemes. We took the deductive approach to code the policies in value chain segments, policy plans on hydrogen production methods, and the policy cycle progression of each city. We adopted the inductive approach to code the policy instruments and the motivation. Moreover, the extracted policy information on value chain segments and policy instruments was divided into two groups based on policy intentions: (1) enabling technological development and (2) supporting technology application. A simplified scheme structure is presented in Supplementary Tables 1 and 2. The detailed strategies are described below.

We summarized eight value chain segments for the coding scheme: hydrogen production; hydrogen storage/conversion; hydrogen transportation; refueling infrastructure; and hydrogen utilization in urban transportation, the power sector, buildings, and industries[84]. Coders read through the policy documents and identified the textual description relevant to policy support for these eight segments and then categorized the texts in our database in Excel. Similarly, we included four production methods drawn from the literature for our case study[52,85,86].

A complete policy cycle includes several steps, such as agenda setting, issue definition, policy formulation, the policy decision, policy implementation, assessment, adaptation, succession, and termination[87–89]. The hydrogen economy is still in its infancy; thus, this policy area is relatively new to most Chinese cities. Although most cities are still within the first few steps of the cycle outlined above, examining the policy cycle progression in each city may reveal the varying degrees of policy investment made by each. We defined four policy activities for coding (Table 1): vision/goal setting, strategy/roadmap making, planned policies, and implemented policies. Notably, cities might use multiple policy measures simultaneously. Thus, for a specific city, some policies might be in the planning stages, while others might already be implemented.

We randomly selected 10 cities for the preliminary classification of policy instruments. The first coder read through the policy documents of these 10 cities to record and categorize all policy measures mentioned in the documents. Next, the coders applied this categorization to the rest of the cities and supplemented it with new instrument types as needed. The identified instruments include institutional arrangements (adjusting institutional settings to accommodate emergent hydrogen economy situations), regulations, financing mechanisms (e.g., seed funding to leverage investments from other stakeholders), demonstration projects, tax incentives, subsidies, industrial parks, pilot districts, R&D funding, land-use policy, and government procurement.

The last coding dimension was the motivations of frontrunner cities for adopting hydrogen strategies. We identified 21 frontrunner cities out of 39 based on the release date of their hydrogen strategy. Cities with strategies issued before the Fuel Cell Vehicle Pilot City Policy (2020) were selected because the hydrogen adoption goals of these cities were not directly encouraged by this national pilot program. The coders scanned the strategies of these 21 cities and recorded the motivations reported in the documents. Subsequently, the researchers summarized and categorized the extracted textual information into 11 groups based on the similarity of the descriptions.

Limitations of the methodology

There are two limitations in the methodology of this research. First, policy documents are secondary data. Thus, the information extracted from policy documents might not be comprehensive in terms of interpreting motivations, tracking implementation, and identifying barriers. Content analysis can draw information based only on what cities have disclosed in documents. Nevertheless, this analytical approach is sufficient for the purpose of this research—to understand the overall landscape of city-level hydrogen plans in China, identify frontrunner cities, and explore the motivations of cities for supporting technological development.

Table 1. The definition of policy activities in the coding scheme.

Policy activity	Definition
Vision/goal setting	The expected policy outcomes in a short-term and/or long-term period
Strategy/roadmap	A set of planned measures/activities that the city government will follow to accomplish the goals
Planned policies	Policy solutions or instruments that the government intends to employ but on which it has not yet taken concrete actions
Implemented policies	Policies that have already been implemented in real-world scenarios or for which implementation details have been finalized and announced (and that will be ready to launch soon)

Second, a variety of stakeholders are involved in developing the hydrogen economy, such as research institutes and those in the private sector. The policy document analysis reveals a potential role of city governments in this emergent transition but may not be able to comprehensively reflect the real-world situation, in which many other actors are actively engaged. Interviews with stakeholders will supplement this preliminary research if follow-up studies are conducted.

DATA AVAILABILITY

The data that support the findings of this study are available from the authors upon reasonable request; see the author contributions for specific datasets.

CODE AVAILABILITY

The coding scheme is defined in the method section. Supplementary tables are provided to shed more light on the collected data. The tables consist of names of selected cities (39 in total), names of included policies for each city (122 in total), and a simplified scheme structure with the mark of '√' indicating the policy information coded under relevant categories.

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AUTHOR CONTRIBUTIONS

Y.P. and X.B. conceived of the presented idea and developed the coding scheme and theoretical framework. Y.P. conducted the coding work and supervised the coding process, and performed the analysis. The two authors discussed the results, and policy and theoretical implications, and contributed to the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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