

Article

How Institutional Configurations Drive the Regional Adoption of Hydrogen Fuel Cell Vehicles

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Abstract

Hydrogen fuel cell vehicles (HFCVs) are critical to low-carbon transport. However, the collective influence of government, market, and society on regional HFCVs adoption remains insufficiently examined. Drawing on the institutional configuration theory, this study integrates Necessary Condition Analysis (NCA) with multi-period fuzzy-set Qualitative Comparative Analysis (fsQCA), utilizing panel data from 31 Chinese provinces between 2019 and 2024. The findings reveal that no single institutional factor is necessary for HFCVs adoption; instead, multiple effective configurations emerge from the interplay of institutional components. In Period one, adoption is driven by government–market synergy, government–society regulation, and full triadic coordination. In Period two, adoption pathways converge toward infrastructure-led development, government–society regulation, and trilateral collaboration becoming dominant patterns. Regional comparisons further reveal divergent adoption pathways across eastern, central, and western provinces. The findings elucidate the temporal-spatial evolution of institutional dynamics in green technology diffusion and offer targeted policy implications for HFCVs adoption.

Keywords: hydrogen fuel cell vehicle; multi-period fsQCA; NCA; institutional configuration; regional adoption

1. Introduction

Faced with the dual pressures of accelerating climate change and energy transition, hydrogen energy is gaining growing strategic importance as a zero-carbon energy carrier [1–3]. Hydrogen fuel cell vehicles (HFCVs), characterized by zero emissions and extended driving range, have emerged as a key pathway for deep decarbonization in the transport sector [4]. The International Energy Agency projects that global hydrogen demand will reach 520 million tons annually by 2050, with over two-thirds allocated to the transportation sector [5]. Governments worldwide are accelerating efforts to industrialize HFCVs. According to Interact Analysis [6], by 2024, South Korea had built 193 hydrogen refueling stations and deployed 34,000 HFCVs. Under its “hydrogen society” strategy, Japan has established 166 HRs and deployed over 8000 HFCVs. These cases illustrate that the adoption of HFCVs heavily depends on the systematic deployment of policy instruments and the coordination among institutional logics [7].

As the world’s largest carbon emitter and automobile market, China has elevated the hydrogen industry to a national strategic priority. Since the release of the “Medium and



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Long-term Plan for the Development of the Hydrogen Energy Industry (2021–2035) (hereafter MLT Plan),” by 2024, China has built 540 HRSs and deployed over 20,000 HFCVs, ranking second globally. However, compared with the large-scale electric vehicles adoption, HFCV commercialization remains relatively sluggish and uneven across regions. This sluggish diffusion is widely constrained by high costs and the immaturity of hydrogen supply–refueling systems, while regional unevenness largely reflects differences in infrastructure readiness, industrial bases, and policy implementation capacity [8]. Developed regions such as the Beijing–Tianjin–Hebei Region and the Yangtze River Delta have made significant progress, whereas central and western provinces lag due to inadequate infrastructure and low market acceptance. For example, by 2024, Hebei had 1163 HFCVs, whereas Guizhou had none. Against this backdrop of pronounced regional heterogeneity in institutional environments, effectively coordinating institutional elements across government, market, and society to enable large-scale HFCVs adoption has become a pressing issue. Addressing this issue not only helps optimize China’s policy strategies but also offers valuable insights for other countries advancing hydrogen economy development, as it is increasingly regarded as a future-oriented solution [2].

Compared to conventional vehicles, HFCVs adoption is subject to a more complex institutional environment. It involves not only government and market evaluations but also requires public oversight. Therefore, the interplay of governmental, market, and societal logics must be effectively coordinated. The institutional theory suggests that the coexistence of multiple institutional logics creates both uncertainty and opportunities for synergy [9,10]. However, three gaps remain. First, existing HFCVs studies predominantly examine isolated net effects of single drivers (e.g., policy incentives, technological innovation, or market acceptance) [11–13], leaving unclear which combinations of government, market, and societal conditions jointly enable high adoption [14]. Second, although regional institutional environments exhibit temporal evolution and spatial heterogeneity [4], evidence is still limited on how these enabling configurations change across diffusion stages. Third, conventional regression models with linear and additive assumptions are ill-suited to capture conjunctural causation and causal asymmetry among multiple conditions [15], and configurational evidence in the HFCVs context remains scarce despite the broader use of fsQCA in management and energy studies [16–18].

To fill these gaps, this study utilizes panel data from 31 Chinese provinces (2019–2024) and applies multi-period fsQCA alongside Necessary Condition Analysis (NCA) to investigate how institutional elements interact to form distinct configurations driving regional HFCVs adoption. This study makes three key contributions: First, it transcends single-factor perspectives to reveal the nonlinear synergies of institutional configurations. Second, it pioneers the application of multi-period fsQCA in the HFCV domain, revealing the transformation of the government’s role from direct intervener to institutional facilitator. Third, through the integration of regional heterogeneity analysis, this study provides targeted policy recommendations for HFCVs adoption and offers governance insights for hydrogen transport in China and other emerging economies. Overall, this study advances the application of institutional theory in the context of green technology diffusion and contributes empirical evidence and strategic guidance to support global hydrogen transition efforts.

2. Literature Review and Theoretical Framework

2.1. HFCV Development Research

HFCVs constitute a core application of the hydrogen economy. Existing studies primarily focus on three aspects: developmental prospects and barriers, public acceptance, and mechanisms of market diffusion (see Figure 1). Scholars have identified several chal-

lenges impeding HFCVs adoption, including inadequate infrastructure, hydrogen storage and safety concerns, limited manufacturer engagement, technological constraints, high costs, and insufficient policy support [18,19]. These challenges have highlighted the importance of institutional foundations underlying regional HFCVs adoption.

Public attitudes toward HFCVs have evolved from early-stage technological preference to structured support based on consumer attributes (e.g., social status and knowledge level) [12,20], technological features (e.g., driving range, vehicle type, and interior design [21–23], infrastructure availability (e.g., refueling time and station accessibility) [24,25], policy and economic conditions (e.g., government subsidies and vehicle costs) [26,27], and risk-benefit assessment (e.g., carbon reduction contribution) [11]. Most existing studies adopt micro-level psychological methods, such as survey questionnaires, while macro-level research often employs market simulation and scenario modeling. For instance, Liu et al. [28] performed scenario analysis in Shenzhen to estimate the number of HFCVs and daily hydrogen demand, based on projected hydrogen needs and station costs. Tuofu et al. [29] constructed a tripartite evolutionary game model among the central government, local governments, and enterprises, and demonstrated that regulatory enforcement and competitive pressure play key roles in promoting HFCVs adoption.

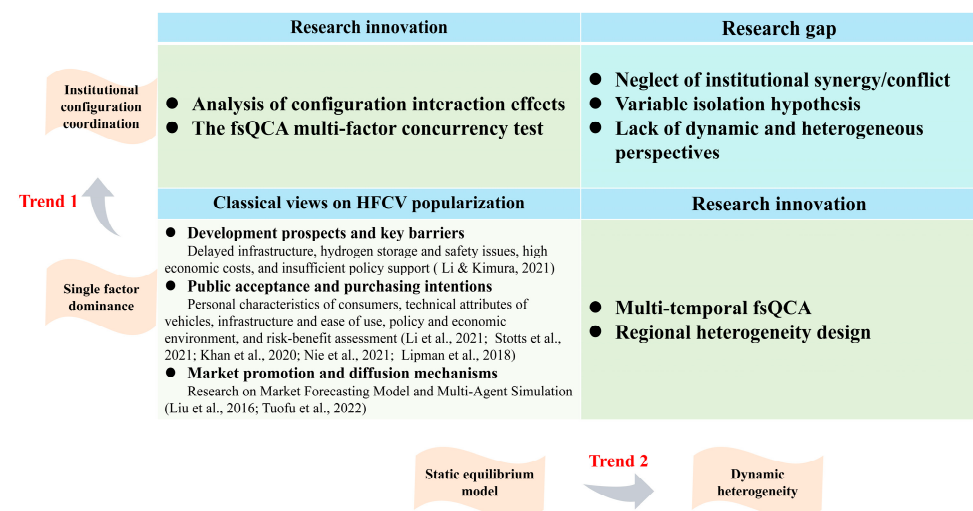


Figure 1. HFCVs adoption research status. The “Author+Year” expressions shown in the figure are citations, corresponding to Li & Kimura (2021) [18]; Li et al. (2021) [21]; Stotts et al. (2021) [25]; Khan et al. (2020) [26]; Nie et al. (2021) [27]; Lipman et al. (2018) [12]; Liu et al. (2016) [28]; Tuofu et al. (2022) [29].

Overall, HFCVs adoption results from the interplay among public, market, and governmental forces. However, existing studies often isolate individual factors—such as subsidies or infrastructure—while neglecting the broader institutional context. Institutional factors encompass both formal rules (e.g., subsidies, environmental regulations) and informal mechanisms (e.g., market access, public perception), which jointly shape the trajectory of HFCVs adoption [30]. Yet, their interactive effects remain underexplored. Moreover, traditional regression models assume independent and unidirectional causality, limiting their capacity to capture configurational and nonlinear relationships [31]. The institutional theory, rooted in organizational sociology, offers a perspective that emphasizes complementarities among multiple institutional elements rather than additive effects [32]. It argues that institutional effectiveness arises not from linear accumulation but from synergistic bundles of complementary institutional elements [13,31]. This theory has been widely applied in low-carbon governance, including studies of environmental performance [33] and green technology diffusion [34,35].

Empirical findings suggest that coupling policy incentives with public environmental concern can enhance adoption, while infrastructure upgrades can independently spur market growth [36]. It indicates that multiple effective pathways for HFCVs adoption may exist, contingent on institutional configurations. However, most literature remains policy-centric, overlooking the combined roles of market and societal mechanisms. Furthermore, linear models lack the flexibility to capture complex institutional configurations. To fill these gaps, this study applies the institutional theory and integrates multi-period fsQCA with NCA to identify institutional configurations driving HFCVs adoption in 31 Chinese provinces and trace their spatial-temporal evolution.

2.2. Theoretical Framework

Greenwood et al. [32] proposed the Institutional complexity framework, highlighting how governmental, market, and societal logics jointly shape green technology adoption. However, the impact of institutional factors on HFCVs adoption remains underexplored both theoretically and empirically. Recent developments in institutional theory emphasize that different institutional configurations can lead to diverse adoption pathways [13,31,32]. Given the heterogeneity in resources, policies, and market maturity across regions, uncovering effective institutional configurations is essential to explain regional variations in HFCVs adoption.

China's MLT Plan categorizes HFCV development into three stages: initial demonstration, accelerated promotion, and large-scale application. The current acceleration phase shows marked interprovincial differences in institutional environments. The current approach to HFCVs adoption research remains fragmented and fails to account for the combined effects of government, market, and society. Guided by the institutional theory, this study employs fsQCA to identify configurations of multiple institutional factors and integrates NCA to assess the necessity of each element. A two-dimensional analytical framework is constructed to examine how institutional configurations evolve across time and space in shaping HFCVs adoption (see Figure 2).

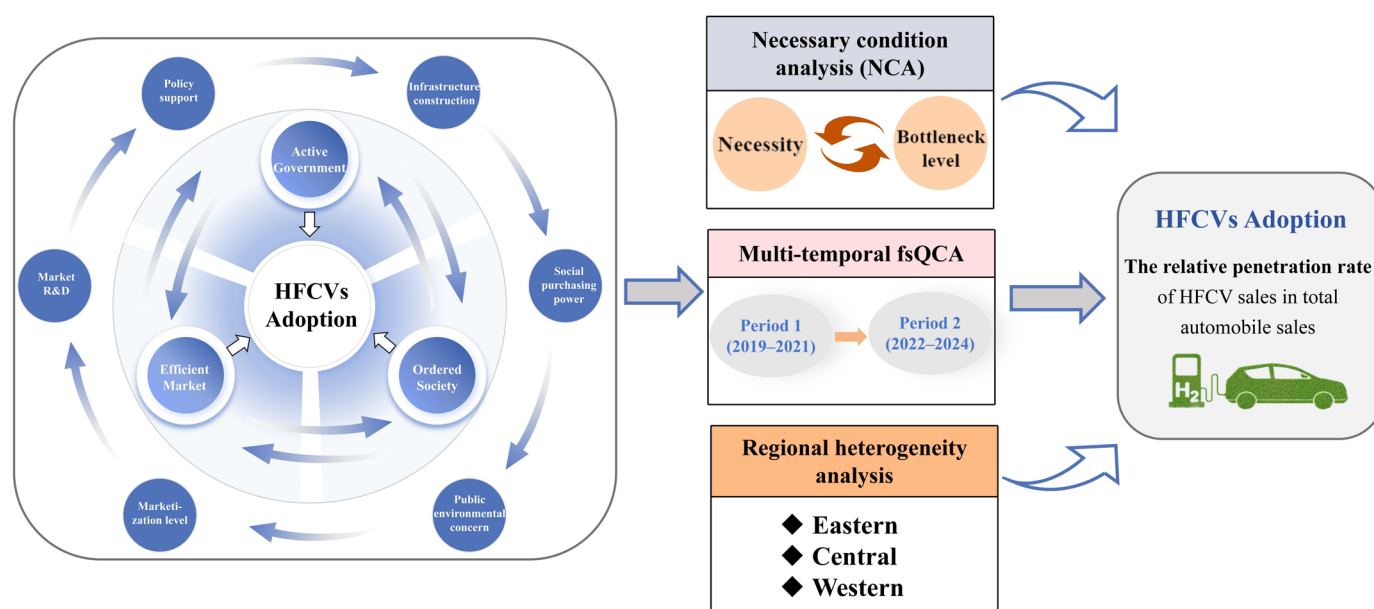


Figure 2. HFCV extension system configuration framework.

First, Active Government is captured by two antecedent variables: policy support and infrastructure development. The government allocates resources directly and shapes market incentives via regulatory frameworks [10]. As the primary institutional actor, the

government shapes the hydrogen ecosystem through policy and regulation. Infrastructure underpins HFCVs adoption by aligning market supply and demand [10,20]. HRs support industry operations and enable practical use by consumers [37,38]. Li and Kimura [18] noted that while HFCVs show advantages in some markets, infrastructure and policy support remain critical to adoption. Hence, this study emphasizes policy support and infrastructure development.

Second, Efficient Market includes marketization level and market R&D capability. Marketization level reflects economic maturity, determining the incentives for market competition, the effectiveness of industrial policies, and the autonomous innovation capacity of market actors [39]. Greater marketization improves resource allocation, accelerates technology diffusion, and strengthens hydrogen commercialization [40]. Furthermore, Schumpeter's innovation theory identifies continuous technological innovation as a key driver of economic growth [41,42]. Improvements in market R&D capability promote technological maturity and commercialization, further advancing HFCVs adoption [43]. Therefore, this study examines the marketization level and market R&D capability.

Third, Well-Ordered Society comprises social purchasing power and public environmental concern. Under the consumption theory, income determines purchasing power [44]. Higher income reduces sensitivity to the initial investment cost of high-priced green technologies such as HFCVs, thereby enhancing market acceptance [24]. With economic growth and rising per capita income, public demand for environmental protection and pollution control has increased [45,46], gradually influencing consumption behavior. Public environmental concern reflects societal emphasis on environmental issues and plays a significant role in promoting HFCVs adoption. Studies show that increased environmental awareness drives demand for clean energy technologies [45,47]. Hence, this study considers social purchasing power and public environmental concern.

3. Research Design

3.1. Research Methodology

This study combines NCA and multi-period fsQCA to identify the necessary and sufficient configurations that influence HFCVs adoption in Chinese provinces [12,30]. QCA has been widely applied in alternative fuel vehicle research, such as the adoption of compressed natural gas in urban transit [48], electric vehicle deployment [16], and public acceptance of alternative fuels [49], confirming its suitability for studying HFCVs adoption. Furthermore, identifying key institutional factors and bottlenecks in HFCVs adoption facilitates policy optimization. NCA precisely quantifies the critical and bottleneck levels of necessary conditions [47,50], thereby complementing QCA findings and addressing scholarly recommendations that “combining NCA and QCA enhances analytical value” [51].

Based on data types, QCA methods are categorized into multi-value QCA (dichotomous data), crisp set QCA (multi-valued data), and fuzzy set QCA (continuous data). As the variables in this study are continuous, fsQCA is adopted to determine optimal configurations for HFCVs adoption. fsQCA comprises three key steps [14,52]. First, calibration assigns set membership scores to cases and conditions. Second, it evaluates whether single conditions are consistently present when the outcome occurs, using Boolean algebra to compute consistency and coverage. The formulas for calculating consistency and coverage are as follows:

$$\text{Consistency } (X_i \geq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(Y_i)} \quad (1)$$

$$\text{Coverage } (X_i \geq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(X_i)} \quad (2)$$

Note: where X_i represents the calibrated antecedent condition, and Y_i represents the calibrated outcome condition for the unit.

Step 3 entails analyzing the sufficiency of condition configurations. First, a truth table is constructed to evaluate whether different condition combinations produce the same outcome [14]. Next, the truth table is refined by applying consistency and frequency thresholds. Finally, Boolean minimization and the Quine–McCluskey algorithm are employed to identify the configurations. The formulas for consistency and coverage indices corresponding to the sufficiency analysis are as follows:

$$\text{Consistency } (X_i \leq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(X_i)} \quad (3)$$

$$\text{Coverage } (X_i \leq Y_i) = \frac{\sum[\min(X_i, Y_i)]}{\sum(Y_i)} \quad (4)$$

3.2. Data Construction

3.2.1. Sample Selection

This study uses data from 2019 to 2024 for 31 Chinese provincial-level regions, excluding Hong Kong, Macao, and Taiwan due to data gaps. On the one hand, provincial governments, as the highest governing authorities within their jurisdictions, play a pivotal role in HFCVs adoption. On the other hand, the release of the MLT Plan has had a profound impact on both China's domestic hydrogen strategy and the global energy landscape. Therefore, data from both before and after 2022 are useful for evaluating the policy's implementation effects. The sample size also meets the QCA requirements for small- to medium-sized datasets. Based on these considerations, data from 2019 to 2024 for 31 provinces form the study's empirical foundation.

To capture the dynamic evolution of regional HFCVs adoption and identify intertemporal similarities and differences, this study uses the release year (2022) of China's MLT Plan as the temporal dividing point. Accordingly, the sample period is divided into two phases: Period 1 (2019–2021), representing the preliminary demonstration stage before the policy's release; and Period 2 (2022–2024), corresponding to the accelerated promotion stage following the policy implementation.

3.2.2. Measurement of Variables

Measurement of Outcome Variables

HFCVs adoption level (HAL). Based on Rogers's innovation diffusion theory [53], the rate of technology adoption serves as a key indicator of adoption effectiveness. Compared to absolute sales or per capita ownership, the relative penetration rate better reflects the structural substitution process of HFCVs in the automotive market. Therefore, this study measures HFCVs adoption using the "relative penetration rate of HFCV sales as a percentage of total vehicle sales," calculated as shown in Equation (5). HFCV sales data is sourced from the Orange Association, while total vehicle sales for each province (or city) are obtained from the China Automotive Industry Yearbook.

$$\text{HFCV relative penetration rate} = \frac{\text{Annual HFCV sales in the province}}{\text{Total annual vehicle sales in the province}} \times 100\% \quad (5)$$

Measurement of Antecedent Conditions

Policy support (PS). The development of strategic emerging industries relies on the joint promotion of a capable government and an effective market [54,55]. This study measures policy support intensity by counting "the number of hydrogen-related policies" is-

sued by each province between 2022 and 2023. Data is sourced from the “Hydrogen World” platform of the China Hydrogen Energy Alliance.

Infrastructure construction (IC). Sufficient HRSs are essential for HFCV deployment, particularly in the early stages of industrialization, as their availability directly impacts market feasibility [24]. This study quantifies infrastructure development by counting “the number of HRSs,” with data sourced from Liu et al. [56] and the “Hydrogen World” platform.

Marketization level (ML). Market competition, legal oversight, and social credit are key indicators of market efficiency. The “marketization index” developed by Wang et al. [57] is widely used to assess regional marketization levels. Therefore, this study employs this index to represent provincial marketization levels, with data sourced from the China Provincial Marketization Index Database.

Market R&D (MR). The maturity and commercialization of HFCV technology depend on sustained R&D investment. Following Borgstedt et al. [58], this study measures market R&D levels using “the number of HFCV industry patents.” The patent retrieval strategy is as follows: IPC = (B60W10/28 OR B60L11/18 OR H01M8) AND TIAB = (vehicle OR car OR automobile) AND TIAB = (“fuel cell”). Data is sourced from the IncoPat database.

Social purchasing power (SP). Variations in income levels among potential early adopters significantly influence their HFCV purchasing decisions [24]. Following Ruan and Yan [59], this study measures social purchasing power using the “per capita disposable income of residents.” Data is sourced from each province’s Statistical Bulletin of National Economic and Social Development.

Public environmental concern (PE). This study employs the “Baidu haze total search index” to measure public environmental concern for the following reasons: (1) As the largest Chinese search engine, Baidu offers extensive coverage and high data availability, effectively capturing public attention across regions. (2) Compared to other environmental keywords, “haze” elicits a stronger public perception of environmental issues [60]. Since haze severity is directly observable through air visibility, it tends to attract greater public attention [61], making it a strong proxy for overall environmental concern. The Baidu Index consists of three categories based on search channels: total search index, PC search index, and mobile search index. This study adopts the weighted composite total search index as the measurement indicator, with data sourced from the Baidu platform, as shown in Table 1.

Table 1. Measurement and source of variables.

Variable Type	Variable Name	Indicator Description	Indicator Source	Identifier
Antecedent variables	PS	The number of hydrogen-related policies	Hydrogen World	https://www.chinah2data.com/#/client/home (accessed on 15 July 2025)
	IC	The number of HRSs	Liu et al. [56] and Hydrogen World	https://www.chinah2data.com/#/client/home (accessed on 15 July 2025)
	ML	The marketization index	China Provincial Marketization Index Database	https://cmi.ssap.com.cn (accessed on 13 July 2025)
	MR	The number of HFCV industry patents	IncoPat database	https://www.incopat.com/ (accessed on 17 July 2025)
	SP	Per capita disposable income of residents	Statistical Bulletin of National Economic and Social Development	https://www.stats.gov.cn/ (accessed on 20 July 2025)
	PE	Baidu haze total search index	Baidu platform	https://index.baidu.com/v2/index.html#/ (accessed on 23 July 2025)
Outcome variables	HAL	HFCV relative penetration rate	Orange Association and China Automotive Industry Yearbook	https://www.shujuku.org/china-automobile-industry-yearbook.html (accessed on 26 July 2025)

3.3. Variable Calibration

This study employs the direct calibration method to transform antecedent and outcome variables into fuzzy set membership scores. Following Furnari et al. [13], three calibration thresholds are set for both antecedent and outcome variables: full out, crossover, and full in, corresponding to the upper quartile (75%), median (50%), and lower quartile (25%), respectively. Table 2 provides calibration details for each antecedent and outcome variable.

Table 2. Calibration of condition and result variables.

Conditions and Outcome	Period 1 (2019–2021)			Period 2 (2022–2024)		
	Full Out	Crossover	Full In	Full Out	Crossover	Full In
HAL	7.120	41.672	0.000	31.208	10.944	0.416
PS	5.000	1.000	0.000	21.000	8.000	3.000
IC	6.000	2.000	0.000	19.000	8.000	3.000
ML	9.822	8.946	7.129	10.992	9.954	8.033
MR	5.000	2.000	0.000	3.000	1.000	0.000
SP	34,108.400	27,904.000	24,810.100	39,889.760	33,355.000	29,932.000
PE	172.027	122.595	85.879	160.825	122.000	94.822

4. Empirical Analysis

4.1. Necessary Condition Analysis

To investigate the constraining effects of various institutional elements on the regional adoption of HFCVs, this study employs NCA to determine whether the antecedent variables constitute necessary conditions for HFCVs adoption. In necessity analysis, NCA mainly utilizes two techniques—ceiling envelopment (CE) and ceiling regression (CR)—to assess the necessity degree of the antecedent conditions [62]. Specifically, CR is appropriate for continuous variables or categorical variables with more than five categories, while CE is more appropriate for binary or few-category discrete variables. Since all antecedent variables in this study are multi-categorical discrete variables, the CR method is adopted for necessity analysis.

NCA is employed not only to identify necessary conditions, but also to quantify their effect size, i.e., the bottleneck level, to determine the minimum requirements for different levels of HFCVs adoption. The effect size ranges from 0 to 1, with higher values indicating stronger constraints on HFCVs adoption [62]. Specifically: $0 < d < 0.1$ represents a “low effect,” $0.1 < d < 0.3$ a “medium effect,” $0.3 < d < 0.5$ a “high effect,” and $d > 0.5$ a “very high effect.”

The NCA is conducted using R 4.5.0, strictly adhering to the procedures recommended by Dul [62] and Dul et al. [50]. A variable qualifies as a necessary condition for HFCVs adoption if it meets all three criteria: (1) effect size ≥ 0.1 , (2) accuracy $\geq 95\%$, and (3) statistical significance in the Monte Carlo permutation test ($p < 0.01$). As shown in Table 3, none of the six antecedent conditions in either period simultaneously satisfies all three thresholds. This indicates that while these factors contribute to HFCVs adoption, no single factor alone is a necessary prerequisite for adoption.

The bottleneck level represents the threshold at which the outcome reaches its maximum observed range [48]. It indicates the minimum required level of an antecedent condition within its observed range, shown in Table 4. For example, in Period 1, achieving 100% HFCVs adoption requires at least 13.7% infrastructure construction, 1% marketization level, and 2.3% social purchasing power. There are no bottleneck levels in the remaining conditions.

Table 3. Analysis results of the NCA method necessary conditions.

Conditions	Method	Period 1 (2019–2021)					Period 2 (2022–2024)				
		Accuracy	Ceiling Zone	Scope	Effect Sizes	<i>p</i> Values ^a	Accuracy	Ceiling Zone	Scope	Effect Sizes	<i>p</i> Values ^a
PS	CR	100%	0.000	0.900	0.000	1.000	100%	0.000	0.950	0.001	0.004
	CE	100%	0.000	0.900	0.000	1.000	100%	0.002	0.950	0.002	0.003
IC	CR	100%	0.007	0.900	0.007	0.000	100%	0.000	0.950	0.000	1.000
	CE	100%	0.013	0.900	0.014	0.000	100%	0.000	0.950	0.000	1.000
ML	CR	100%	0.005	0.950	0.005	0.001	100%	0.000	0.960	0.000	1.000
	CE	100%	0.009	0.960	0.010	0.000	100%	0.000	0.960	0.000	1.000
MR	CR	100%	0.000	0.900	0.000	1.000	100%	0.000	0.910	0.000	1.000
	CE	100%	0.000	0.900	0.000	1.000	100%	0.000	0.910	0.000	1.000
SP	CR	89.2%	0.012	0.950	0.013	0.000	100%	0.000	0.960	0.000	0.099
	CE	100%	0.018	0.950	0.019	0.000	100%	0.000	0.960	0.000	0.098
PE	CR	100%	0.000	0.950	0.000	1.000	100%	0.000	0.960	0.000	1.000
	CE	100%	0.000	0.950	0.000	1.000	100%	0.000	0.960	0.000	1.000

Note: ^a Substitution test employed in NCA via a permutation test with 10,000 redraws.

Table 4. Analysis results of the NCA method bottleneck level (100%).

HFCVs Adoption	Period 1 (2019–2021)						Period 2 (2022–2024)					
	PS	IC	ML	MR	SP	PE	PS	IC	ML	MR	SP	PE
0	NN	NN	NN	NN	0.3	NN	NN	NN	NN	NN	NN	NN
10	NN	NN	0.1	NN	0.5	NN	NN	NN	NN	NN	NN	NN
20	NN	NN	0.2	NN	0.7	NN	NN	NN	NN	NN	NN	NN
30	NN	NN	0.3	NN	0.9	NN	NN	NN	NN	NN	NN	NN
40	NN	NN	0.4	NN	1.1	NN	NN	NN	NN	NN	NN	NN
50	NN	NN	0.5	NN	1.3	NN	NN	NN	NN	NN	NN	NN
60	NN	NN	0.6	NN	1.5	NN	NN	NN	NN	NN	NN	NN
70	NN	NN	0.7	NN	1.7	NN	NN	NN	NN	NN	NN	NN
80	NN	NN	0.8	NN	1.9	NN	NN	NN	NN	NN	NN	NN
90	NN	0.7	0.9	NN	2.1	NN	NN	NN	NN	NN	NN	NN
100	NN	13.7	1.0	NN	2.3	NN	4.0	NN	NN	NN	1.0	NN

Note: NN = unnecessary.

This study further employs the QCA method to examine necessary conditions. As shown in Table 5, the consistency of individual necessary conditions is generally low (<0.9) [14]. This finding aligns with the NCA results, indicating that no single necessary condition exists for HFCVs adoption.

Table 5. Necessity test of the single condition of the QCA method in each period.

Conditions	Period 1 (2019–2021)		Period 2 (2022–2024)	
	Consistency	Coverage	Consistency	Coverage
PS	0.854	0.779	0.763	0.759
~PS	0.259	0.263	0.318	0.322
IC	0.826	0.781	0.801	0.772
~IC	0.292	0.285	0.311	0.326
ML	0.745	0.718	0.636	0.641
~ML	0.343	0.329	0.457	0.456
MR	0.777	0.770	0.576	0.638
~MR	0.310	0.289	0.504	0.462
SP	0.717	0.700	0.652	0.662
~SP	0.370	0.350	0.434	0.431
PE	0.712	0.700	0.645	0.638
~PE	0.382	0.359	0.418	0.426

Note: “~” indicates the not of a logical operation.

4.2. Adequacy Analysis

This study employs the fsQCA 4.1 software to analyze the institutional configurations influencing HFCVs adoption. Following Zhang and Du [63], the raw consistency threshold is set at 0.8, the PRI consistency threshold at 0.7, and the case frequency threshold at 1. The analysis compares parsimonious and intermediate solutions to identify core and peripheral conditions. Solution representation adheres to established research conventions [31]. Table 6 presents the configuration results for the two periods.

Table 6. Multi-temporal configuration results of high HFCVs adoption level.

Conditions	Period 1 (2019–2021)						Period 2 (2022–2024)					
	H1a	H1b	H2a	H2b	H2c	H3	S1a	S1b	S2a	S2b	S2c	S3
PS	●	●	●	●	●	●	●	●	●	●	●	○
IC	●	●	●	●	●	●	●	●	●	●	●	●
ML	●	●	○	○	●	●	○	●	●	○	○	●
MR	●	●	○	●	●	●	●	●	○	○	○	●
SP	○	○	○	○	●	●	○	○	○	○	○	●
PE	○	○	○	○	●	●	○	○	○	○	○	●
raw coverage	0.199	0.178	0.134	0.114	0.488	0.563	0.173	0.158	0.235	0.232	0.231	0.118
unique coverage	0.052	0.020	0.026	0.011	0.015	0.043	0.035	0.023	0.069	0.000	0.012	0.017
consistency	0.894	0.946	0.906	0.868	0.904	0.877	0.892	0.891	0.893	0.893	0.916	0.909
solution coverage	0.728						0.501					
solution consistency	0.853						0.892					

Note: ● = presence of a core condition, ● = the presence of a peripheral condition, ○ = the absence of a core condition, ○ = the absence of a peripheral condition, blank space = either presence or absence.

4.2.1. Period 1 Configuration Analysis

Government–Market Driven Model (H1a and H1b). Configuration H1a identifies high policy support, infrastructure construction, and market R&D as core conditions, with low social purchasing power as a peripheral condition, jointly facilitating HFCVs adoption. Typical cases include Henan_2021 and Sichuan_2020. For example, although Sichuan ranked 18th nationwide in per capita disposable income in 2020, indicating relatively weak purchasing power, the province issued the Sichuan Hydrogen Energy Industry Development Plan (2021–2025) to promote HFCV demonstrations. In 2021, five relevant policies were introduced and seven HRSs were built, ranking fifth nationally. Moreover, Sichuan possessed strong R&D capacity and an industrial hydrogen cluster, with key enterprises such as Dongfang Electric and Rongchuang New Energy achieving technological breakthroughs around 2020, thus providing solid technical support for local HFCV demonstration projects.

Configuration H1b also underscores the central role of government, but replaces infrastructure and R&D with marketization level and low public environmental concern as core conditions, while market R&D and social purchasing power serve as peripheral supports. Representative cases include Tianjin_2020 and Chongqing_2021. Taking Chongqing in 2021 as an example, despite a relatively low public environmental concern level as indicated by a Baidu Pollution Search Index of only 116.11, the combined force of institutional and market elements helped compensate for limited environmental consciousness. In that year, four hydrogen-related policies were enacted, four refueling stations were built, and eight HFCV-related patents were filed, demonstrating strong policy and R&D foundations. Furthermore, Chongqing's marketization index reached 9.822, and its per capita

disposable income was RMB 33,802.6, reflecting strong market functioning and consumption capacity, favorable conditions for HFCVs adoption.

Government and Society Supervision Model (H2a, H2b, and H2c). All three configurations emphasize infrastructure construction and public environmental concern as core conditions but differ in their peripheral factors, reflecting varied institutional logics. In H2a, policy support is a key peripheral driver alongside low marketization level and social purchasing power, suggesting that in regions with adequate infrastructure and strong environmental awareness, HFCVs adoption can be advanced even in the absence of well-developed market mechanisms or high consumer spending power through social initiative supplemented by government support. Typical cases include Shanxi_2021 and Hebei_2020. In 2021, for instance, Shanxi built seven HRSs, and its Baidu Pollution Search Index reached 136.95, indicating strong infrastructure and public concern. Although market mechanisms were immature and household spending power was limited, policy interventions ensured a dual-force approach combining “infrastructure readiness plus environmental awareness” that effectively unlocked local adoption potential.

In H2b, high market R&D replaces policy support as a peripheral condition, suggesting a functional substitution. Typical cases include Henan_2020 and Henan_2019. For example, in 2020, Henan constructed seven hydrogen stations and had a Baidu Pollution Index of 137.81, showing strong performance in infrastructure and environmental concern. Despite issuing only two hydrogen-related policies that year, the province filed seven HFCV-related patents and had a marketization index of 8.872, indicating robust R&D capacity. This demonstrates a government retreat and market compensation pathway for promoting HFCV development.

Configuration H2c maintains infrastructure construction and public environmental concern as core conditions, while marketization level, market R&D, and social purchasing power jointly serve as peripheral factors, forming a supportive institutional structure for HFCVs adoption. Typical cases include Tianjin_2020, Chongqing_2021, and Anhui_2020. In 2020, Tianjin stood out for its hydrogen infrastructure and public concern, forming the core foundation for HFCV development. Although policy support was moderate, the city ranked fourth nationally in both marketization and per capita income, effectively stimulating broader adoption potential.

Government, Market, and Society Synergistic Model (H3). Configuration H3 reveals that high levels of policy support, marketization, and social purchasing power act as core conditions, complemented by strong infrastructure construction as a peripheral factor. Typical cases include Guangdong_2020 and Guangdong_2021. For example, in 2021, Guangdong was officially approved as a demonstration city cluster for fuel cell vehicles. That year, 39 hydrogen stations were completed and 10 were under construction, the highest figures in the country. Concurrently, Guangdong’s hydrogen sector exhibited growing market maturity, with companies such as Horizon Fuel Cell, Xiongchuan Hydrogen, and SinoHytec accelerating their deployment in vehicle and fuel cell system production, forming an integrated government, industry, research, and application ecosystem. Moreover, Guangdong’s leading consumer spending nationally further supported HFCV applications in public transport and logistics scenarios.

4.2.2. Period 2 Configuration Analysis

Infrastructure-Led Model (S1a and S1b). Configuration S1a identifies high infrastructure construction and low marketization level as core conditions, complemented by high policy support and low public environmental concern as peripheral conditions, collectively promoting HFCVs adoption. Typical cases include Inner Mongolia_2024, Shanxi_2023, and Xinjiang_2024. Taking Inner Mongolia_2024 as an example, by 2024, policy initia-

tives and infrastructure provision compensated for deficiencies in market and social mechanisms, realizing a government-led promotion. This pathway illustrates that in resource-rich but market-underdeveloped regions, HFCVs adoption can advance through strong government intervention combined with infrastructure development, forming a typical “government backstop” institutional pathway.

Configuration S1b shows that high infrastructure construction and low public environmental concern serve as core conditions, complemented by high marketization level and high social purchasing power as peripheral conditions, facilitating HFCVs adoption. Representative cases include Tianjin_2024 and Chongqing_2024. For instance, Tianjin built nine HRSs in 2024, ranking among the top nationwide, demonstrating robust infrastructure support. The marketization index reached 9.651, and per capita disposable income was RMB 49,530, both ranking high nationally, indicating strong market mechanisms and consumer payment capacity. By contrast, the pollution search index was only 86.12, reflecting relatively low public environmental awareness. Under these conditions, Tianjin leveraged mature infrastructure and market systems to effectively promote HFCVs despite limited public concern, embodying a “supply-driven, market-responsive” institutional pathway. These findings suggest that in regions where environmental awareness is not yet a main driver, infrastructure and market factors can offer alternative institutional support beyond policy.

Government–Society Supervision Model (S2a, S2b, and S2c). Configuration S2a indicates that high policy support, high public environmental concern, and low social purchasing power serve as core conditions, with high infrastructure construction as a peripheral condition, jointly facilitating HFCVs adoption. This pathway demonstrates that in areas with strong environmental awareness but limited consumer capacity, policy-driven efforts combined with infrastructure compensate for market deficiencies, establishing an institutional basis favorable to adoption. Typical cases include Henan_2023, Hebei_2022, and Henan_2022. For example, Henan issued 14 hydrogen-related policies in 2022, while the Baidu pollution search index reached 189.592, indicating strong public environmental concern; however, per capita disposable income was only RMB 28,222, reflecting limited consumption capacity. Against this backdrop, intensive policy supply and infrastructure investment (21 HRSs) activated social cognition advantages, accelerating HFCV penetration in this traditional energy province.

Configuration S2b replaces high policy support with high social purchasing power and low market R&D as core conditions, maintaining high infrastructure construction peripherally, thereby facilitating adoption. This indicates that in contexts with weak innovation capacity, policy incentives and consumer purchasing power can form a substitute support mechanism. Typical cases include Guangdong_2024, Zhejiang_2023, and Inner Mongolia_2022. For instance, Guangdong led the nation with 66 hydrogen policies in 2024 and had a per capita disposable income of RMB 51,474. Despite limited hydrogen-related patent output and weak innovation momentum, the province built 65 HRSs, forming an integrated pattern of policy promotion, consumer acceptance, and infrastructure support.

Configuration S2c identifies high policy support, high public environmental concern, and low market R&D as core conditions, with high infrastructure construction as peripheral, supporting HFCVs adoption. In contrast to S2b, public environmental awareness replaces consumer capacity as key support, emphasizing that social cognition can enhance technology acceptance amid weak innovation, creating a “policy–society” collaborative substitution mechanism. Representative cases include Zhejiang_2023 and Hebei_2023. In 2023, Zhejiang issued nine hydrogen policies, maintaining strong government guidance. Its pollution search index was 187, ranking fourth nationally, reflecting high environmen-

tal awareness. Although patent output was limited to seven and R&D momentum was weak, the province completed 33 HRSs, providing critical support for HFCVs adoption.

Government, Market, and Society Synergistic Model (S3). Configuration S3 identifies high infrastructure construction, high market R&D, high social purchasing power, and low policy support as core conditions, complemented by a high marketization level as a peripheral condition, collectively promoting HFCVs adoption. This configuration reflects a tripartite institutional synergy, particularly important when policy intervention is weak, highlighting the transformation and coordination of institutional functions. A typical case is Tianjin_2022. In 2022, Tianjin had no hydrogen-related policies, indicating limited government intervention, yet it built ten HRSs with strong infrastructure support. The city also showed strong market R&D capacity, with a marketization index of 10.296 and per capita disposable income of RMB 48,976, reflecting high resource allocation efficiency and consumer payment ability. Under limited policy intervention, adequate infrastructure, mature market mechanisms, and strong consumer willingness and capacity jointly created a multi-faceted driving force for HFCVs adoption, demonstrating a typical government–market–society collaborative mechanism.

4.2.3. Evolution Analysis of HFCVs Adoption Effects in Multiple Phases

Analyzing configurational changes across the two periods reveals the evolving dynamics among “government–market–society” elements. From the perspective of conditions (rows in Table 6), high government support intensity appears frequently in both periods and is mostly a core condition, highlighting its institutional stability in China’s HFCVs adoption. It is primarily present in H1a, H1b, H2a, and H3 during Period 1, and in S2a, S2b, and S2c during Period 2. However, the scope of governmental influence has shifted; in some configurations (e.g., S1a), it becomes a peripheral condition, reflecting a transition from strong state dominance to multi-actor collaboration, where institutional functioning depends more on inter-variable linkages. The role of infrastructure construction has notably weakened, from a core condition in H1a and H2c during Period 1 to a peripheral one in Period 2, indicating a strategic shift from physical deployment toward market regulation and societal recognition. The core status of market and social variables has strengthened. For example, public environmental concern was merely a peripheral condition in Period 1 (e.g., H2c) but emerged as a core condition in S1b, S2a, and S2c in Period 2, suggesting that public opinion, environmental awareness, and societal oversight have become integral to green technology diffusion. Simultaneously, market R&D capabilities and social purchasing power frequently emerged as core or significant peripheral conditions in Period 2, indicating a strategic shift from solely supply-side stimulation toward dual emphasis on market mechanisms and consumer demand. Overall, HFCVs adoption is driven by the interplay of multiple factors rather than any single decisive condition.

From the configurational perspective (columns in Table 6), the driving mechanisms of HFCVs adoption exhibit a clear trend toward simplification over time. First, while the infrastructure-oriented pathways (S1a, S1b) partially overlap with the government–social supervision configurations (H2a, H2b, H2c) from Period 1, no evident subset relationships are observed, suggesting a reconfiguration of their core mechanisms. Notably, government policy support has shifted from a core to a peripheral or even absent condition, signaling a relative decline in government intervention. S2a and S2c can be viewed as the continuation and refinement of the government–social supervision model from Period 1. Both public environmental concern and policy support are core conditions, suggesting that the synergistic effect of policy and social cognition mechanisms tends to be stable. In contrast, S3 evolved from the government–market–society collaborative type (H3) in Period 1 and, on the other hand, clearly contrasts with the government–market driven pathways (H1a,

H1b). The core mechanism of S3 centers on market R&D capabilities and social purchasing power, with government support absent, reflecting the marked strengthening and growing autonomy of market–consumption-driven mechanisms. Overall, the adoption pathways of HFCVs are transitioning from unilateral government dominance to collaborative governance involving government, market, and society. This shift aligns with the intrinsic logic of China’s green innovation governance and offers a stable, adaptive, and replicable model for low-carbon technology diffusion.

4.2.4. Robustness Test

This study follows the prior research strategy of Zhang and Du [61]. Specifically, the raw consistency threshold was increased from 0.8 to 0.85, the calibration anchor points were reselected, the full in point was adjusted from 0.25 to 0.20, the crossover point remained unchanged, the full out point was adjusted from 0.75 to 0.80, and the PRI consistency threshold was adjusted from 0.7 to 0.8. It can be found that the adjusted new configuration has a clear subset relationship with the original model (see Appendix A). This proves that the research conclusion is relatively robust.

4.3. Regional Pathways to HFCVs Adoption

Significant regional disparities in HFCVs adoption pathways arise from differences in resource endowment, economic development, and geography [3]. This study explores the configurations of government, market, and social institutions in eastern, central, and western provinces over two periods (Table 7) to identify key regional drivers. Figure 3 illustrates the spatial distribution of HFCVs adoption from 2019 to 2024, supporting the regional variation analysis.

Table 7. Configuration results of high HFCVs adoption level in different regions.

Conditions	Eastern						Western				Central					
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16
PS	●		●		○	●	●	●	●	●	●	●	●	●		○
IC	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●
ML	○	●	●	○	●	○	○	○			●	○	●	○	●	●
MR	○	○	○	●	●		●	●	●	●	●			○	●	○
SP	○	●	●	●	○	○		●	●			●	●	○	●	○
PE		○		●	●	●	●		●	○		○	●	●	●	●
raw coverage	0.170	0.135	0.209	0.122	0.069	0.117	0.145	0.185	0.426	0.210	0.359	0.157	0.367	0.281	0.110	0.039
unique coverage	0.078	0.038	0.102	0.022	0.023	0.004	0.000	0.047	0.288	0.036	0.024	0.059	0.101	0.178	0.040	0.011
consistency	0.886	0.960	0.840	0.970	0.898	0.964	0.957	0.826	0.801	0.868	0.832	0.935	0.864	0.876	1.000	0.989
solution coverage				0.492					0.473				0.677			
solution consistency				0.887					0.794				0.858			

Note: ● = presence of a core condition, ● = the presence of a peripheral condition, ○ = the absence of a core condition, ○ = the absence of a peripheral condition, blank space = either presence or absence.

As shown in Table 7, HFCVs adoption in China exhibits significant regional differentiation. The eastern region, with its solid economic foundation and leading technological capabilities, serves as the primary hub for HFCV diffusion. All seven pathways in this region take infrastructure as the core condition, indicating that infrastructure deployment capacity is a key driver for its adoption. Notably, pathways R1, R4, R6, and R7 all show a core absence of market mechanisms, suggesting that with the support of a high-level industrial and R&D foundation, market-oriented mechanisms are not a necessary condition for promotion, and government leadership and technological input can serve as effective substitutes. The absence of market R&D capabilities in pathways R2 and R3 further confirms this point. Against the backdrop of mature infrastructure, HFCVs adoption can achieve

breakthroughs relying on physical deployment and engineering capabilities. In pathway R5, policy support is a core absence, indicating that when institutional resource input is insufficient, technology and infrastructure can independently support diffusion. Overall, policy support is mostly a peripheral condition in the eastern pathways, and their promotion relies more on the synergistic support of industrial systems and R&D capabilities rather than policy safeguards.

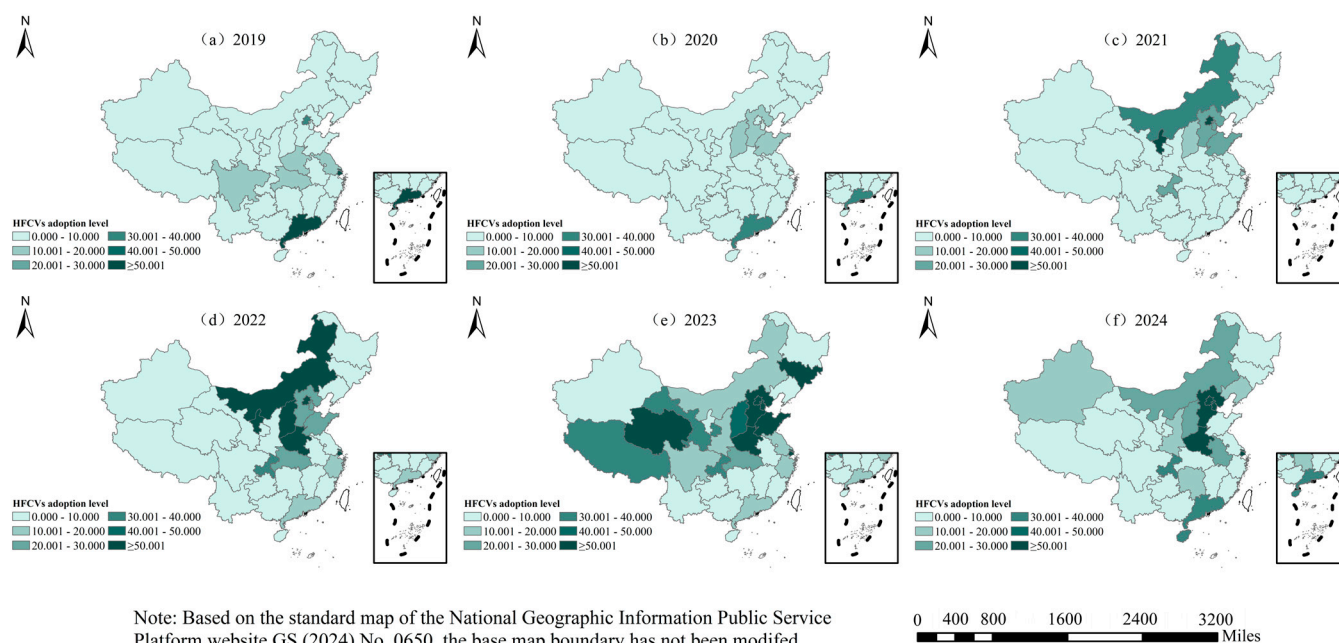


Figure 3. HFCVs adoption levels in various provinces of China from 2019 to 2024. All values are percentages. In the figure, “ ≥ 50.000 ” should be interpreted as $\geq 50\%$.

In contrast, constrained by resource endowments and economic foundations, the western region has a relatively concentrated pathway structure, showing typical policy-led characteristics. Pathway R8 relies on the dual-core driving force of policy support and infrastructure, while pathway R9 features policy guidance combined with social purchasing power and public attention, demonstrating that a green consumption culture is gradually taking shape under policy traction. The fact that market mechanisms do not enter the core structure in either pathway indicates that this region is still in the early promotion stage, dominated by policies.

The central region exhibits significant configurational differences, presenting a typical pattern of multi-actor collaboration. Pathways R11, R13, and R15 simultaneously rely on infrastructure and marketization level, forming strong promotion momentum. Pathways R10, R12, R14, and R16, on the other hand, reflect the characteristics of “infrastructure-led and multi-actor collaborative type,” which can still achieve effective adaptation and support through multi-dimensional institutional factors even when the core conditions are relatively single.

Overall, although HFCVs adoption generally depends on infrastructure construction, there are significant differences in institutional configurations across regions: the eastern region takes technological progress and infrastructure construction as the core driving forces, the western region relies on policy-led mechanisms, and the central region shows a composite pathway characterized by multi-actor collaboration. This spatial heterogeneity reveals the important shaping role of institutional evolution pathways in green technology promotion mechanisms.

5. Discussion and Implications

5.1. Discussion

This study, employing NCA and multi-period fsQCA methods, reveals the institutional configurations and dynamic evolution laws of HFCVs adoption in China, providing a dynamic perspective on the interplay among governmental, market, and societal forces.

Firstly, HFCVs adoption does not rely on a single factor but on the configuration effect of institutional elements. While prior studies mostly focus on the net effect of individual variables on HFCVs adoption, such as policy support, market environment, or technological R&D [10–12], they neglect the overall configuration effect of institutional elements [13]. Drawing on a government–market–society institutional framework, this study constructs a regional system for HFCVs adoption through fsQCA, addressing the limitations of prior studies that fail to account for institutional complementarity. For example, in Period 1, configurations H1a and H1b indicate that the government compensates for deficits in social purchasing power and public oversight through targeted policy interventions and technological reserves; configuration H3 underscores the synergistic effects of government support, market mechanisms, and social purchasing capacity. These diversified pathways substantiate the core tenet of institutional configuration theory: technology diffusion does not depend on the linear aggregation of isolated elements but rather on their synergistic interaction under institutional complementarity [13].

Secondly, the dynamic adjustment of institutional logic is the key mechanism for HFCVs adoption. In Period 1, the government acted more as a direct intervenor, which is consistent with the conclusion of Yang et al. [64] on the importance of administrative intervention in the early promotion stage of new energy vehicles. However, the configurational pathways in Period 2 were significantly simplified, retaining the government-led type (S1a and S1b), government–social supervision type (S2a, S2b, and S2c), and government–market–society collaborative type (S3). Among them, in configuration S2, high public environmental concern has become a core condition, indicating that social supervision is gradually replacing part of the government’s regulatory functions. According to Moon et al. [65], with the improvement of social environmental awareness, social public opinion and environmental actions have prompted enterprises to pay attention to environmental benefits, sharing the pressure of government supervision. This evolutionary trend reveals that the government’s role has shifted from an early “policy promoter” to an “institutional designer”, aiming to guide market and social subjects to participate independently through rules. In addition, this study overcomes the static limitation of traditional QCA through multi-period QCA, revealing that the coupling relationship between government, market, social factors, and HFCVs adoption exhibits clear temporal dynamics, enriching the literature in the field of dynamic QCA [66].

Thirdly, the regional heterogeneity of institutional configurations offers a configuration-based extension to institutional evolution and technology diffusion theory. Rather than treating diffusion as driven by single dominant factors or assuming institutional convergence, our results show that diffusion operates through region-specific institutional “diffusion regimes”—i.e., different combinations of government, market, and societal conditions can generate adoption, and these combinations evolve through recombination of complementarities across stages [67]. This implies a shift in theoretical emphasis from “how much” policy/market/social support matters to “which institutional bundle works under which regional context and stage.” Empirically, the eastern region in Period 2 exhibits a “government–market” dual-core regime, whereas the western region remains government-led, indicating that diffusion in developed regions becomes increasingly market-mediated while less developed regions remain more policy-dependent [53].

5.2. Management Implications

The research findings have significant implications for policy practice. First, the government must dynamically adjust its role based on technological maturity. In the initial promotion phase, the market should be rapidly cultivated through subsidies and infrastructure. Once in the scale-up stage, policy focus should shift towards developing market-oriented mechanisms (such as carbon trading linked to hydrogen) and platforms for social participation. Second, optimize HFCVs adoption strategies from a collaborative “government–market–society” perspective. Policy formulation should consider regional resource endowments and economic structures to create differentiated development models. The eastern region can leverage market and technological advantages to accelerate the improvement of its industrial chain and business models. The central region should strengthen the synergy between government support and market mechanisms, enhance technological innovation capabilities, and optimize the industrial ecosystem. The western region can harness the advantages of new energy resources, such as wind and solar hydrogen production, alongside local policies, to explore resource-oriented promotion models. Third, the increased public environmental concern suggests that public opinion guidance and social supervision play a positive role in the diffusion of green technology. Governments and enterprises should strengthen science popularization and public awareness campaigns, improve public understanding of hydrogen energy and fuel cell vehicles, and enhance consumer acceptance. Simultaneously, they can use social media, industry reports, and other channels to increase public attention to carbon reduction and green travel, foster the integration of social supervision and market mechanisms, and form a synergy to promote HFCVs adoption. In summary, the government, market, and society must collaborate to optimize institutional configuration, integrate regional development stages and market maturity to implement precise policies, promote the high-quality development of the HFCV industry, and provide strong support for achieving carbon neutrality.

6. Conclusions and Limitations

6.1. Conclusions

This study applies multi-period fsQCA to data on HFCVs adoption across 31 Chinese provinces from 2019 to 2024, aiming to explore how institutional configurations drive regional HFCVs adoption. The findings indicate that high levels of HFCVs adoption are driven by the synergistic interaction among governmental, market, and societal factors, with different regions achieving the same outcome through diverse institutional configurations. In Period 1, multiple distinct configurations emerged, including government–market-driven, government–social-supervision, and government–market–society collaborative models, highlighting the dominant role of the government during the early stage of HFCVs adoption. In Period 2, the configurations became more streamlined, comprising government-led, government–social-supervision, and government–market–society collaborative models. This evolution reflects the strengthening roles of market and societal forces, as well as the government’s transition from a direct actor to an institutional architect. Regarding individual conditions, government support remains a central factor, whereas market-oriented research and development, along with social cognition, have shown increasing significance. In terms of configurational evolution, HFCVs adoption pathways have evolved from initial pluralism to mechanism simplification. Infrastructure and social cognition alternately serve as dominant conditions across different stages, while the market–consumption-driven mechanism has gradually gained strength and evolved into an independent driver. Concurrently, the government’s role has demonstrated a phased decline, while multi-actor collaborative governance has emerged as a prevailing trend in HFCVs adoption. This study further explores differentiated HFCVs adoption pathways in

eastern, central, and western China, revealing the adaptive evolution of regional institutional configurations.

6.2. Limitations and Future Directions

This study does not include cross-national comparisons and does not compare China's hydrogen energy promotion models with those of Japan and Germany. Future research could extend the analysis to a longer time frame to examine the long-term effects of institutions. Additionally, cross-national comparisons could be incorporated to explore promotion pathways within different institutional systems. Additionally, building on fsQCA analysis, future research could explore the use of complex system methods, such as system dynamics, to simulate long-term development trends under different institutional scenarios. This could provide more accurate predictions and recommendations for regional policy formulation.

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Abbreviations

The following abbreviations are used in this manuscript:

CE	Ceiling Envelopment
CR	Ceiling Regression
fsQCA	fuzzy-set Qualitative Comparative Analysis
HAL	HFCVs adoption level
HFCV(s)	Hydrogen fuel cell vehicle(s)
HRSs	Hydrogen refueling stations
IC	Infrastructure construction
IPC	International Patent Classification
ML	Marketization level
MLT Plan	Medium- and Long-term Plan for the Development of the Hydrogen Energy Industry (2021–2035)
MR	Market R&D
NCA	Necessary Condition Analysis
PC	PC search index
PE	Public environmental concern
PRI	Proportional Reduction in Inconsistency
PS	Policy support
QCA	Qualitative Comparative Analysis
SP	Social purchasing power

Appendix A

Table A1. Adjusting the original consistency threshold to 0.85 configuration results.

Conditions	Period 1										Period 2				
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15
PS	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●
IC	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
ML	○	○	○	●	●	●	●	●	●	○	●	●	●	○	○
MR	●	○	○	●	○	●	●	○	●	○	○	○	●	○	○
SP	○	○	○	●	○	●	●	○	○	○	○	○	○	○	○
PE	○	●	●	○	●	●	●	○	○	○	○	○	○	○	○
raw coverage	0.130	0.134	0.114	0.178	0.128	0.489	0.488	0.199	0.590	0.173	0.158	0.235	0.118	0.232	0.231
unique coverage	0.013	0.026	0.011	0.013	0.003	0.011	0.015	0.000	0.036	0.035	0.023	0.069	0.017	0.000	0.012
consistency	0.912	0.906	0.868	0.946	0.845	0.910	0.904	0.894	0.882	0.892	0.891	0.893	0.909	0.893	0.916
solution coverage					0.748							0.501			
solution consistency					0.839							0.892			

Note: ● = presence of a core condition, ● = the presence of a peripheral condition, ○ = the absence of a core condition, ○ = the absence of a peripheral condition, blank space = either presence or absence.

Appendix B

Table A2. Calibrates the configuration results of anchors 0.8, 0.5, and 0.2.

Conditions	Period 1							Period 2				
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	
PS	●	●	●	●	●	●	●	○	●	●	●	●
IC	●	●	●	●	●	●	●	●	●	●	●	●
ML	○	○	○	●	●	○	○	○	○	○	○	○
MR	●	○	○	●	●	○	○	○	○	○	○	○
SP	○	○	○	●	●	○	○	○	○	○	○	○
PE	○	○	○	○	○	○	○	○	○	○	○	○
raw coverage	0.242	0.176	0.211	0.507	0.505	0.237	0.245	0.134	0.204	0.247	0.140	
unique coverage	0.044	0.029	0.033	0.015	0.023	0.027	0.018	0.022	0.043	0.000	0.005	
consistency	0.911	0.912	0.955	0.894	0.889	0.914	0.898	0.888	0.920	0.891	0.914	
solution coverage			0.699						0.453			
solution consistency			0.875						0.888			

Note: ● = presence of a core condition, ● = the presence of a peripheral condition, ○ = the absence of a core condition, ○ = the absence of a peripheral condition, blank space = either presence or absence.

Appendix C

Table A3. Configuration results of the PRI consistency threshold of 0.8.

Conditions	Period 1					Period 2				
	C1	C2	C3	C4	C5	C6	C7	C8	C9	
PS	●	●	●	●	●	●	●	●	○	○
IC	●	●	●	●	●	●	●	●	●	●
ML	○	○	○	○	○	○	○	○	○	○
MR	●	●	●	○	○	○	○	○	○	○
SP	○	○	○	○	○	○	○	○	○	○
PE	○	○	○	○	○	○	○	○	○	○
raw coverage	0.142	0.178	0.526	0.107	0.220	0.232	0.126	0.173	0.118	
unique coverage	0.477	0.020	0.358	0.049	0.032	0.087	0.008	0.034	0.044	
consistency	0.983	0.946	0.895	0.952	0.931	0.893	0.885	0.948	0.909	
solution coverage			0.655				0.425			
solution consistency			0.900				0.914			

Note: ● = presence of a core condition, ● = the presence of a peripheral condition, ○ = the absence of a core condition, ○ = the absence of a peripheral condition, blank space = either presence or absence.

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