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RESEARCH ARTICLE

Greenization and Digitization Transformation of Hydrogen Energy Technology Based on a Fuzzy Decision-Making Model

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ABSTRACT The global energy transition is increasingly driven by hydrogen energy, making digital green innovation crucial for hydrogen energy enterprises. This article explores effective strategies for these enterprises to select digital green innovation partners and provides actionable guidance for their transformation and development. First, an evaluation index system is developed using fuzzy set theory, grounded in the principles of digital green innovation partner selection for hydrogen energy enterprises. Next, a dual-combination weighting evaluation method is proposed, integrating combination weighting theory and field theory to build a decision model that supports partner selection for these companies. The model is then applied in a real-world case analysis of Baotailong, demonstrating its practical effectiveness in addressing digital green innovation challenges within hydrogen energy enterprises. The study concludes that a green and digital transformation approach, guided by a fuzzy decision-making model, enables hydrogen energy companies to identify suitable innovation partners. This approach not only aligns with the broader trends of socio-economic development but also enhances the companies' core competitiveness.

INDEX TERMS Hydrogen energy enterprises, digital green innovation, dual combination empowerment, partner selection.

I. INTRODUCTION

In recent years, extreme weather events have become increasingly severe worldwide. Rising temperatures, floods, and droughts, along with more frequent and intense extreme conditions, have inflicted significant economic and social costs, causing widespread environmental damage and threatening biodiversity. Amid these unprecedented global changes, the green industry is gaining momentum, with many countries accelerating institutional and technological innovations to promote economic, energy, and industrial transformation and upgrading, aiming for sustainable development. On October 13, 2022, the International Energy Agency released its World Energy Outlook 2022, highlighting that as more nations hasten their energy transitions, the global clean energy industry has entered a period of rapid growth. With the accelerated evolution of a new round of technological revolution and industrial transformation, and the consensus of countries around the world to actively respond to climate change, hydrogen energy, as a source of abundant, green, low-carbon,

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and widely used secondary energy [1], is gradually becoming a new strategic focus of global competition and an important direction for countries to cultivate emerging industries. An important lever for promoting green and low-carbon transformation of energy production and consumption, and an important carrier for global energy transformation and development [2]. At present, through industrial exploration and development, China's hydrogen energy industry layout is spread throughout the country, and a preliminary industrial form and system have been established, ushering in a window of development. Since the 14th Five-Year Plan, hydrogen energy has attracted more attention with the proposal of China's carbon peak by 2030 and carbon neutrality by 2060.

Under the dual carbon goal, the hydrogen energy industry is rapidly developing, the scale of hydrogen production is increasing, energy sources and application scenarios are becoming more diverse, and hydrogen production stations are upgrading from equipment to system dimensions. Operation and maintenance management, system efficiency, and safety assurance face greater challenges [3]. Based on the industry's present general development, the hydrogen energy sector has a long chain, many business scenarios, great collaboration difficulties, and many data islands [4]. Its large-scale application development still faces high costs, low efficiency of hydrogen energy utilization, insufficient coordination of all links of the industry chain, and complex safety problems [5]. To solve these problems, hydrogen energy enterprises need to seek digital green innovation partners, use digital green means to reduce costs and increase efficiency, generate new business combinations, promote high-quality green and intelligent development of enterprises, and build core competitiveness.

In recent years, researchers have used a variety of approaches and viewpoints to study the growth and transformation of hydrogen energy firms, exploring effective ways for green and high-quality development of hydrogen energy enterprises. In terms of the digital development of hydrogen energy enterprises, Bondarenko et al. explored the prospects of introducing digital technology in the industrial production, transportation, and storage processes of hydrogen energy products [6]. Li et al. examined hydrogen energy firms' issues from an enterprise standpoint, and proposed targeted measures and suggestions around technological development and other aspects [7]. Wang and Miao studied the digital transformation development of hydrogen station through big data analysis, and explored the way to establish an intelligent management system to realize intelligent and Internet based management of various business links such as production, safety and environment of the hydrogen energy industry chain [8]. In terms of the green advancement of hydrogen energy industry, Li et al. analyzed the advantages of the advancement of hydrogen energy in Shanxi Province, then indicated the way design of the green advancement of hydrogen energy industry under the two-carbon development goal [9]. Qin et al. put forward targeted suggestions on the advancement of hydrogen energy in Jiaxing based on the perspective of green, low-carbon and circular city construction [10]. In terms of the innovative development of hydrogen energy enterprises, Shi and Wang focused on building an innovative platform for hydrogen energy, promoting the use of scenarios for hydrogen energy, and provided suggestions for the advancement of Ningbo's hydrogen energy [11]. Yin et al. revealed the innovative development trend of clean energy use from behavioral willingness fields, and put forward targeted countermeasures and suggestions [12]. The above literature provides useful references for the transformation and development of hydrogen energy enterprises from the perspectives of digital development and green development. However, in previous research, there has been a lack of relevant research on the digital and green collaborative innovation development of hydrogen energy enterprises in terms of research content, a lack of research based on digital sustainable economic theory in terms of research theory, and a lack of research on the dual combination empowerment evaluation method based on the combination of combination empowerment theory and field theory in terms of research methods. As a result, it's essential to carry out a thorough investigation about the choice of digital green innovation partners of hydrogen energy enterprises, so as to improve the scientific and rational choice of partners, and provide new ideas for the transformation and development of digital green innovation of hydrogen energy enterprises.

To better align with national policy directives and contribute to the realization of carbon reduction targets, this paper examines the digital and green innovation transformation of hydrogen energy enterprises within the context of global trends and intelligent manufacturing. Focusing on the selection of digital and green innovation partners for these enterprises, the study is framed by the ongoing technological revolution and industrial transformation worldwide. The research begins by designing an evaluation index system for selecting digital and green innovation partners, utilizing fuzzy set theory. By integrating combination empowerment theory and field theory, which emphasize holism and continuity of action, a dual combination weighting evaluation method for assessing digital green innovation capabilities is proposed. A scientifically sound decision model for selecting digital green innovation partners in hydrogen energy enterprises is then constructed, offering a comprehensive method for partner selection. The model is applied in a real-world case study of Baotailong, a hydrogen energy company, to demonstrate its practical utility in addressing the challenges of partner selection. The findings confirm the model's scientific validity and practical effectiveness.

This research fills a gap in existing studies by providing a structured approach to selecting digital green innovation partners for hydrogen energy enterprises. It offers a solution to overcoming the bottlenecks in digital green innovation, fostering a virtuous cycle within the industry chain, enhancing product value, promoting management innovation, and reducing operational costs.

II. LITERATURE

A. FUZZY DECISION MODEL AND ENERGY MANAGEMENT

In previous studies, many scholars have applied fuzzy set theory to energy management: in terms of power management, Liu et al. verified the effectiveness of Fuzzy Set Pair Analysis for power quality assessment by establishing a model [13]. Hussain et al. applied the algorithm of fuzzy logic reasoning to the management of available power of electric vehicles in parking lots [14]. Hussain et al. utilized a two-stage fuzzy logic inference based algorithm (TSFLIA) and a fuzzy logic weight-based charging scheme (FLWCS) to maximize the QoP for the parking lot operators under the operational constraints of the power grid [15], [16]. Yu et al. used a method according to extension cloud model and fuzzy closeness to effectively resolve the subjectivity and uncertainty problems in power quality assessment [17]. In terms of solar energy management, Qeays et al. proposed a mechanism for multi-functional optimization of hybrid photovoltaic photothermal systems by circulating nanofluids around photovoltaic panels for cooling based on fuzzy synthesis methods [18]. Lee et al. applied qualitative evaluation with fuzzy sets to the case of solar photovoltaics to explore the ideal way of energy transformation [19]. Singh put forward to double hesitation fuzzy precision measurement in the research for mode recognition and site selection of solar power plants [20]. In terms of energy transformation management, Li and Tu combined the analysis framework of multi-level perspective with the qualitative comparative analysis method of fuzzy sets to build a variety of low-carbon energy transformation modes [21]. Wu et al. used the fuzzy set theory and decision-making experimental analysis method to find the most critical path to build the pacesetter of the energy revolution [22]. Zhu et al. designed a hybrid electric propulsion energy management system based on fuzzy logic control to promote efficient control and management of energy [23]. However, in the past studies related to energy management, most of them only applied the fuzzy decision model to one direction of energy management, and rarely paid attention to the collaborative development of digital, green and innovative aspects of energy at the same time. Therefore, further research is necessary and urgent.

B. INNOVATIVE DEVELOPMENT OF HYDROGEN ENERGY

With the quick advancement of contemporary technology, hydrogen energy industry is in urgent need of continuous innovation to better adapt to the development trend. Experts and scholars have carried out research on this with different focuses and given feasible suggestions. In terms of the digital innovation and development of hydrogen energy industry, Li took the utilization of hydrogen energy in the digital industry as the research content, and focused on analyzing the development opportunities, growth space and existing problems of hydrogen energy industry [24]. Wang and Miao paid attention to the digital transformation and development of hydrogen refueling stations, and explored effective ways to realize intelligent and Internet-based management of hydrogen energy industry chain [8]. Shi and Wang mainly discussed the digitalization of hydrogen energy industry, and gave suggestions on the improvement of hydrogen energy innovation platform and the promotion of scenario application [11]. Bondarenko et al. mainly explored the prospects of introducing digital technology in the industrial production, transportation, and storage processes of hydrogen products [6]. In terms of green innovation development of hydrogen energy industry, Löhr et al. conducted a systematic historical analysis of past energy projects with the goal of promoting a more just green development transformation of hydrogen economy [25]. Cao et al. focused on green hydrogen energy and revealed its development and utilization approaches and industrial development trend [26]. In terms of the innovation of hydrogen energy industry, Gao and An took note of the industry chain's coordinated advancement for hydrogen energy, and concluded that government-enterprise cooperation is the best way to achieve its collaborative development [27]. Wang mainly studied the patent layout and innovation development trend of hydrogen energy industry and put forward targeted suggestions for China [28]. Based on the perspective of value innovation, Shi put forward the value innovation strategy of hydrogen mobile power from three aspects: application scenario, marketing strategy and profit model [29]. Gao focused on the construction of characteristic hydrogen energy town, and took Taizhou hydrogen energy town as the breakthrough point, providing reference for the planning, design and development of the spatial structure of hydrogen energy town [30]. To sum up, scholars have studied and analyzed the innovation and development of hydrogen energy from different perspectives and focuses, pointing out the direction for the innovation of hydrogen energy sector. However, in the past research, there are few studies on hydrogen energy enterprises, and targeted studies focusing on the digital, green and innovative development of hydrogen energy enterprises are even more scarce. The partner selection of hydrogen energy enterprises in the process of digital, green and innovative development is lacking of reference opinions.

C. DIGITAL GREEN INNOVATION MANAGEMENT

In recent years, digital economy, green and low-carbon, innovation driven, industry collaboration, and open sharing have become hot topics. In terms of the role of digital green innovation management, Zhao et al. pointed out that digital transformation can promote the increase of total factor productivity by improving innovation capabilities and reducing costs through mechanisms [31]. Dai and Yang found through empirical study that digital empowerment can push the green transformation of firms [32]. Li and Zhao believed that the highly coordinated development of digital economy and green economy system will effectively improve the efficiency of financial services and optimize resource allocation [33]. Yu et al. concluded through their research that advocating digital green finance contributes to the advancement of green energy and decrease environmental pollution [34]. Du et al. believed that digital rural areas can promote the improvement of agricultural green total factor productivity [35]. Hu et al. explored the significance of green digital technology and green HRM in the growth of tourism in China in their research [36]. In terms of research methods, Li and Zhao mainly investigated the role of collaborative development between digital economy and green economy systems in optimizing resource allocation by using a coupled coordination degree model [33]. Yin and Yu conducted an empirical study to confirm the relationship between digital green science and innovatione merits [37]. Ji empirically researched the short-term nonlinear and long-term dynamic impact of digital technology on tourism green total factor productivity by constructing GMM and PVAR models [38]. Lan and Zhang used a bidirectional fixed effects model based on relevant data analysis to find that the development of digital inclusive finance can significantly promote green innovation in enterprises [39]. In terms of methods for digital green innovation management, Lan and Han believed that the effective development strategy for China's industrial green transformation is to improve the green policy system, actively promote industrial technology upgrading, develop agglomeration economy, and promote industrial integration [40]. Jin et al. found through analysis and research that effective measures to achieve green digitization include promoting technological upgrades, energy management, and technology applications to achieve potential efficiency, as well as increasing the penetration of advanced digital technologies [41]. Yin et al. created an assessment index framework for the level of digital green innovation and proposed policy and practical guidance for accelerating the development of green intelligent manufacturing industry through digital technology [42]. In summary, experts and scholars have used different methods to study and explore digital green innovation management for different industries, providing important reference for the transformation and development of digital green innovation.

D. PARTNER SELECTION METHOD

In the selection of digital development partners, Yang and Cai researched a supply chain partnership management method based on the new distributed computing framework Jini technology [43]. Chen proposed a method combining multi-level fuzzy comprehensive evaluation and genetic algorithm when evaluating the manufacturing partners of virtual enterprises [44]. Qu believed that the best evaluation method for calculating the selection of alliance partners was ANP method [45]. Li et al. put forward a digital transformation capacity assessment approach that relies on double combination weighting, which sufficiently integrates objective weight and subjective weight [46]. Yin et al. solved the problem of DGI partner selection by introducing triangular fuzzy number and prospect theory and combining VIKOR method to build DGI resource complementary field model [47]. In terms of the selection of green development partners, Liu and Long applied the hierarchy of analysis process to research the selection of green agricultural products alliance partners based on technical standards [48]. Zhang utilized the hierarchy of analysis process algorithm to provide reference for the selection of virtual enterprise partners in green manufacturing [49]. Gong provided reference for the selection of strategic alliance partners of iron and steel enterprises from the perspective of low carbon through analytic hierarchy process [50]. Eduard et al. proposed a rapid business process modeling and evaluation method based on specific business process lean principles, providing a solution for selecting the most reliable partner [51]. Li et al. introduced the evaluation model into the prospect theory and combined with VIKOR method to ensure the suitability and matching of ecological partner selection to a certain extent [52]. Haseli et al. developed an evaluation framework to solve the selection of recycling partners by considering sustainability and resilience factors [53]. To sum up, experts have conducted in-depth and fruitful study on choosing digital and environmentally friendly partners, and achieved a large number of research results, which have made important contributions to the correct decision-making of partner selection.

E. PARTNER SELECTION CRITERIA

Regarding the standards for choosing digital collaborators, Hou and Lv investigated the issue of virtual company collaborator choice using the general principles of partner selection: core competitiveness principle, agility principle, total cost optimization principle, and risk minimization principle [54]. Qu believes that the selection of cloud computing alliance partners should follow the principles of complementary advantages, compatibility, trust based, and risk minimization [45]. Jill explored the criteria for selecting suitable digital partners in his research, providing reference for choosing digital partners for businesses [55]. Yin and Zhao designed an all-round, comprehensive and practical vigorous development index of emerging technologies have compressed the space for traditional value creation, which is based on the digital transformation, namely, goal, comprehensiveness, diversity, comparability and operability [56].

In terms of the criteria for selecting green partners, Zhang summarized the general principles commonly believed to be followed in partner selection: core competency principle, total cost accounting principle, agility principle, risk minimization principle, green principle, and member goal consistency principle [49]. Tian conducted in-depth research on the mechanism of partner selection in the innovation ecosystem, analyzing the principles and motivations of partner selection in the innovation ecosystem, mainly including following four principles: complementary resource advantages, pursuing maximum cooperation benefits, achieving coupling of cooperation relationships, and minimizing cooperation risks [57]. Hu summarized through research and analysis that the principles for establishing a green supply chain evaluation index system for the steel manufacturing industry are the principles of completeness and comprehensiveness, conciseness and scientificity, flexibility and expandability, the combination of qualitative and quantitative indicators, and informatization [58]. Gong classified the main indicators affecting the selection of strategic alliance partners of iron and steel enterprises from the low-carbon perspective as low-carbon technology R&D capability, low-carbon technology transformation capability, technological innovation performance capability, resource status, compatibility level, and trust relationship and commitment [50]. Yue et al. studied the option of green collaborators for virtual businesses based on Pareto genetic algorithm and introduced the importance of the ‘‘green standard’’ criterion in PSP [59]. Xiao et al. used gravity search formula to improve the option of green collaborators in online businesses, enriching the general criteria for green partner selection [60]. Eduard et al. proposed in their study the application of lean principles for sustainable partner selection, which can help improve the sustainability of collaborative networks [51].

In terms of criteria for selecting partners in other directions, Chen believes that the establishment of a partner indicator system includes the principles of purposiveness, comprehensiveness and conciseness, practicality, and consistency [44]. Xie believes that core enterprises should consider whether the selection of partners can maximize the overall efficiency of the supply chain when making decisions [61]. Hai et al. studied and analyzed the principles of partner selection in dedicated line freight transportation alliances, and summarized the indicator system for partner selection in dedicated line freight transportation alliances [62]. Lee et al. confirmed in their study that the driving factors for selecting technology licensing partners vary depending on the motivations of the enterprise, and analyzed their partner selection criteria [63]. The research conclusion conducted by Sha et al. explains why companies are more inclined to select Vendor Managed Inventory collaborators, and its results demonstrate the sub-optimal feature of this trend [64]. Lefebvre et al. expanded their understanding of the effectiveness of non-profit sports cooperation and enriched research on partner selection issues by empirically testing the relationship between the effectiveness of non-profit sports cooperation and partner selection factors and cooperation processes [65].

In summary, scholars have conducted targeted analysis on partner selection issues in different enterprises and scenarios, enriching the general principles of partner selection and laying a solid foundation for further research.

III. THEORETICAL BASIS AND INDICATOR EVALUATION SYSTEM

In the context of a new round of global technological and industrial transformation, as well as a business environment characterized by globalization, dynamism, diversification, innovation, and balanced development, the option of digital green innovation collaborators is a key link in the transformation and development of hydrogen energy enterprises. The option of digital green innovation partners for hydrogen energy businesses is a very complex issue that involves consideration of multiple factors. In the process of selecting digital green partners for hydrogen energy enterprises, it is necessary to design and construct a complete evaluation index system based on the selection of scientific and effective evaluation methods. The design of evaluation index systems should also vary according to different business environments, enterprise characteristics, institutional backgrounds, and development needs. Therefore, in order to better adapt to the trend of socio-economic development and provide reference for the digital green innovation development of hydrogen energy enterprises, it is necessary to design a comprehensive, effective, and ability index evaluation framework for choosing digital green innovation collaborators that meets the actual situation and development needs of hydrogen energy enterprises.

A. DESIGN BASIS FOR EVALUATION INDEX SYSTEM

1) DESIGN PRINCIPLES OF INDICATOR SYSTEM

Certain design criteria must be adhered to while creating the evaluation index system for choosing digital green innovation partners in hydrogen energy firms. On the basis of organizing relevant literature on the development and transformation of digital green innovation in hydrogen energy enterprises, this article summarizes the principles for designing evaluation indicators for the option of digital green innovation collaborators in hydrogen energy enterprises into the following five points: first, targeting. The designed evaluation indicators must serve the goal of evaluating the digital, green, innovative, development, and transformation capabilities of hydrogen energy enterprises. Based on scientific screening, candidate indicators that are not closely related to the goals should be eliminated. Secondly, comprehensiveness. The designed assessment metrics ought to be clearly defined as much as feasible and can fully reflect the Digital transformation capability and green innovation development potential of hydrogen energy enterprises' innovative development transformation partners. Thirdly, diversity. On the premise of following the evaluation objectives, the evaluation indicators for choosing digital green innovation collaborators of hydrogen energy enterprises should be enriched to the greatest extent to adapt to the dynamic, global, and uncertain characteristics of the business environment. Fourthly, comparability. To guarantee the comparable validity of the assessment outcomes for the choice of collaborators in digital green innovation in hydrogen energy enterprises, it is necessary to choose clearly defined, representative, and measurable evaluation indicators that meet the evaluation objectives. Fifth, operability. To guarantee the scientific, accurate, and promoteable nature of the evaluation measure framework for choosing digital green innovation partners of hydrogen energy enterprises, the indicator system design should be integrated with actual circumstances of the development background of these businesses [66].

2) THEORETICAL EXAMINATION OF INDICATION SYSTEM ARCHITECTURE

Digital transformation development is used to describe how businesses utilize digital technology and platform capabilities to improve operational efficiency, enhance enterprise value and realize revenue growth by restructuring and optimizing business processes and business models. In the process of digital innovation and development, enterprises continuously accumulate digital management and development experience by exploring digital business models and development strategies, and continuously improve their digital development level. Green transformation and development refers to the transformation of the development mode to sustainable development, which is led by the construction of ecological civilization, based on circular economy, and guaranteed by green management, so as to achieve resource conservation, environmental friendliness, balance of nature, and harmonious development of human, nature, and society. The core content is to transform from a traditional development model to a scientific development model, which is a development form that deviates from humans and nature, and separates economy, society, and ecology. The transformation towards a harmonious coexistence between humans and nature, as well as a coordinated development form of economy, society, and ecology, aims to make the connotation of green transformation more three-dimensional and intuitive. Green development is related to the well-being of the people and the future of the nation. The choice of digital green innovation partners for hydrogen energy businesses helps to improve the industry's safety management, which helps to hasten the growth of individual businesses and potentially the sector as a whole. Therefore, considering the ongoing development of the digital economy and the continuing advancement of the dual carbon targets, choosing digital green innovation partners to build a digital green innovation development community has become the only way for hydrogen energy enterprises to survive and develop. Hydrogen energy enterprises must rely on digital green innovation partners, optimize resource integration among partners, stimulate the innovation and development momentum of hydrogen energy enterprises, push the digital green transformation and advancement of businesses, and create greater commercial and social value.

The reciprocity of transformation and development, similarity of cooperation vision, and embeddedness of business models between hydrogen energy enterprises and digital green innovation partners correspond to the characteristics of ecosystem ''regeneration'', ''symbiosis'', and ''mutualism'', respectively. The construction of a digital, green, innovative and development community for hydrogen energy enterprises is committed to improving the functions and roles of the community through the selection of partners. In the face of profound changes in the internal and external environment of enterprises, Huarun actively implements the new development concept. At the 2023 APEC Business Leaders' China Forum, it was proposed that achieving green development with harmonious coexistence between humans and nature requires multiple measures and comprehensive governance, among which the most fundamental and crucial is to rely on the power of technological innovation. The current new energy technology revolution is constantly emerging with new trends and characteristics. Huarun is highly concerned about the following three directions and strives to achieve technological breakthroughs: first, comprehensive energy services, second, the new energy storage industry chain, and third, the hydrogen energy and derivative industry chain. On the basis of the previous analysis, this paper constructs a theoretical framework to describe the digital green innovation collaboration capacity of hydrogen energy enterprises, as illustrated in Figure 1.

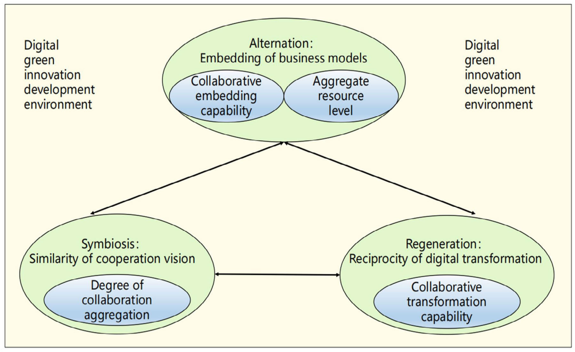

FIGURE 1. Theoretical model of digital green innovation cooperation capacity of hydrogen energy companies.

B. DESIGN OF EVALUATION INDEX SYSTEM

This paper comprehensively considered the characteristics of hydrogen energy enterprises and their digital green innovation transformation environment, referred to the relevant literature on partner selection indicators at home and abroad [67], [68], and according to the traits of ''symbiosis'', ''mutualism'' and ''regeneration'' of the digital green innovation development community of hydrogen energy enterprises, comprehensively investigated the similarity of the cooperation vision between hydrogen energy enterprises and digital green innovation partners, the integration of company structures, and the reciprocity of digital transformation. The goal degree metrics for the assessment structure for the digital and green innovation cooperation ability of hydrogen energy enterprise innovation partners are summarized on the basis of the design principles and theoretical framework for the evaluation index system, expert evaluation and summary, and social investigation and research. It includes digital technology innovation level, green technology innovation level, hydrogen technology innovation level, hydrogen technology market development ability,the level of green development of hydrogen energy, the effectiveness of digital technology driving hydrogen energy, mutual trust in cooperation, and the degree of cooperation aggregation are as displayed in Table 1. The level of digital technology innovation includes three sub indicators: digital technology innovation capability, research and development investment, and embedded hydrogen energy level. The level of green technology innovation includes three sub indicators: green technology innovation capability, research and development investment, and embedded

TABLE 1. Evaluation index system for digital and green cooperation capability of hydrogen energy enterprise innovation partners.

Target layer	Indicator layer	Explanation of the indicator
Digital technology Innovation level(C_1)	Digital technology innovation capability(C_{11})	Partner's current innovation capabilities in digital technology
	Investment in digital technology research and development(C_{12})	Partner's investment in digital technology research and development
	Embedding digital technology into hydrogen energy levels(C_{13})	Partner's level in embedding hydrogen energy into digital innovation
Green technology innovation level(C_2)	Green technology innovation capability(C_{21})	Partner's current innovation capabilities in green technology
	Green technology research and development investment(C_{22})	Partner's investment in green technology research and development
	Green technology embedded in hydrogen energy level(C_{23})	Partner's level of green development embedded in hydrogen energy
Innovation level of hydrogen energy technology(C_3)	Innovation awareness of hydrogen energy technology(C_{31})	Partner's current innovation capabilities in digital technology
	Hydrogen energy technology support capability(C_{32})	Partner's investment in digital technology research and development
	Hydrogen energy technology innovation capability(C_{33})	Partner's level in embedding hydrogen energy into digital innovation
Market development capability of hydrogen energy technology(C_4)	Market judgment ability(C_{41})	Partner's ability to identify and select market opportunities for hydrogen energy technology
	Explore market capabilities(C_{42})	The ability of partners to collect customer information and accurately grasp the overall changes in the hydrogen technology market
	Ability to integrate market development resources(C_{43})	Resource integration capabilities of partners in hydrogen technology market development
Green development level of hydrogen energy(C_5)	Hydrogen energy utilization rate(C_{51})	Current utilization of hydrogen energy technology by partners
	Fixed asset investment in renewable energy(C_{52})	Partner's investment in renewable energy fixed assets
	Value added of energy industry(C_{53})	Achievements of energy industry production activities by partners during the reporting period
	Environmental adaptability(C_{54})	Partner hydrogen technology's adaptability to the environment
Digital technology drives hydrogen energy effects(C_6)	Operation of hydrogen energy market(C_{61})	Current operational situation of partners' digital technology in the hydrogen energy market
	Hydrogen energy collection efficiency(C_{62})	Current digital technology efficiency of partners in hydrogen energy collection
	Ability to promote new energy consumption methods(C_{63})	The ability of partners' current digital technology to promote new energy consumption patterns
Cooperation and mutual trust(C_7)	Organizational culture compatibility(C_{71})	Compatibility of organizational atmosphere and values between both parties
	Awareness of digital green innovation in energy technology(C_{72})	Awareness of partners participating in hydrogen energy digital green technology innovation
	Team integration level(C_{73})	Integration degree of digital green innovation research and development teams for hydrogen energy technology between both parties
	Reasonable price(C_{74})	Reasonable price for hydrogen energy technology digital green
		innovation projects
Degree of collaboration aggregation(C_8)	Value fit(C_{81})	The similarity of value orientation between partners and hydrogen energy enterprises in the process of energy technology innovation
	Cooperation reputation(C_{82})	The stickiness, durability, and trust level of cooperation among partners
	Compatibility degree of strategic objectives(C_{83})	Compatibility between partners and the strategic goals of digital green innovation in energy technology for hydrogen energy enterprises

hydrogen energy level. The level of hydrogen energy technology innovation includes three sub indicators: hydrogen energy technology innovation awareness, support ability, and innovation ability. The market development ability of hydrogen energy technology includes three sub indicators: market judgment ability, market exploration ability, and market

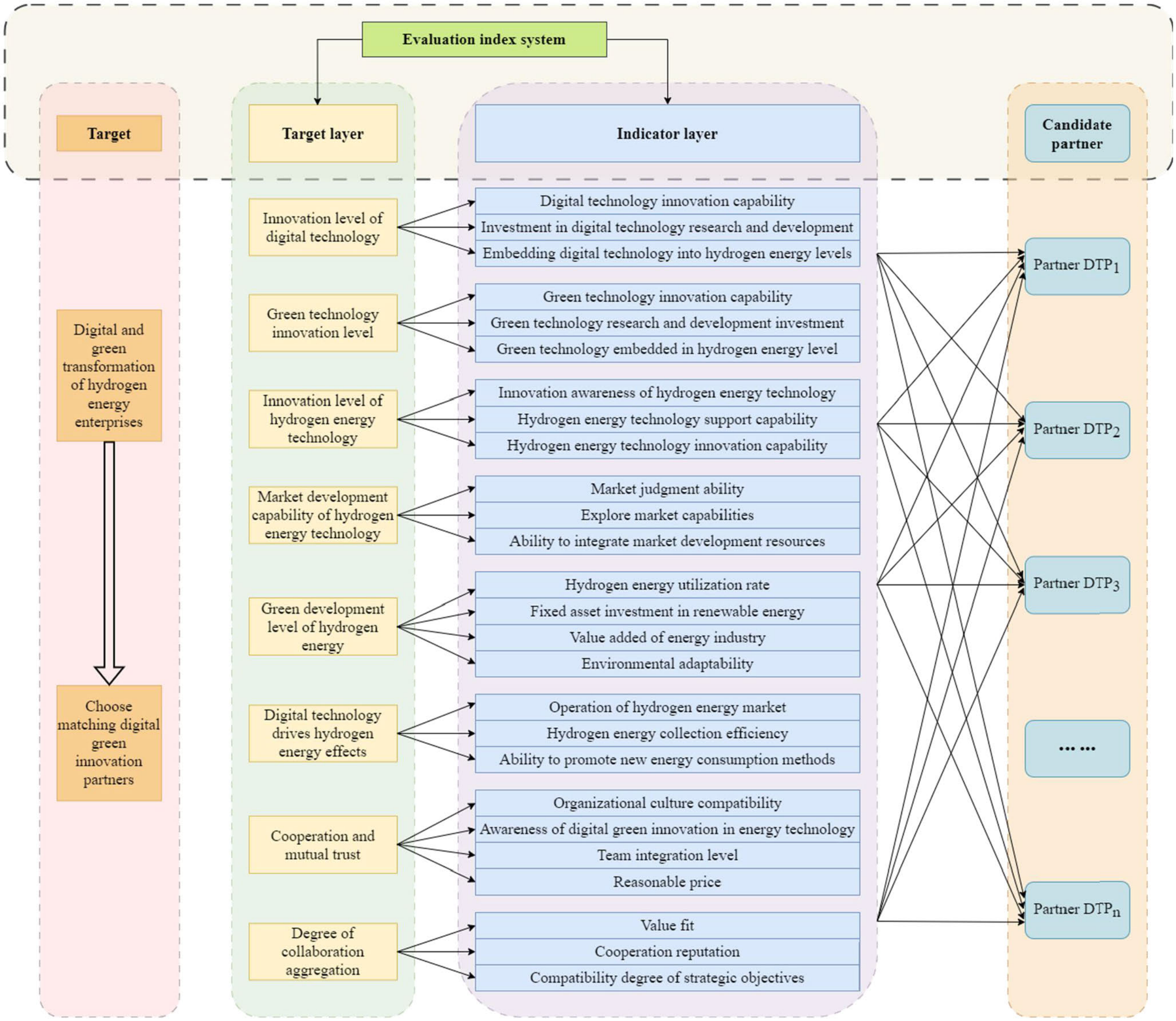

FIGURE 2. **Framework of evaluation indicators for digital and green cooperation capabilities of innovation partners in hydrogen energy enterprises.**

development resource integration ability. The level of green development of hydrogen energy includes four sub indicators: hydrogen energy utilization rate, fixed asset investment in renewable energy, added value of energy industry, and environmental adaptability. The effect of digital technology driving hydrogen energy includes three sub indicators: the operation of the hydrogen energy market, the efficiency of hydrogen energy collection, and the ability to promote new energy consumption modes. Cooperation and mutual trust include four sub indicators: organizational cultural compatibility, awareness of digital green innovation in energy technology, team integration level, and reasonable price. The degree of collaboration aggregation includes three sub indicators: value alignment, collaboration reputation, and strategic goal compatibility. The evaluation index system framework for the digital and green cooperation capability of hydrogen energy enterprise innovation partners constructed from this is shown in Figure 2.

IV. METHODOLOGY

A. EVALUATION METHOD FOR DIGITAL GREEN INNOVATION CAPABILITY

1) BASIC KNOWLEDGE

Definition 1 [69]: In general, if a pair of ordered numbers $\left(\left[\mu_A^L(x), \mu_A^R(x)\right], \left[\nu_A^L(x), \nu_A^R(x)\right]\right)$ comprises the membership degree gap $\left[\mu_A^L(x), \mu_A^R(x)\right]$ and non membership degree gap $\left[\nu_A^L(x), \nu_A^R(x)\right]$ of x for A in a non-empty set X,in that way $\left(\left[\mu_A^L(x), \mu_A^R(x)\right], \left[\nu_A^L(x), \nu_A^R(x)\right]\right)$ is an interval intuitive fuzzy number.

Definition 2 [70]: If ($\widetilde{a} = ([a,b],[c,d])$) is an interval intuitionistic fuzzy number, then the score function is:

$$S(\widetilde{a}) = \frac{(a+b)(a+c)-(c+d)(b+d)}{2} \quad (1)$$

Definition 3 [71]: Let $\widetilde{a}_i = ([a_i,b_i],[c_i,d_i])(i = 1,2,\ldots,n)$ be a set of interval intuitionistic fuzzy set, and $p,q \geq 0$, attribute weight $\omega = (\omega_1,\omega_2,\cdots,\omega_n)^T$ satisfy $0 \leq \omega_j \leq 1$, $\sum_{j=1}^{n}\omega_j = 1$, then operator *IVIFGWHM* is:

$$IVIFGWHM^{p,q}(\widetilde{a}_1,\widetilde{a}_2,\cdots,\widetilde{a}_n) = \frac{1}{p+q}\left(\bigotimes_{i=1,j=1}^{n}\left(\left((p\widetilde{a}_i)^{\omega_i}\oplus(q\widetilde{a}_i)^{\omega_j}\right)^{2/n(n+1)}\right)\right) \quad (2)$$

2) COMBINATION ATTRIBUTE WEIGHTS

Definition 4: Let $\widetilde{a}_{ij} = \left(\left[a_{ij}^L, b_{ij}^R\right],\left[c_{ij}^L, d_{ij}^R\right]\right)(i = 1,2,\ldots,n; j = 1,2,\ldots,m)$ be a group of interval intuitionistic Fuzzy set, then the interval intuitionistic fuzzy entropy of the jth attribute is:

$$E_j = \frac{1}{n}\sum_{i=1}^{n}\frac{4-\left(\left|a_{ij}^L - c_{ij}^L\right| + \left|b_{ij}^R - d_{ij}^R\right| + \left|\pi_{ij}^L + \pi_{ij}^R\right|\right)}{8} \quad (3)$$

Then the objective weight of the jth attribute is $\omega^* = (1-E_j)/\left(m-\sum_{j=1}^{m}E_j\right)$.

Definition 5: Let $\widetilde{a}_i = \left(\left[a_i^L, b_i^R\right],\left[c_i^L, d_i^R\right]\right)(i = 1,2,\ldots,n)$ be a set of given interval intuitionistic fuzzy attribute weights, and the score of each interval intuitionistic fuzzy number in the interval intuitionistic fuzzy set is s_{ij}, then the subjective weight ω_j^{**} is:

$$\begin{cases} \max M = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(\omega_j^{**}\times s_{ij}\right) \\ \sum_{j=1}^{n}\omega_j^{**} = 1, \omega_j^{**}\in[0,1] \end{cases} \quad (4)$$

According to the subjective and objective weights, the combined attribute weight is $\omega_j = \theta\omega_j^* + (1-\theta)\omega_j^{**}$.

3) COMBINATION TIMELINESS WEIGHTS

Drawing inspiration from the ideal solution of time measure and information entropy, if $\varphi = \sum_{k=1}^{p}\frac{p-k}{p-1}\lambda(t_k)$, then φ is called the time measure of $\lambda(t_k) = \left(\lambda(t_1),\lambda(t_2),\cdots,\lambda(t_p)\right)^T$, $\varphi = 0$ indicates that decision-makers only value current information, $\varphi = 1$ indicates that only the most recent information is valued, and $\varphi = 0.5$ indicates that all time period information is equally valued, where $0 \leq \varphi \leq 1$. The combined temporal weighting based on ideal solutions and information entropy is:

$$\begin{cases} \max G \\ = \rho\dfrac{\sqrt{(1-\lambda(t_1))^2+\sum_{k=2}^{p}\lambda(t_k)^2}}{\sqrt{\sum_{k=1}^{p-1}\lambda(t_k)^2+\left(1-\lambda(t_p)\right)^2}+\sqrt{(1-\lambda(t_1))^2+\sum_{k=2}^{p}\lambda(t_k)^2}} \\ -(1-\rho)\sum_{k=1}^{p}\lambda(t_k)\ln\lambda(t_k) \\ s.t.\varphi = \sum_{k=1}^{p}\frac{p-k}{p-1}\lambda(t_k), \sum_{k=1}^{p}\lambda(t_k) = 1, \lambda(t_k)\in[0,1], \\ k = 1,2,\ldots,p \end{cases} \quad (5)$$

B. MODEL FOR PARTNER SELECTION IN HYDROGEN ENERGY ENTERPRISES BASED ON FIELD THEORY

1) QUALITY OF DIGITAL GREEN INNOVATION CAPABILITIES

Set the field source as O, indicating the advantage of hydrogen energy enterprises in creating resources due to their own digital green innovation capabilities.

The quality of digital green innovation capability of hydrogen energy enterprises is determined by the resource vector and resource utilization rate, which describes the resource creation situation of their digital green innovation capability. The resource vector is represented by P, $P = (p_1,p_2,\cdots,p_n)$, n represents the dimension of resource space, and any resource $p_i \in [0,1]$, $p_i = 1$ represents that the digital green innovation capability creates resources that meet the needs of partners. Conversely, $p_i = 0$ represents not meeting. The resource utilization rate is represented by Y, $Y = (y_1,y_2,\cdots,y_n)$, $y_i \in [0,1]$, and y_i represents the availability of p_i. Due to changes in market demand and other factors, the supply of resources for creating digital green innovation capabilities in hydrogen energy enterprises will undergo dynamic changes at different times. Therefore, by introducing the time vector T, $T = (t_1,t_2,\cdots,t_n)$, the calculation formula for the quality of digital green innovation capabilities in hydrogen energy enterprises is:

$$M_T = P_T \times Y_T = \sum_{i=1}^{n}p_i y_{1i} \quad (6)$$

The resource vector of the selected partner is represented by Q, $Q = (q_1,q_2,\cdots,q_n)$. To reflect the complementarity of resources created by the digital green innovation capability of the selected partner and hydrogen energy enterprises, the resource space saturation vector $P_m = \overbrace{(1,1,\cdots,1)}^{n}$ and resource demand vector $\overline{P}$ are introduced. The calculation formula for the quality of digital green innovation capability of the selected partner is:

$$m_T = \left(\left(P_m \oplus \overline{P}\right)\cap Q\right) = \sum_{i=1}^{n}\left[(1\oplus p_i)\wedge q_i\right]y_{2i} \quad (7)$$

2) DIGITAL GREEN INNOVATION CAPABILITY FIELD STRENGTH AND GRAVITY

The closer the hydrogen energy enterprise is to the field source O, the greater the field strength E. The farther away from the field source O, the smaller the field strength E. The field strength of digital green innovation capability is directed from the selected partner to the field source, and the calculation formula for field strength is:

$$E_T = K_T \frac{M_T}{R_T^2} \tag{8}$$

Among them, M_T represents the quality of the digital green innovation capability of the field source, R_T represents the radius of digital green innovation capability, and K_T represents the digital green innovation capability creation effect generated by hydrogen energy enterprises and selected partners. There are:

$$K_T = \frac{M_T}{R_T^2} \tag{9}$$

The gravity of digital green innovation capability $\overrightarrow{F}$ describes the degree of attraction of field source O to the digital green innovation capability of selected partners in the field. The calculation formula for the gravity of digital green innovation capability is:

$$\overrightarrow{F} = E_T \times m_T = \frac{Z_T M_T m_T}{R_T^2 \left(M_T + m_T\right)} \tag{10}$$

3) DIGITAL GREEN INNOVATION CAPABILITY RADIUS

Assuming the radius of digital green innovation capability R for hydrogen energy enterprises, C_f for the quality and capability of hydrogen energy enterprises, and C for the quality and capability of selected partners in digital green innovation, the calculation formula for the radius of digital green innovation capability field is:

$$R_T = 1 + C_f - C, \quad C \in [0, 1] \tag{11}$$

Define the digital green innovation capability at R_1 as C_1, then $C_f \in [C_1, 1]$. Hydrogen energy enterprises have reason to believe that their digital green innovation cooperation capability is 1, that is, $C_f = 1$, and the radius of digital green innovation capability is $R_T = 2 - C$.

For the convenience of discussion and without loss of generality, the digital green innovation capability field is divided into different circles according to the size of the digital green innovation capability radius, which are $(0, R_1]$ strong digital green innovation capability, $(R_1, R_2]$ medium digital green innovation capability, $(R_2, R_3]$ weak digital green innovation capability, and (R_3, ∞) "0" digital green innovation capability, as shown in Figure 3.

The virtual coil in Figure 3 represents the radiation range of different digital green innovation capability field strengths, R_i represents the radius of digital green innovation capability in different circles, and $\delta_1 \sim \delta_9$ represents the selected partners in different circles. Assuming willingness resistance

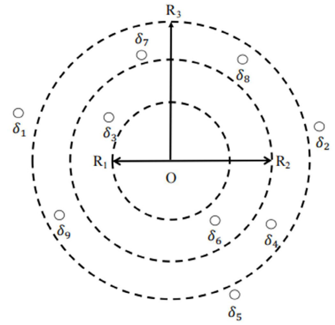

FIGURE 3. Digital green innovation capability field model.

describes the opportunity cost and risk cost of the selected partner joining the digital green innovation of hydrogen energy enterprises. If D_1 is the opportunity cost and D_2 is the risk cost, the calculation formula for willingness resistance of the selected partner is:

$$\overleftarrow{F} = D_1 + D_2 \tag{12}$$

The selected partner in the radius circle layer needs to meet the requirement of being less than the radius threshold ε_T, i.e. $R_T \leq \varepsilon_T$, and meet the requirement that the gravitational force $\overrightarrow{F}$ of the cooperative value creation ability is greater than the gravitational threshold ς_T and greater than the willingness resistance $\overleftarrow{F}$, i.e. $\overrightarrow{F} \geq \varsigma_T$, $\overrightarrow{F} \geq \overleftarrow{F}$, which is also the trigger point for the partner to enter or exit digital green innovation.

The process of selecting partners for hydrogen energy enterprises is shown in Figure 4, where the number in the circle represents the hydrogen energy enterprise number.

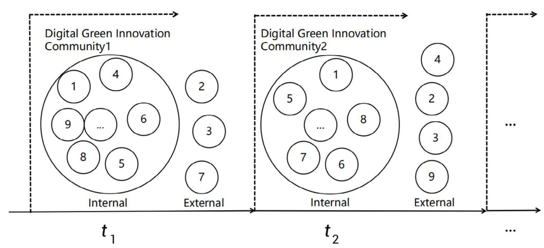

FIGURE 4. Dynamic selection process of digital green innovation partners for hydrogen energy enterprises.

V. CASE STUDY

As an independent coking enterprise with a relatively complete industrial chain in the northeast region of China, Baotailong has been adhering to the principles of "reduction, reuse, and resource utilization" since its establishment in 2003, focusing on extending the circular economy industry chain of "interconnected and mutually beneficial industries", mainly involving five major fields: new materials, coal based clean energy, advanced carbon materials, coal chemical industry, and urban public services. In recent years, Baotailong has seen opportunities for the advancement of hydrogen energy and is committed to promoting the construction of the ''production storage transportation processing use'' hydrogen energy industry ecosystem in cold regions. During the two sessions, chairperson Jiao Yun of Baotailong expressed that hydrogen energy is a sustainable energy, and the advancement of the hydrogen energy sector is of great significance for building modern energy system, and promoting high-quality economic and social development. However, Jiao Yun also pointed out that although the northeast region has rich wind and light resources for electrolysed water hydrogen production, high-tech enterprises in various links of the hydrogen energy industry chain such as equipment, materials, processes, batteries and other fields are basically blank, and the ''carbon neutral'' ecology of hydrogen purification, storage of hydrogen and transportation, hydrogen injection, hydrogen application, coal chemical industry, oil chemical industry and other all-round industrial chains has not yet been established. In order to help the growth of the hydrogen energy sector in Heilongjiang Province, Baotailong actively explores and layout the hydrogen energy industry based on the abundant by-product hydrogen resources in the coal chemical industry chain. In August 2021, Baotailong made breakthrough progress in the substantive utilization of hydrogen energy, and reached cooperation with PetroChina Heilongjiang Sales Branch, Harbin Electric Co., Ltd., and Qitaihe City Urban Investment Company to build the first oil hydrogen power comprehensive demonstration station in Qitaihe, and jointly promote the comprehensive breakthroughs in the core technology, equipment development and market promotion of the hydrogen energy industry. Simultaneously, in the trend of digital green evolution and economic globalization competition, Baotailong actively explores the path of promoting digital green innovation transformation and development, promoting low-carbon transformation of high energy consuming industries, extending the industrial and value chains, and solving the advancement difficulties of the hydrogen energy sector, in order to achieve both economic and social benefits. The choice of digital green innovation collaborators is the main problem that Baotailong needs to address. Baotailong currently has two hydrogen energy digital green innovation partners (AES1 and AES2), however it's challenging to depend only on these partners for digital green innovation development transformation. Therefore, it will select two partners from multiple candidate partners and dynamically adjust the existing partners. Based on the steps and evaluation indicators for selecting digital green innovation partners designed in this article, Baotailong has preliminarily identified four digital green innovation partners (DTP1 to DTP4) to be selected through some quantitative and qualitative indicators selection and market research, inviting 10 chief information officers and practical experts in digital greening. Primarily, every collaborator to be selected in three distinct time frames is subjected to an anonymous interval intuitionistic fuzzy inspection, then the interval intuitionistic fuzzy weight of every attribute index is provided. This process is done in accordance with the evaluation index of digital green innovation collaborators selection of hydrogen energy enterprises constructed in this paper. Subsequently, consider the eight resource types (DTR1 to DTR8) needed for Baotailong's digital green transformation when assessing the complementarity of digital green transformation resources. Table 2 and Table 3 display the consistency outcomes of several rounds of assessment and feedback evaluation. Figure 5 clearly shows the overall mechanism of the digital green innovation collaborator option model for hydrogen energy companies [72], [73].

A. EVALUATION OF DIGITAL TRANSFORMATION CAPABILITY BASED ON DUAL COMBINATION EMPOWERMENT

Stage 1: The interval intuitionistic fuzzy evaluation matrix for every time period, the interval intuitionistic fuzzy weights for every attribute indicator, and the status of digital green innovation transformation resources for Baotailong AES and selected partners are shown in Tables 2 and 3.

Stage 2: Compute the aggregate attribute weights of Baotailong AES and the evaluation indicators for the digital green transformation capability of the selected partners. Set $\theta = 0.4$ to calculate objective weights, subjective weights, and combined attribute weights as shown in Table 4.

Stage 3: Compute the temporal weighting of multiple combinations of time periods. As indicated in Table 4, presume the time degree $\phi = 0.3$, $\beta = 0.6$, then solve formula (11) nonlinear programming model using Lingo software to get the combined time degree weight [74].

Stage 4: Integrate the attribute values of the evaluation indicators for the digital and green transformation capabilities of Baotailong AES and the selected partners. The comprehensive capabilities of Baotailong AES and selected partners in digital, green, innovative development and transformation are calculated using equation (7), as illustrated in Table 5.

B. DYNAMIC SELECTION OF ECOLOGICAL PARTNERS OF ENTERPRISE STRATEGIC ALLIANCE BASED ON FIELD THEORY

Stage 1: The comprehensive capacities of Baotailong AES and selected partners in digital, green, innovative development and transformation have been calculated in step 4 of 5.1.

Stage 2: Utilize formulas (1) and (2) to compute the quality M and m of the digital green innovation development ability of Baotailong AES and the selected partner. Use formulas (3) - (6) to compute the field strength E, gravity $\overrightarrow{F}$, radius R, and willingness resistance $\overleftarrow{F}$ of the digital green innovation development ability of Baotailong AES and the selected partner, and then calculate the combined force F, where K is taken as 0.9, and the outcomes are displayed in Table 6.

Stage 3: Sort each AES and candidate partner of Baotailong, including:

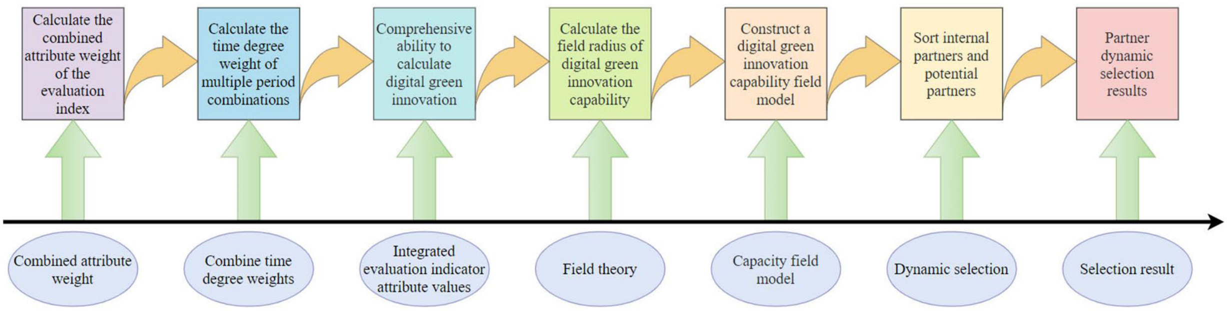

FIGURE 5. Overall mechanism of digital green innovation collaborator option model for hydrogen energy companies.

① Set the radius threshold ε_T and calculate the gravitational threshold ς_T. Based on the opinions of professionals like CIO, set the radius threshold $\varepsilon_T = 1.5$; The gravitational threshold ς_T of the selected partner is $F_0 = 0.3725$.

② Based on the trigger point, rule out some possible partners, and choose which partners to bring into the community according to the collaborative effort F. The following are the steps to follow:

- ε_T based screening. From Table 5, as can be observed, all AES and chosen collaborators have radiuses that are smaller than the radius threshold $\varepsilon_T = 1.5$, and they are all in the digital green innovation development and transformation capability circle of (1, 1.5], which cannot be optimized and selected.
- ς_T based screening. According to the data from $F_0 = 0.3725$ and Table 6, if $\overrightarrow{F} = 0.3718 < F_0 = 0.3725$ for DTP3, then the candidate partner DTP3 will be eliminated.
- Group and choose according to F. Table 6 shows that the requirements are met by the resultant force since the gravitational force is greater than the willingness resistance. The resulting force on each partner to be chosen, ranked from large to little, is as follows: DTP1>DTP2>DTP4.
- Therefore, after Baotailong selected the Model selection of digital green innovation partners of hydrogen energy enterprises based on field theory, the final selection order of digital green innovation partners is: DTP1>DTP2>DTP4. The partners to be selected, DTP1 and DTP2, were selected as digital green innovation partners, and DTP4 was eliminated.

C. COMPARATIVE EVALUATION OF THE OPTION OUTCOMES OF DIGITAL GREEN INNOVATION COLLABORATORS FOR HYDROGEN ENERGY ENTERPRISES

To confirm the efficacy and scientificity of the approach proposed in this study, the score function a in this study, the score function b in the literature [75], the subjective time degree and the objective time degree are selected and compared with the methods proposed in this paper to analyze the differences in the evaluation and option outcomes of digital green innovation collaborators of hydrogen energy enterprises by different methods. The option results of digital green innovation collaborators of hydrogen energy enterprises by using five methods are shown in Table 7.

Table 7 illustrates the variations in the ranking and selection outcomes of the digital green innovation partners to be chosen. The overall ranking results are altered, but the digital green innovation community of hydrogen energy firms has remained the same. The evaluation value based on score function b has a total deviation of 0.008973, while the evaluation value based on score function a has a total deviation of 0.017235. It is clear that this paper's score function a has clear advantages over others. Table 7 shows that there are some variations in the sorting and option outcomes between the unused field theory and the used field theory. For example, the reason for the result DGIP1>DGIP3 is that although DGIP1 has a low attraction of digital green innovation capability and few complementary resources with AES's digital green innovation capability, its willingness to resist digital green innovation capability is small, and its willingness to cooperate in digital green innovation is very strong, which makes the resultant force of DGIP1 greater than that of DTP3. Therefore, in the grouping result according to field theory, DTP1 partner is ahead of DTP3 partner. The outcomes of this method are congruent with the outcomes according to the field theory method and the subjective and objective time scales. On the one hand, it shows that the application of field theory is more rational and logical. In addition, from the perspective of discrimination, the total deviation based on the subjective time scale approach is 0.013729, the total deviation based on the objective time scale approach is 0.013312, and the total deviation of this approach is 0.042675. Apparently, this approach has obvious distinguishing advantages.

D. DISCUSSION

1) MANAGEMENT SIGNIFICANCE

Hydrogen energy is rich in sources, widely used and characterized by eco-friendly and sustainable. It's recognized by the industry as one of the important carriers of energy transformation and development, and contributes favorably to the achievement of carbon peak and carbon neutralization targets. The digital and green revolution of hydrogen energy enterprises can inject new momentum into accelerating the energy revolution, scientific and technological revolution and industrial reform. Based on the perspective of enterprises,

TABLE 2. Intuitive fuzzy evaluation value matrix and weights for each time period interval.

T1	C1	C2	C3	C4	C5	C6	C7	C8
DTP1	([0.5,0.6], [0.3,0.4])	([0.5,0.6], [0.3,0.4])	([0.3,0.4], [0.4,0.6])	([0.4,0.7], [0.1,0.3])	([0.2,0.3], [0.5,0.6])	([0.3,0.6], [0.3,0.5])	([0.2,0.2], [0.4,0.6])	([0.4,0.6], [0.3,0.3])
DTP2	([0.3,0.5], [0.2,0.3])	([0.2,0.3], [0.6,0.7])	([0.4,0.5], [0.2,0.4])	([0.6,0.6], [0.2,0.3])	([0.2,0.4], [0.3,0.3])	([0.2,0.3], [0.5,0.6])	([0.5,0.6], [0.3,0.3])	([0.6,0.8], [0.2,0.2])
DTP3	([0.4,0.5], [0.1,0.3])	([0.4,0.6], [0.3,0.4])	([0.7,0.9], [0.2,0.3])	([0.2,0.5], [0.2,0.2])	([0.4,0.6], [0.3,0.4])	([0.6,0.8], [0.4,0.6])	([0.5,0.8], [0.3,0.4])	([0.4,0.6], [0.4,0.6])
DTP4	([0.7,0.9], [0.3,0.5])	([0.5,0.6], [0.1,0.2])	([0.2,0.5], [0.2,0.2])	([0.3,0.4], [0.1,0.3])	([0.6,0.7], [0.2,0.3])	([0.6,0.8], [0.2,0.2])	([0.4,0.5], [0.2,0.2])	([0.6,0.7], [0.2,0.4])
AES1	([0.4,0.5], [0.3,0.3])	([0.5,0.5], [0.2,0.2])	([0.4,0.5], [0.2,0.3])	([0.5,0.6], [0.2,0.3])	([0.3,0.5], [0.2,0.3])	([0.4,0.6], [0.3,0.4])	([0.3,0.5], [0.2,0.2])	([0.3,0.6], [0.1,0.2])
AES2	([0.5,0.5], [0.3,0.4])	([0.6,0.8], [0.2,0.4])	([0.5,0.5], [0.3,0.4])	([0.3,0.6], [0.1,0.2])	([0.5,0.6], [0.2,0.2])	([0.5,0.7], [0.5,0.5])	([0.5,0.6], [0.2,0.2])	([0.3,0.5], [0.2,0.2])
T2	C1	C2	C3	C4	C5	C6	C7	C8
DTP1	([0.5,0.7], [0.2,0.4])	([0.5,0.7], [0.3,0.3])	([0.3,0.3], [0.4,0.7])	([0.4,0.6], [0.1,0.2])	([0.2,0.4], [0.5,0.6])	([0.3,0.5], [0.1,0.2])	([0.2,0.3], [0.4,0.6])	([0.3,0.5], [0.1,0.3])
DTP2	([0.3,0.5], [0.3,0.2])	([0.4,0.4], [0.6,0.7])	([0.5,0.7], [0.3,0.4])	([0.3,0.6], [0.1,0.2])	([0.3,0.4], [0.2,0.2])	([0.3,0.4], [0.4,0.6])	([0.5,0.6], [0.3,0.4])	([0.6,0.7], [0.2,0.2])
DTP3	([0.2,0.3], [0.3,0.5])	([0.4,0.6], [0.2,0.2])	([0.6,0.8], [0.1,0.2])	([0.2,0.4], [0.4,0.5])	([0.4,0.6], [0.1,0.2])	([0.5,0.6], [0.2,0.3])	([0.8,0.9], [0.2,0.3])	([0.4,0.5], [0.6,0.7])
DTP4	([0.2,0.5], [0.2,0.2])	([0.3,0.4], [0.5,0.6])	([0.3,0.7], [0.1,0.3])	([0.3,0.6], [0.2,0.2])	([0.3,0.5], [0.1,0.1])	([0.6,0.7], [0.2,0.2])	([0.4,0.5], [0.3,0.3])	([0.3,0.5], [0.6,0.7])
AES1	([0.4,0.5], [0.1,0.3])	([0.4,0.6], [0.3,0.4])	([0.4,0.6], [0.2,0.4])	([0.4,0.7], [0.2,0.3])	([0.4,0.6], [0.5,0.5])	([0.4,0.6], [0.5,0.5])	([0.5,0.6], [0.4,0.4])	([0.5,0.6], [0.2,0.4])
AES2	([0.6,0.7], [0.2,0.2])	([0.5,0.8], [0.3,0.3])	([0.4,0.6], [0.3,0.5])	([0.6,0.8], [0.3,0.3])	([0.5,0.7], [0.1,0.2])	([0.4,0.5], [0.3,0.4])	([0.6,0.7], [0.3,0.4])	([0.3,0.7], [0.2,0.2])
T3	C1	C2	C3	C4	C5	C6	C7	C8
DTP1	([0.3,0.5], [0.2,0.2])	([0.4,0.5], [0.1,0.2])	([0.3,0.3], [0.5,0.6])	([0.4,0.6], [0.2,0.3])	([0.1,0.3], [0.5,0.6])	([0.6,0.6], [0.3,0.4])	([0.1,0.2], [0.4,0.4])	([0.4,0.5], [0.6,0.8])
DTP2	([0.6,0.7], [0.3,0.3])	([0.3,0.4], [0.5,0.6])	([0.5,0.7], [0.3,0.4])	([0.7,0.7], [0.2,0.2])	([0.2,0.3], [0.4,0.6])	([0.3,0.4], [0.4,0.5])	([0.3,0.5], [0.1,0.2])	([0.6,0.7], [0.2,0.2])
DTP3	([0.5,0.8], [0.1,0.3])	([0.4,0.5], [0.2,0.3])	([0.7,0.8], [0.2,0.2])	([0.3,0.3], [0.3,0.6])	([0.3,0.4], [0.2,0.3])	([0.3,0.7], [0.2,0.2])	([0.7,0.8], [0.1,0.3])	([0.2,0.3], [0.5,0.6])
DTP4	([0.6,0.7], [0.3,0.5])	([0.4,0.6], [0.2,0.2])	([0.3,0.5], [0.2,0.2])	([0.5,0.7], [0.4,0.4])	([0.5,0.6], [0.2,0.2])	([0.5,0.7], [0.1,0.2])	([0.2,0.4], [0.1,0.2])	([0.2,0.3], [0.4,0.5])
AES1	([0.4,0.8], [0.2,0.3])	([0.3,0.4], [0.4,0.6])	([0.2,0.4], [0.4,0.5])	([0.2,0.5], [0.1,0.2])	([0.3,0.6], [0.1,0.4])	([0.3,0.5], [0.2,0.4])	([0.2,0.6], [0.1,0.1])	([0.3,0.6], [0.2,0.3])
AES2	([0.3,0.6], [0.2,0.2])	([0.4,0.4], [0.2,0.2])	([0.3,0.3], [0.1,0.2])	([0.3,0.6], [0.2,0.3])	([0.4,0.7], [0.2,0.3])	([0.4,0.6], [0.2,0.2])	([0.4,0.6], [0.3,0.4])	([0.4,0.7], [0.3,0.3])

this paper designs a complete evaluation index system for the selection of digital green innovation partners of hydrogen energy enterprises, proposes an evaluation method for the transformation ability of digital green innovation according to double combination weighting, and introduced the field theory with the characteristics of holism and continuity of

TABLE 3. Digital transformation resources of AES partners and candidates.

	DTR1	DTR2	DTR3	DTR4	DTR5	DTR6	DTR7
DTP1	0(0.82)	1(0.91)	1(0.89)	1(0.89)	0(0.69)	0(0.76)	1(0.93)
DTP2	0(0.68)	1(0.95)	1(0.93)	0(0.76)	1(0.93)	0(0.79)	1(0.93)
DTP3	0(0.71)	1(0.94)	0(0.76)	1(0.88)	1(0.93)	0(0.67)	1(0.91)
DTP4	1(0.94)	0(0.75)	1(0.89)	0(0.8)	1(0.92)	1(0.89)	0(0.77)
AES1	1(0.96)	0(0.74)	1(0.95)	1(0.95)	0(0.75)	1(0.93)	0(0.81)
AES2	0(0.82)	1(0.94)	0(0.67)	1(0.92)	0(0.85)	1(0.95)	1(0.92)

TABLE 4. Objective weights, subjective weights, and combined attribute and time weights.

T		T1			T2			T3		
Time weight		0.1832			0.2337			0.5832		
Attribute weights		Objective weight	Subjective weight	Combination weight	Objective weight	Subjective weight	Combination weight	Objective weight	Subjective weight	Combination weight
AES	**C1**	0.1212	0.1000	0.1085	0.1439	0.1000	0.1176	0.1095	0.1500	0.1338
	C2	0.1185	0.1000	0.1074	0.1192	0.1500	0.1377	0.1301	0.2000	0.1720
	C3	0.1270	0.1500	0.1408	0.1078	0.1000	0.1031	0.1119	0.1000	0.1048
	C4	0.1312	0.1500	0.1425	0.1306	0.1000	0.1122	0.1203	0.1000	0.1081
	C5	0.1368	0.1500	0.1447	0.1307	0.1500	0.1423	0.1282	0.1500	0.1413
	C6	0.1202	0.1000	0.1081	0.1212	0.1500	0.1385	0.1233	0.1000	0.1093
	C7	0.1203	0.1500	0.1381	0.1131	0.1000	0.1052	0.1229	0.1000	0.1091
	C8	0.1249	0.1000	0.1099	0.1161	0.1500	0.1364	0.1117	0.1000	0.1047
DTP	**C1**	0.1414	0.1000	0.1165	0.1023	0.1000	0.1009	0.1110	0.1500	0.1344
	C2	0.0958	0.1000	0.0983	0.1154	0.1500	0.1362	0.1381	0.2000	0.1752
	C3	0.1366	0.1500	0.1446	0.1407	0.1000	0.1163	0.1463	0.1000	0.1185
	C4	0.1134	0.1500	0.1353	0.0935	0.1000	0.0974	0.1362	0.1000	0.1145
	C5	0.1239	0.1500	0.1395	0.1337	0.1500	0.1435	0.1212	0.1500	0.1385
	C6	0.1427	0.1000	0.1171	0.1678	0.1500	0.1571	0.1347	0.1000	0.1139
	C7	0.1193	0.1500	0.1377	0.1171	0.1000	0.1069	0.1305	0.1000	0.1122
	C8	0.1270	0.1000	0.1108	0.1153	0.1500	0.1361	0.1251	0.1000	0.1100

action. This can furnish certain management revelations for the digital and green innovative transformation of hydrogen energy enterprises, provide salutary references for the selection of their digital and green innovation collaborators, and possesses definite practicality. This paper provides a uniform structure for choosing digital green innovation partners for hydrogen energy enterprises, which includes 8 target layers and 26 sub indicators. These indicators can fully reflect the market background of digital green innovation development and transformation of hydrogen energy enterprises, as well as the characteristics of ''symbiosis'', ''mutualism'', and ''regeneration'' of commercial systems. This paper's management enlightenment is mostly represented by the two components listed below: (1) the construction of evaluation index system, quantitative methods and evaluation standards based on fuzzy set theory are designed, which can organically combine quantitative and qualitative evaluation, make the evaluation results more objective and fair, and have the characteristics of high reliability, logic, standardization and universality. It presents a novel conception for the selection of digital and green innovation collaborators of hydrogen energy enterprises. Implementing it in the process of enterprise management and development will render the decision-making more scientifically. The judicious selection of digital and green innovation collaborators of hydrogen energy enterprises will steer the sustained and wholesome development of the hydrogen energy industry via technological innovation and construct a modern hydrogen energy safety governance system and governance capacity by relying on the new-generation information technology. (2) the combination weighting theory and field theory are combined to evaluate the suitability of the candidate partners of digital green innovation of hydrogen energy companies by specifying the weight of the combination of attribute weights. Taking into account the scientific nature of partner selection and the complementarity of customer value creation resources among digital green innovation partners, it can take the psychological factors of decision makers into account in the option

TABLE 5. Comprehensive capability of digital greenization, innovation, development and transformation.

	DTP1	DTP2	DTP3	DTP4	AES1	AES2
C1	([0.3712,0.5593], [0.2154,0.2670])	([0.4494,0.6084], [0.2785,0.2729])	([0.3875,0.5837], [0.1293,0.3380])	([0.4774,0.6775], [0.2729,0.4036])	([0.4000,0.6577], [0.1832,0.3000])	([0.3874,0.6016], [0.2154,0.2271])
C2	([0.4390,0.5593], [0.1581,0.2496])	([0.2979,0.3795], [0.5395,0.6398])	([0.4000,0.5395], [0.2154,0.2876])	([0.3896,0.5458], [0.2182,0.2585])	([0.3523,0.4581], [0.3294,0.4463])	([0.4539,0.5340], [0.2199,0.2496])
C3	([0.3000,0.3162], [0.4556,0.6220])	([0.4800,0.6582], [0.2785,0.4000])	([0.6752,0.8174], [0.1701,0.2154])	([0.2785,0.5409], [0.1701,0.2199])	([0.2670,0.4581], [0.2996,0.4322])	([0.3523,0.3874], [0.1581,0.2813])
C4	([0.4000,0.6172], [0.1498,0.2729])	([0.5583,0.6564], [0.1701,0.2154])	([0.2533,0.3523], [0.2979,0.4702])	([0.4041,0.6095], [0.2639,0.3227])	([0.2781,0.5593], [0.1335,0.2368])	([0.3528,0.6417], [0.1937,0.2785])
C5	([0.1335,0.3209], [0.5000,0.6000])	([0.2199,0.3382], [0.3227,0.4088])	([0.3382,0.4737], [0.1832,0.2876])	([0.4588,0.5914], [0.1701,0.1832])	([0.3209,0.5803], [0.1654,0.3998])	([0.4390,0.6805], [0.1701,0.2533])
C6	([0.4494,0.5750], [0.2321,0.3544])	([0.2785,0.3795], [0.4167,0.5395])	([0.3838,0.6919], [0.2271,0.2689])	([0.5395,0.7173], [0.1335,0.2000])	([0.3382,0.5395], [0.2669,0.4214])	([0.4167,0.5914], [0.2601,0.2781])
C7	([0.1335,0.2199], [0.4000,0.4737])	([0.3712,0.5395], [0.1581,0.2533])	([0.6790,0.8223], [0.1438,0.3162])	([0.2670,0.4390], [0.1468,0.2199])	([0.2669,0.5803], [0.1570,0.1570])	([0.4581,0.6220], [0.2785,0.3523])
C8	([0.3740,0.5170], [0.3477,0.5315])	([0.6000,0.7173], [0.2000,0.2000])	([0.2670,0.3838], [0.5009,0.6220])	([0.2689,0.3948], [0.3873,0.5192])	([0.3380,0.6000], [0.1762,0.2979])	([0.3548,0.6582], [0.2533,0.2533])
Value	0.6816	0.6377	0.6184	0.6594	0.8012	0.6774

TABLE 6. Quality, field strength, gravity, radius and desired resistance of digital transformation capability.

	M	E	R	$\overrightarrow{F}$	$\overleftarrow{F}$	F
AES1	0.6223	0.3897	1.1988	0.4844	0.0622	0.4222
AES2	0.6145	0.3162	1.3226	0.3905	0.0614	0.3291
	m	E	R	$\overrightarrow{F}$	$\overleftarrow{F}$	F
DTP1	0.6146	0.3182	1.3184	0.3924	0.0615	0.3309
DTP2	0.6265	0.3038	1.3623	0.3782	0.0626	0.3156
DTP3	0.6310	0.2975	1.3816	0.3718	0.0631	0.3087
DTP4	0.6107	0.3059	1.3406	0.3759	0.0611	0.3149

TABLE 7. Evaluation and selection results of five methods.

	DGIP1	DGIP2	DGIP3	DGIP4	AES1	AES2
Double combination weighting	0.3309	0.3156	0.3087	0.3149	0.4222	0.3291
Result	Y	Y	N	N	Y	Y
Subjective time degree	0.2833	0.2813	0.2764	0.2815	0.3121	0.2991
Result	Y	N	N	Y	Y	Y
Objective time degree	0.2769	0.2755	0.2496	0.2683	0.2894	0.2781
Result	Y	Y	N	N	Y	Y
Score function *a*	0.6286	0.6170	0.5839	0.6155	0.6328	0.6196
Result	Y	Y	N	N	Y	Y
Score function b	0.6445	0.6511	0.6280	0.6438	0.6527	0.6391
Result	Y	Y	N	N	Y	Y

of digital green innovation partners, overcome limitations of the combination weighting method in selecting partners from the evaluation results, help decision makers effectively avoid risks, and make the management and development decisions of hydrogen energy enterprises more rational. This furnishes a resolution for the digital and green metamorphosis of hydrogen energy enterprises, which is propitious to advancing the digital and intelligent synergetic management of hydrogen energy enterprises, elevating product value, innovating management paradigms and lowering production costs, expediting the intensive utilization and efficient allocation of overall resources, and facilitating the large-scale application and green, safe and efficient development of hydrogen energy.

2) THEORETICAL SIGNIFICANCE

This paper summarizes the design principles of the evaluation index system for the selection of digital green innovation partners in hydrogen energy enterprises, and constructs the evaluation index system for the option of digital green innovation partners in hydrogen energy enterprises. In this paper, the evaluation criteria based on fuzzy set theory are designed, and the selection model of digital green innovation partners for hydrogen energy enterprises is designed by utilizing the double combination weighting approach combining combination weighting theory and field theory. This decision-making model not only takes into account the embeddedness and compatibility of the selection indicators of digital green innovation partners of hydrogen energy enterprises, but also integrates the reciprocity of digital green innovation transformation and development of hydrogen energy enterprises into the target levels of aggregation and trust of partner cooperation. The results show that the evaluation method and index system constructed in this paper are effective and scientific, and the evaluation system can be used to choose digital green innovation partners in the actual operation and development process of hydrogen energy enterprises. This article enriches the business model doctrine of digital and green innovative transformation, the methodological framework for the selection of digital and green innovation cohorts of hydrogen energy enterprises, and the theoretical foundation for the efficient utilization and transformation development of new energy and the mutually beneficial cooperation of interdisciplinary and cross-domain enterprises, offering exemplary methods and theories for subsequent related studies. Thus, it propels the further expansion of the depth and breadth of research on the selection of digital and green innovation cohorts of hydrogen energy enterprises, and provides novel theories and data support for the transformation and development of hydrogen energy enterprises, with the anticipation of integrating all resources to enhance resource utilization efficiency and attain the optimal allocation level.

VI. CONCLUSION AND ENLIGHTENMENT

A. CONCLUSION

In the context of dual carbon, the digital green innovation development of hydrogen energy enterprises can effectively improve their economic and social benefits, so as to better comply with the global development trend and the trend of intelligent manufacturing. The digital and green transformation of hydrogen energy enterprises can promote the solution of problems such as high cost, low utilization rate and insufficient coordination in the process of large-scale application and advancement of hydrogen energy sector. The selection of appropriate digital green innovation partners can significantly better the development effectiveness of digital green innovation of hydrogen energy enterprises. In contrast to previous studies, this treatise concentrates on the development predicaments of hydrogen energy from the enterprise perspective. The novelty of this paper is chiefly manifested in the following respects: With regard to the future development dimensions of digitalization, greening and innovation, an evaluation index system for the selection of digital and green innovation consorts of hydrogen energy enterprises based on fuzzy set theory is contrived. A decision-making model for the selection of digital and green innovation consorts of hydrogen energy enterprises is fabricated based on a dual combined weighting evaluation approach integrating the combination weighting theory and field theory. By introducing the intuitionistic fuzzy theory with vigorous flexibility and generalization, the decision-making model can handle uncertain information and complex interrelationships more effectively, enhance the classification accuracy and generalization capability, and render the decision-making of digital and green innovation consorts of hydrogen energy enterprises more comprehensive and precise. On this basis, the decision-making model incorporates the field theory that takes into account the subject perspective, the rationality of partner selection, resource complementarity and the continuity of interaction. It fully considers the complementarity of customer value creation resources between hydrogen energy enterprises and the selected digital and green innovation consorts. Hence, the selected ecological consorts are more congruous, attaining the optimum of partner selection to a certain extent and surmounting the deficiency of choosing partners merely based on evaluation results. Analyzing and researching the hydrogen energy industry from a fresher perspective and a broader development dimension is more conducive to proffering novel development concepts for the salubrious development of the hydrogen energy industry. This case study shows that the decision-making model can be applied to the digital green transformation of hydrogen energy enterprises in reality, which is effective and practical, and can help hydrogen energy enterprises to improve the hydrogen energy system and build the core competitiveness of enterprises by selecting appropriate digital green innovation partners.

B. ENLIGHTENMENT

From the perspective of digital and green transformation of hydrogen energy enterprises, hydrogen energy enterprises should closely follow the development trend, identify the development orientation, use scientific and reasonable index evaluation system and decision-making methods to find digital green innovation partners, build a platform for upstream and downstream communication and cooperation of the industrial chain, innovation and release of emerging technology products, focus on hot topics of hydrogen energy, and analyze the development opportunities and challenges faced by the hydrogen energy industry. Hydrogen energy enterprises should adhere to the guidance of science and technology, cooperate to tackle key problems, carry out forward-looking and strategic research, focus on promoting the technological progress, large-scale and commercial development of hydrogen energy industry, actively undertake social responsibilities, improve environmental benefits, then encourage the industry's transition to digital, green and innovative practices.

From the perspective of the government promoting the cross sector cooperation of hydrogen energy enterprises, the government should focus on the frontier and emerging fields such as hydrogen energy, promote the participation of hydrogen energy enterprises in the innovation and opening-up construction of smart city scenes, provide financial subsidies and policy support for specialized and special new enterprises to participate in the construction of innovative technology breakthrough scenes and innovative technology application scenes, encourage the scale promotion of achievements, and promote the transformation of scene achievements. At the same time, the government should implement the ''service aggregation'' action, rely on the hydrogen energy enterprise demonstration base, carry out precise services for hydrogen energy enterprise financing, industrial chain financing and digital transformation, and promote the development of specialized and special new enterprises. The government can also pay attention to the establishment of specialized and special new service stations, and expand the team of policy service experts for the selection of digital green innovation partners of hydrogen energy enterprises, so as to achieve accurate policy access.

C. LIMITATIONS

In the research of this paper, there are still some inevitable shortcomings and deficiencies, which are worthy of attention and improvement in the future in-depth research. First, hydrogen energy enterprises can be further subdivided according to their production scale, development planning, policy environment, geographical location and other factors. At the same time, the hydrogen energy industry chain is long and there are many key links. The selection criteria, principles, needs and methods of digital green innovation partners for hydrogen energy enterprises with different types or production links are bound to be different. Therefore, the decision model created in this research can not accurately meet the needs of digital and green transformation of all hydrogen energy enterprises, but needs to be adjusted and optimized in combination with the actual application. In addition, the emergence of some emerging technologies can also be used in the option of digital green innovation collaborators for hydrogen energy enterprises, like AI and other technologies are also gradually playing a role in the business decision-making of enterprises. Therefore, the selection of digital green innovation partners for hydrogen energy enterprises in the future can also be closely combined with emerging technologies, so as to simplify the decision-making process, improve the decision-making efficiency, make the decision more scientific and reasonable, so as to better help hydrogen energy enterprises choose suitable digital green innovation partners, then expand the path of digital green innovation transformation of hydrogen energy firms.

AUTHOR CONTRIBUTIONS

All authors agreed to the manuscript.

DATA AVAILABILITY STATEMENT

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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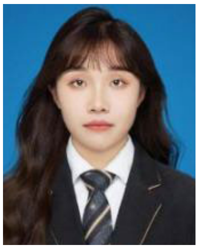

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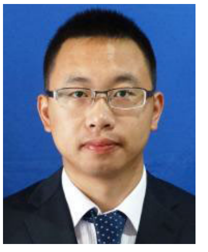

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