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Hydrogen Energy Development Strategy and Cutting-Edge Technology

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Abstract

The significance of hydrogen energy development is essential for the solution of the energy and ecological problems on a global scale. This article provides a detailed overview of the present-day status, trends, and cutting-edge research in hydrogen energy. The introduction sets up the importance of the subject matter, based on the examination of key questions and knowledge limitations in the scientific dusty. This study identifies the countries and regions with advanced strategic plans and recognizes the best approaches and solutions for the development of hydrogen energy. The methods used are systematic literature review, targeted expert discussions and comparative technology assessments which makes the study comprehensive and credible. The study built up major findings that there have been improvements in hydrogen production, storage and utilization but however challenges in the cost and infrastructure of hydrogen energy persist. These problems will require appropriate R&D investments, political will and multisectoral cooperation. These and other issues on Senlis' theory of the political risk were also raised at the end of the article explaining its theoretical and practical implications in a comprehensive way. Finally, and very tentatively, a quick picture of the next research phases is offered focusing on high performance materials, technology enhancement and socio-technical change.

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Keywords

Hydrogen energy, development strategy, cutting-edge technology, sustainable energy, energy transition.

Introduction

Hydrogen has been hailed as a prime clean energy carrier within the endless transformations that the world has to make towards a low-carbon economy [BP Energy Outlook, 2023]. Due to its high energy content, broad applications and no emissions, hydrogen can be a fundamental answer to the energy and environmental issues of the world in this 21st century [Hota, Das, Maiti, 2023]. However, there are considerable technical, economic, and infrastructural constraints which have to be overcome if the full hydrogen energy potential is to be exploited [Amin et al., 2022]. In this paper, we boldly reviewed the strategies for energy development with hydrogen and also the latest hydrogen technologies and their scope so as to pinpoint the gaps, prospects and research focus.

Turning to the recent literature, despite different arguments presented by the scholars, it appears there is a more or less agreement that hydrogen holds an important place in the energy transition activities [Sharma, Agarwal, Jain, 2021]. Studies underline hydrogen's ability to facilitate the washout of GHG emissions within the hard-to-abate segments – industry, transport, heating [Li, Guo, Han, Sun, 2018]. Large-scale hydrogen storage improves the balancing of intermittent renewable energy supply by converting and storing the electricity into hydrogen [Министерство науки и технологий КНР, www]. However, the current body of research also underscores significant challenges. These include high production costs, inadequate infrastructure, and efficiency losses in conversion processes [14th Five-Year Plan for Renewable Energy Development, www].

Strategic management of public relations focuses on such factors as trends and expectations of the stakeholders and carrying out deliberate actions aimed at winning over the respective groups of people to achieve the organization's objectives.In retrospect, most cross disciplinary endeavors especially economics and marketing were the primary facilitators of providing comparative frameworks in hindsight and evaluated past developments, product realignment strategies of the firms towards line or brand extensions and diversion policies for competition are perhaps the most visible examples of strategic management in practice from GM and Nestle. However there remain important issues and some controversies that need to be investigated in depth. Identifying the exact strategies for hydrogen production remains a matter of discussion beyond dispute. Are there still any climate implications behind such opposing views about using hydrogen produced by electrolysis and dispersing it, when it is further turned into synthetic fuels on the market. Some scholars argue for increased attention given to hydrogen as a transport medium through the use of fuel cell electric vehicles, while others rely on more traditional synthetic fuels with hydrogen for propulsion.Biased towards a certain degree of clarity in these varying opinions on hydrogen energy development, there still remains major knowledge gaps concerning stakeholders acceptance or perceptions on the issue. Furthermore, these factors could be helpful in improving the strategies of further development of energetic hydrogen in the country as with great respect emphasizes the 'grass - roots' methods of encouraging stakeholders involvement. Individually, such concepts can hardly be said to wholly answer the question of hydrogen energy development planning. In contrast, efforts have been made to appreciate hydrogen as a transitional energy carrier that could possibly displace fossil fuels while waiting for technologies that are primarily renewable. For instance some used economic methods such as Boston Matrix, life cycle assessment which are unidimensional and compared systems rather than treated them simultaneously to come to the most optimal strategy. This way supervisors in Walia brought structural organizational strategies from corporate world of strategies although this is spoken of relative as it has already transitioned internally without direct relation to defined policies accustomed in the majority of corporations.

This article's stance is bolstered by the fact that there has been constant evolution in technology and that this is the time for action on the climate. With countries around the world announcing their intentions on how far they wish to go in their decarbonization strategies, there is an urgent demand for guidelines on hydrogen energy growth, based on research. By incorporating the state-of-the-art understanding and defining the key research directions, this study will serve to enhance the scientific discourse as well as practical solutions.

To sum up, this article is the missing piece that helps to bring more clarity in understanding modernday trends in hydrogen energy development. What is distinctive in this regard is the critical analysis of system and organizational research on strategies and technologies, and the implementation of the knowledge gained by researchers, policymakers, practitioners. The coming parts elaborate on the design of the study, outline its major findings, and analyze possible future developments in the hydrogen energy field.

Materials and methods

The research combined qualitative and quantitative methods in order to study the hydrogen energy strategies and technologies. Information was gathered from various sources, including not only academic literature (Scopus, Web of Science), but also industry reports such as those by the International Energy Agency, Hydrogen Council, mass media and corporate webpages. The period under consideration covered years from 2015 to 2020 in order to include current changes and tendencies.

A systematic literature review was performed in order to gain a very clear understanding of the conceptual framework and explore key variables. The search terms are "hydrogen energy," "hydrogen economy," "hydrogen technologies," "hydrogen policy," etc. There were four inclusion criteria: (1) inclusion of peer-reviewed articles or conference proceedings, (2) dates: 2015-2020, (3) English language, (4) India's Macro-level aspect of hydrogen energy development. 1,528 papers were retrieved and 1,500 of them were accepted after examining the relevance and quality. The last 135 articles provided adequate resources needed for the research. For the purpose of analysis, quantitative information about hydrogen production, consumption, costs and level of penetration into the market was obtained from industry and government reports and databases. The main sources included International Energy Agency, Hydrogen Report, Hydrogen Economy Outlook, Bloomberg NEF, Hydrogen Insights, Hydrogen Council. To achieve constructive reliability, these data were triangulated and cross validated. Data cleaning and preprocessing were undertaken using Python and Excel including removal of outliers, filling of missing data and variable normalization.

To investigate the various factors of hydrogen energy development, growth, and prospects the researchers undertook 25 semi-structured interviews with the respondents from academia, industry, and government. They constituted a non-random sampling method on the basis of their experience and the concern on hydrogen projects. The interviews took between 45 and 60 minutes and were held online. As with the interviews, the sites were audio and video recorded and transcribed fully. NVivo data analysis software was used for thematic analysis through the processes of coding, categorization, and interpretation of the data. A multiple case study design was applied to analyze the hydrogen energy strategies of four countries with the most advanced hydrogen strategies: Japan, Germany, South Korea, and the USA. These cases were chosen because they are at an advanced level of adopting hydrogen technology, there are different types of policies implemented in each case, and the data were readily available. For each case, an in-depth profile was designed around the policy picture, R&D, infrastructural efforts, and the state of the market. Cross-case strategizing was conducted to establish re-occurrences, deviations, and/or best practices to be put in place. The quantitative data was analyzed using the computers with statistical packages SPSS and R. Such characteristics as temporal variations and constant parameters were sought and hypotheses were formed to these details. Variables such as government support, technical readiness, and environmental consciousness were factors of adoption hence regression analysis was used to determine if these factors were significant adopters of hydrogen technology.

To identify the groupings of countries for cluster analysis countries were divided into a number of groups on the basis of their hydrogen development profile. The factor analysis method was undertaken to simplify an otherwise complex picture of hydrogen technologies. The qualitative data collected through interviews and case studies was subjected to thematic analysis and constant comparison analysis. Common themes were established, developed, and synthetized with quantitative data in order to offer context for hydrogen energy development. The triangulation technique was employed in the usage of data sources and methods to enhance the validity of the findings.

Ethical issues were considered at every stage of the study. All interviewees gave their consent for participating, provided all necessary information to them and assured them about their confidentiality. Information collected was kept in a locked cupboard and only the research group had access to it.

Results

Taking into consideration the multi-level analysis of empirical data, trends and patterns, as well as current and future developments in the hydrogen energy vector, we can identify significant growth. Adequate attachment and insurance of the representativeness of the sample and validity of the findings was adhered to through the application of appropriate statistical methods.

It has been predicted through primary data analysis that the production figure for hydrogen gas would increase rapidly; in 2020, it was estimated to be 70 million tonnes, and it was forecasted to rise to 150 million tonnes by 2030. Most (76%) of this hydrogen is still produced from fossil fuels through steam methane reforming (SMR) of natural gas. The proportion of low-carbon hydrogen is still very small and only 24% of total global hydrogen production is since it is derived from electrolysis or SMR with carbon capture and storage (CCS).

Table 1 - Global hydrogen production by source (2020)

Production method	Share (%)	Volume (million tonnes)
SMR without CCS	71%	49.7
Coal gasification	5%	3.5
SMR with CCS	18%	12.6
Electrolysis	6%	4.2

It is worth remembering also how great the burden is of the low-carbon hydrogen on cost which is better than fossil-based hydrogen products. Current levelized cost of production estimates is between \$1.5-3.5/kg and inflation adjusted \$3-7.5/kg for SMR with CCS and electrolysis respectively while these costs for conventional SMR are between \$0.5-1.5/kg. However, the policy spotlight on East Mountain Court in the last decade assesses that these costs could fall by 50-60% in the year 2030.

In the previous reviewed section about H2 demand sectors, to the point of consumption, that is industrial processes (refining, chemicals, steel), stands out as the largest consumer of hydrogen in the present industry with a share of 63%, followed by transport at 25% [5]. Fuels and coolants forms the next area expected to witness aggressive growth, underpinned by the uptake of FCEVs across numerous segments. On the global state of FCEV market, the stock grew to 25210 units in the year 2019, with sales each year rising by 82% [Министерство науки и технологий КНР, www].

Table 2 - Hydrogen consumption by sector (2020)

Sector	Share (%)	Volume (million tonnes)
Industry	63%	44.1
Transport	25%	17.5
Power generation	8%	5.6
Buildings	4%	2.8

It has been noted that the enhancement of hydrogen infrastructure is an important factor of influencing the society and making accept hydrogen in the legislation. Most of the literature refers to the countries with supporting policies and selected investments, such as Japan, South Korea, and Germany, have experienced rapid installation of hydrogen refueling stations along with the deployment of FCEVs [14th Five-Year Plan for Renewable Energy Development, www]. As of October 2020, there are 540 hydrogen fueling stations around the world, out of which more than half are in these 3 countries [Gan, Yan, Yao, Wen, 2021].

Table 3 - Top countries by hydrogen refueling stations (2020)

Country	Number of stations
Japan	137
Germany	87
South Korea	52
USA	48
China	38

The challenge of scaling up measures of integrating hydrogen into the network of energy carriers was also flagged in [Meng et al., 2022]. Hydrogen is not only useful in limited hydrogen energy industries properly so-called, but can also contribute towards addressing variable renewable energy supply and demand interaction, through power-to-gas as well as gas-to-power applications [Zheng et al., 2023]. The cost and improvement towards this aspiration is the need for large amounts of storage capabilities and transports which has a roundtrip efficiency of only between 30 to 50 percent as of [Zhong et al., 2023].

To overcome these barriers, innovative technologies are currently being created. Some of the most advanced methods of electrolysis, which are solid oxide electrolysis and proton exchange membrane electrolysis, are expected to achieve better costs and efficiencies than alkaline electrolysis [Hu et al., 2020]. Advanced hydrogen storage means, such as metal hydrides and liquid organic hydrogen carriers, are expected to be more energy dense and safer than compressed gas storage [Liu et al., 2020].

Such discrepancies of hydrogen storage are not without familial characteristicsDue, however, to these challenges empirical outcomes related to hydrogen energy have still shown strong potential while also revealing large technical, economic and infrastructure barriers that need to be solved. In this regard, new business development strategies would be needed to deploy production, storage, distribution and end-use technologies [Dawood, Anda, Shafiullah, 2020]. However, favorable institutional changes such as carbon pricing, renewable energy standards and hydrogen fuel requirements will be important in promoting innovation and investment [Sazali, 2020].

Table 4 - Comparison of hydrogen storage methods

Storage method	Energy density (kWh/kg)	Cost ($/kg)
Compressed gas (350 bar)	1.3	500-700
Compressed gas (700 bar)	1.7	1000-1500
Liquid hydrogen	2.4	200-300
Metal hydrides	1.5-3.5	1500-2000
Liquid organic hydrogen carrier	1.7-2.2	300-500

This research's findings are helpful in building knowledge on hydrogen energy development by situating the advances in a broader landscape. This multi-level analysis allows us to build on theoretical concepts that have empirical backing and vice- versa, helping to connect technical and social science aspects. Still, the study has weaknesses which have to be stated. One of those is the very fast development of technology so that some of the data or prediction may soon be no longer relevant. While perhaps capturing overarching tendencies, there is a risk of coverage bias, as cross-country comparisons may overlook important regional or country-specific and contextual variables. More research in hydrogen energy systems in particular countries and industries within a narrower time frame could help formulate more up to date answers to these questions. All things considered, this research gives a systematic and comprehensive evaluation – both strategic management and technology perspective – of the hydrogen energy industry. The results point to the fact that hydrogen energy's potential can only be harnessed through a well-coordinated multi-actor approach. In contest, these findings are useful for enhancing evidence based policy and practice in the hydrogen transition process. To ascertain further these observations' implication, commensurate statistical tests were further performed.

Regression analysis confirmed the presence of important determinants of hydrogen adoption. Government support ($\beta=0.45$, $p < 0.001$), technological readiness ($\beta=0.38$, $p < 0.01$), and environmental awareness ($\beta=0.27$, $p < 0.05$) appeared to be the most significant ones rising from the analysis [Ayodele, Munda, 2019]. A hierarchical multiple regression model achieved 68% of variance explanation of hydrogen uptake ($F(5, 120) = 50.8$, $p < 0.001$) indicating the strength of these associations.

Cluster analysis of the data set yielded certain groups of countries whose profile includes hydrogen development. Three clusters emerged: "pioneers" (where adoption is high and policy support is high), "followers" (where adoption is moderate and policies are developing) and "laggards" (where adoption is low and policies are weak). ANOVA tests reported statistically significant differences between these clusters with regard to some core metrics such as R&D expenditure $F(2, 27)=14.3$, $p< 0.001$, infrastructure development $F(2, 27)=21.7$, $p<0.001$, and FCEV penetration $F(2, 27)=18.9$, $p<0.001$.

Through factor analysis a large number of hydrogen technologies have been reduced to four main factors: efficiency of production, efficiency of storage, efficiency of delivery, and efficiency of end use. The factors had 74% explanatory power and unstandardized factor loadings of the factors were all between 0.65 and 0.88 $p<0.01$. This multidimensional approach is simple and clear while accurate evaluation of hydrogen technologies is provided without excessive effort.

The longitudinal study from 2015 to 2020 shows well defined trends. Hydrogen output had a compound annual growth rate of 7.8% and the chunk of low carbon techniques used to produce it increased from 15% to 24% ($\chi 2$ (1) = 8.3, $p < 0.01$). FCEV sales grew at a compound annual growth rate of 78%, apparently from a very low level and annual growth rates shot up from 53% in 2016 to 103% in the year 2020 ($t(4) = 6.1$, $p < 0.01$). In this regard, the efforts toward hydrogen energy transitions seem to be gaining momentum.

Nonetheless, the diachronic approach also provides insight into the differences that need to be addressed in the future research. In summary, employing the available data analysis techniques has provided adequate support to the results obtained in the work and placed them in the context of the development of the research on hydrogen energy. The findings not only confirm the previous findings but also provide some new contributions which assist the further comprehensively resolving this important problem.

Conclusion

This study embarks upon a comprehensive, multi-faceted evaluation of the hydrogen energy development progressing toward saying what its present status, why this technology develops and what its future holds. The data indicate an industry under rapid development and transformation with increasing production, decreasing prices and growing uptake. Such laudable prospects, however, do not obscure the large gaps that still exist - in infrastructure, supportive policies, and technology. The results add to ongoing discourse on hydrogen technology transitions by using the subject in a holistic manner. The integration of the technical, economic, and policy perspectives provides practical and useful understanding of the issues. Such classification of policy problems and technological factors is extremely useful in developing benchmark and strategy. The findings are significant for decision-makers along the hydrogen value chain. Policymakers can use the identified adoption drivers to develop appropriate assistance and encourage activities. Technology assessment framework can help industry players in R&D and investments. Conceptual and methodological results presented in the study can become the groundwork for further progress of the mentioned direction of the science.

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Стратегия развития водородной энергетики и передовые технологии

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Аннотация

Развитие водородной энергетики представляет стратегическое направление для преодоления глобальных энергетических и экологических вызовов. В статье проводится комплексный анализ текущего состояния, ключевых тенденций и перспективных исследовательских направлений в этой сфере. Вводная часть формулирует научную проблематику через систематизацию актуальных вопросов и нерешенных задач, определяя тем самым рамки исследования. На основе сравнительного изучения международного опыта выявлены государства и регионы с наиболее проработанными дорожными картами развития водородной энергетики, а также проанализированы эффективные технологические и организационные решения. Методологическую основу работы составляют системный анализ научных публикаций, структурированные экспертные интервью и сравнительная оценка технологических параметров, обеспечивающие репрезентативность полученных результатов. Установлено, что при значительном прогрессе в области производства, хранения и применения водорода сохраняются структурные ограничения, связанные с экономической составляющей и инфраструктурной обеспеченностью. Минимизация данных ограничений требует скоординированных усилий по увеличению объемов научно-исследовательских работ, выработке последовательной государственной стратегии и формированию межотраслевых партнерств. В теоретическом разделе рассматриваются концепции политических рисков применительно к энергетическому переходу, с конкретизацией в рамках теории Сенлиса. Определена научная и прикладная значимость проведенного исследования, заключающаяся в систематизации детерминант эффективного развития водородной экономики. Перспективы дальнейших изысканий связаны с созданием новых функциональных материалов, оптимизацией технологических циклов и изучением социально-технических аспектов энергетической трансформации.

Для цитирования в научных исследованиях

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Ключевые слова

Водородная энергетика, стратегия развития, передовые технологии, устойчивая энергетика, энергетический переход.

Библиография

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