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Hydrogen as a Secondary Energy Carrier: Modeling Its Integration in National Grids

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Abstract- Hydrogen is increasingly recognized as a pivotal secondary energy carrier with the potential to accelerate the global transition toward low-carbon energy systems. Its versatility allows it to function as a medium for storing, transporting, and converting energy derived from diverse primary sources, including renewables and fossil fuels with carbon capture. This examines the modeling of hydrogen's integration into national electricity grids, emphasizing its role in enhancing system flexibility, supporting sector coupling, and enabling deep decarbonization. This explores various modeling frameworks, including integrated energy system models, capacity expansion models, power flow analyses, and multi-sector optimization tools. It addresses key technical, economic, and environmental factors influencing hydrogen integration, such as production pathways, storage options, transport infrastructure, and conversion efficiencies. The analysis also considers regulatory environments, policy incentives, and market dynamics that shape the feasibility and scalability of hydrogen-based systems. By analyzing case studies from Europe, Japan, the United States, and Australia, this highlights practical applications of hydrogen integration, including cross-border pipeline initiatives, import-based hydrogen supply chains, and localized grid-hydrogen projects. Despite its significant potential, integrating hydrogen into national grids presents challenges related to model complexity, uncertainty in technology evolution, data gaps, and interoperability with existing infrastructure. Furthermore, socioeconomic implications such as affordability, energy equity, and public acceptance must be carefully managed. This identifies emerging trends, including artificial intelligence-driven modeling, digital twins, and advanced scenario analysis, which offer new opportunities for more precise and adaptive planning. Ultimately, thisunderscores the importance of comprehensive, data-driven modeling to inform investments, regulatory frameworks, and policy interventions necessary to unlock hydrogen's full value as a secondary energy carrier in future national and regional energy systems.

Keywords: Hydrogen, Secondary energy carrier, Modeling, Integration, National grids

I. INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by escalating energy demands, climate change imperatives, and the urgent need to reduce greenhouse gas (GHG) emissions (Mustapha *et al*., 2018; Oyedokun*et al*., 2019). As countries commit to net-zero targets and seek sustainable pathways for economic development, the decarbonization of energy systems has become a central policy priority (Olaoye *et al*., 2016; SHARMA *et al*., 2019). In this context, hydrogen is emerging as a critical enabler of clean energy transitions. Its unique versatility—spanning electricity storage, fuel substitution, and industrial decarbonization—positions it as a promising secondary energy carrier capable of addressing some of the most pressing challenges in modern energy systems (Oduola *et al*., 2014; Akinluwade*et al*., 2015).

Hydrogen's value lies not in being a primary source of energy, but in its ability to act as a flexible intermediary that stores, transports, and delivers energy originally derived from diverse primary sources, including solar, wind, nuclear, and fossil fuels (Adeoba *et al*., 2018; Adeoba *et al*., 2019). When produced via electrolysis, hydrogen is generated by splitting water using electricity, ideally from renewable sources, resulting in so-called "green hydrogen." Alternatively, it can be produced through steam methane reforming (SMR) or coal gasification, which are currently dominant methods but produce significant carbon emissions unless combined with carbon capture technologies ("blue hydrogen")

(Adeoba and Yessoufou, 2018; Adeoba, 2018). In all cases, hydrogen effectively decouples energy production from consumption in time and space, allowing it to support load balancing, seasonal storage, and sector coupling between electricity, heating, transport, and industry (Robiniuset *et al*., 2017; Taibi *et al*., 2018).

As a secondary energy carrier, hydrogen functions similarly to electricity, but with distinct advantages in terms of long-term storage and high-temperature industrial applications (Singh *et al*., 2016; Nadeem *et al*., 2018). Its integration into national power grids represents a transformative opportunity to enhance system resilience, enable higher penetration of renewables, and reduce dependency on fossil fuels. However, realizing this potential requires robust modeling approaches to understand how hydrogen infrastructure, production systems, and demand profiles interact with existing grid architectures (Markert *et al*., 2017; Subramanian *et al*., 2018).

The purpose of this review is to explore the modeling strategies employed in integrating hydrogen into national energy grids, emphasizing both technical and policy perspectives. It investigates various classes of energy system models—ranging from power system optimization tools to sectoral coupling frameworks—that assess hydrogen's impact on grid stability, capacity expansion, and emissions reduction. By doing so, this aims to provide a comprehensive understanding of how hydrogen can be systematically embedded in future energy scenarios. It also examines the implications of hydrogen integration on grid reliability, cost-effectiveness, and environmental performance, which are critical for energy planners, regulators, and investors (Groppi *et al*., 2018; Dincer and Acar, 2018). In addition, this highlights key barriers—such as data gaps, infrastructure incompatibility, and regulatory fragmentation—that must be addressed through interdisciplinary research and coordinated policy action.

The integration of hydrogen as a secondary energy carrier offers a compelling pathway toward sustainable energy systems. This contributes to the academic and policy discourse by focusing on the modeling dimension of this integration, providing insights into how hydrogen can be optimally leveraged to meet future energy needs while aligning with global decarbonization goals.

II. METHODOLOGY

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology provides a structured and transparent framework for conducting systematic reviews. In this study, the PRISMA approach was applied to systematically identify, select, and analyze relevant literature on hydrogen as a secondary energy carrier, focusing specifically on its modeling and integration into national grids.

The review began with a comprehensive search of major scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, covering publications from 2000 to 2025 to capture both foundational and contemporary studies. A combination of keywords and Boolean operators was used to refine the search, including terms such as "hydrogen energy carrier," "power grid integration," "energy system modeling," "sector coupling," "hydrogen infrastructure," "electrolysis modeling," and "power-to-gas." Additionally, filters were applied to include only peer-reviewed articles, conference papers, and authoritative reports in English.

Following the initial search, a total of 1,240 records were identified. Duplicates were removed, resulting in 978 unique records. These records were then subjected to a two-stage screening process. In the first stage, titles and abstracts were reviewed to exclude studies unrelated to hydrogen modeling or those focused solely on hydrogen production without considering grid integration. This step narrowed the selection to 312 studies. In the second stage, full-text screening was conducted based on inclusion criteria such as the presence of explicit modeling frameworks, quantitative analyses of grid integration, and assessment of system-wide impacts including emissions, costs, and reliability. Studies focusing purely on experimental hydrogen production technologies or small-scale pilot projects without grid-level modeling were excluded. After this step, 104 studies were retained for detailed analysis.

Data were extracted systematically from the selected studies using a standardized template capturing study objectives, modeling techniques, system boundaries, geographic scope, hydrogen production methods, storage and transportation assumptions, integration with other sectors, and key findings. Specific attention was given to modeling tools such as capacity expansion models, optimization algorithms, power flow simulations, and sector coupling models, as well as assumptions about hydrogen costs, technology maturity, and policy frameworks.

The quality of included studies was assessed using a customized checklist based on methodological rigor, transparency of assumptions, data sources, and reproducibility. Studies that did not clearly explain their models or omitted essential data inputs were noted for limited reliability but retained if their findings contributed to broader thematic insights.

The synthesis process involved thematic coding and narrative analysis, categorizing studies by modeling approach, geographical application, and research focus areas such as flexibility services, renewable integration, storage optimization, and techno-economic assessments. The synthesis highlighted methodological advancements, gaps in current modeling practices, and opportunities for future research.

Through this systematic review using PRISMA methodology, this provides a rigorous, transparent, and replicable foundation for understanding the state of knowledge on modeling hydrogen integration into national grids. The findings inform future research directions, policy formulation, and investment strategies related to hydrogen-based energy transitions.

2.1 The Role of Hydrogen in Energy Systems

Hydrogen has emerged as a critical component in the evolving landscape of global energy systems. Its unique properties and wide range of applications position it as an essential vector for enabling energy transitions toward more sustainable, resilient, and decarbonized infrastructures. As a secondary energy carrier, hydrogen is not only capable of storing large quantities of energy but also of acting as a bridge between different sectors, enhancing energy security, and facilitating sectoral integration (Rosen and Koohi-Fayegh, 2016; Clarke *et al*., 2018).

One of the key characteristics of hydrogen is its high energy density per unit mass. At approximately 120 megajoules per kilogram (MJ/kg), hydrogen possesses the highest energy content among common fuels, nearly three times higher than gasoline on a mass basis. This makes hydrogen highly suitable for energy-intensive applications where weight constraints are crucial, such as aerospace and long-haul transportation. However, its low volumetric energy density poses challenges for storage and transportation, necessitating advanced compression or liquefaction technologies. Beyond its high energy density, hydrogen is exceptionally versatile. It can be converted into electricity via fuel cells or combusted directly to produce heat. It also serves as a feedstock for industrial processes such as ammonia production, steel manufacturing, and petrochemical refining. Moreover, hydrogen can act as a synthetic fuel precursor through processes like methanation or Fischer-Tropsch synthesis, further expanding its application in aviation, shipping, and other hard-to-abate sectors (Ail and Dasappa, 2016; Martens *et al*., 2017).

When compared to other energy carriers, hydrogen presents both advantages and challenges. Relative to natural gas, hydrogen produces no carbon emissions upon combustion, offering a cleaner alternative for heating and power generation. However, hydrogen has a lower volumetric energy density and requires different handling infrastructure, limiting its immediate substitutability. Compared to batteries, hydrogen excels in long-duration and large-scale storage scenarios where batteries become economically and technically infeasible due to degradation and cost issues. For instance, hydrogen can provide seasonal storage of surplus renewable electricity, whereas batteries are generally restricted to short-duration balancing services. Similarly, when contrasted with pumped hydro storage—which is geographically limited—hydrogen offers a more location-flexible solution, particularly in regions lacking suitable hydro topography.

Hydrogen production pathways are central to its sustainability and economic competitiveness. Green hydrogen—produced via electrolysis powered by renewable energy sources—offers the most sustainable route, yielding zero operational emissions.

Electrolysis technologies such as proton exchange membrane (PEM) and alkaline electrolyzers are gaining commercial viability, although challenges related to high capital costs and efficiency losses remain (Feng *et al*., 2017; Saba *et al*., 2018). Blue hydrogen represents a transitional solution, produced from fossil fuels such as natural gas through steam methane reforming (SMR) or auto-thermal reforming (ATR), combined with carbon capture and storage (CCS) technologies to mitigate associated CO_2 emissions. While blue hydrogen can be scaled with existing gas infrastructure, its long-term viability depends on the effectiveness and availability of CCS facilities. In contrast, grey hydrogen—also produced from fossil fuels but without CCS—remains the most widely produced form today, particularly in the industrial sector. However, its high carbon footprint makes it incompatible with decarbonization objectives.

Hydrogen's practical deployment depends heavily on effective storage and transportation solutions. Compressed hydrogen gas storage, typically at pressures up to 700 bar, is the most mature technology for mobile applications, including fuel cell vehicles. For larger-scale or stationary applications, liquefaction at cryogenic temperatures (around -253°C) offers a higher energy density per volume but entails significant energy costs for cooling and maintaining storage conditions. Underground storage in salt caverns or depleted gas fields has also emerged as a promising option for bulk, long-duration storage, particularly for balancing seasonal energy fluctuations.

In terms of transportation, hydrogen pipelines are the most efficient mode for high-volume, continuous transmission over short to medium distances. Repurposing existing natural gas pipelines for hydrogen blends, typically up to 20% by volume, is already under consideration in many countries, though technical limitations related to materials compatibility and safety must be addressed. For longer distances and smaller quantities, tanker transport—either as compressed gas, liquid hydrogen, or hydrogen carriers such as ammonia or liquid organic hydrogen carriers (LOHCs)—is increasingly explored (Bicer and Dincer, 2018; Abdalla *et al*., 2018). Each transportation method involves trade-offs in terms of cost, energy efficiency, and infrastructure requirements.

Hydrogen plays a pivotal role in modern energy systems due to its favorable energy density, versatility across sectors, and ability to provide long-term storage and transport solutions. Its effective integration into energy systems depends on the development of low-carbon production methods, robust storage technologies, and efficient transportation infrastructure. By complementing other energy carriers such as electricity, batteries, and natural gas, hydrogen can bridge critical gaps in the pursuit of reliable, flexible, and low-emission energy systems (Evelo and Gebreegziabher, 2018; Siskos *et al*., 2018). However, large-scale deployment requires addressing technological, economic, and regulatory challenges to fully realize hydrogen's potential in supporting global decarbonization goals.

2.2 Modeling Approaches for Hydrogen Integration

The integration of hydrogen into national energy systems requires sophisticated modeling approaches to assess its technical, economic, and environmental impacts. Due to the multi-faceted role of hydrogen—ranging from energy storage to sectoral coupling—models must address complex interactions across production, conversion, storage, and end-use stages. Various modeling frameworks have been developed to evaluate hydrogen's role within energy systems, with each approach tailored to specific analytical objectives, geographical scales, and time horizons as shown in figure 1 (Hall and Buckley, 2016; Wiese *et al*., 2018). This examines key modeling approaches, including energy system models, power grid models, sector coupling frameworks, and optimization techniques that collectively offer a comprehensive understanding of hydrogen integration.

Energy system models are widely used to analyze the long-term role of hydrogen in decarbonizing energy systems. Integrated Assessment Models (IAMs) are particularly valuable for assessing global and national pathways to meet climate goals. These models incorporate energy, economic, land-use, and climate systems into a unified framework, allowing for the exploration of hydrogen's role in achieving net-zero scenarios. IAMs such as MESSAGE-GLOBIOM, REMIND, and GCAM frequently include hydrogen pathways, enabling researchers to examine trade-offs between hydrogen, renewable electricity, and carbon capture technologies. However, IAMs typically operate at a coarse spatial and temporal resolution, limiting their ability to capture grid-specific operational dynamics.

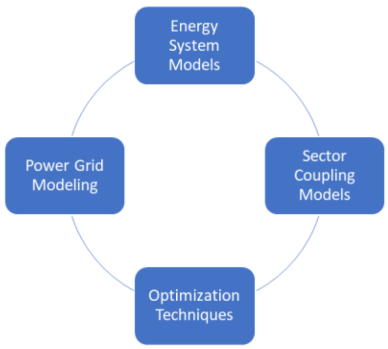

Figure 1: Modeling Approaches for Hydrogen Integration

To complement IAMs, Power-to-Gas (P2G) simulation tools focus on the detailed operational behavior of hydrogen production via electrolysis. These models simulate the conversion of surplus electricity, particularly from intermittent renewable sources, into hydrogen, which can then be stored or injected into gas networks. P2G tools assess factors such as electrolyzer sizing, operating schedules, grid curtailment reduction, and seasonal storage capacity. By explicitly modeling the interaction between electricity and gas systems, these tools provide insights into the operational feasibility of hydrogen-based flexibility solutions and their effects on grid stability.

Power grid modeling plays a crucial role in evaluating the impacts of hydrogen integration on electrical infrastructure. Capacity expansion models are used to optimize investment decisions in generation, transmission, storage, and hydrogen infrastructure over long-term planning horizons (Michalski, 2017; Gacitua*et al.*, 2018). These models identify least-cost pathways for expanding system capacity while meeting reliability and emissions targets. They are particularly useful for assessing when and where to deploy electrolyzers, hydrogen storage units, and pipelines as part of broader energy transitions. Examples include models such as SWITCH and TEMOA, which enable scenario-based analyses of hydrogen's contribution to grid flexibility and renewable integration.

Additionally, power flow and stability analysis models provide detailed assessments of hydrogen's impact on short-term grid operations. These models simulate electrical power flows and voltage stability, considering the dynamics of hydrogen-fueled generators, electrolyzers, and fuel cells. Such analyses are critical for ensuring that hydrogen technologies do not introduce risks to system reliability, especially as their penetration increases. Transient stability models, dynamic simulations, and frequency response analyses help evaluate the role of hydrogen in supporting grid inertia and fast frequency response services.

Hydrogen's cross-sectoral nature necessitates the use of sector coupling models that capture the interactions between electricity, heating, transport, and industrial sectors. These models evaluate the integrated operation of multi-energy systems, considering how hydrogen production and consumption can balance supply and demand across different sectors. For example, excess renewable electricity can be converted into hydrogen and used for district heating, fueling vehicles, or supplying industrial processes, thus optimizing overall system efficiency. Sector coupling models such as TIMES, ETEM, and EnergyPLAN provide critical insights into the synergies and trade-offs between sectors, enabling the design of holistic decarbonization strategies.

Optimization techniques are central to all these modeling approaches, enabling the identification of cost-effective and technically feasible solutions for hydrogen integration. Multi-objective optimization is particularly relevant, as decision-makers must balance multiple criteria such as cost minimization, emissions reduction, and system reliability (Meng *et al.*, 2017; Jafari and Valentin, 2018). These techniques allow for the exploration of Pareto-optimal solutions, where trade-offs between competing objectives are explicitly quantified. For example, a model may simultaneously minimize hydrogen production costs while maximizing grid flexibility and reducing emissions.

Specific mathematical methods such as dynamic programming and mixed-integer linear programming (MILP) are frequently employed in hydrogen modeling (Maroufmashat*et al.*, 2016; Dolara*et al.*, 2017). Dynamic programming is well-suited for solving multi-stage decision problems, such as optimizing hydrogen storage and dispatch under uncertain renewable generation. MILP, on the other hand, is widely used for operational planning and infrastructure investment problems involving discrete decisions, such as the number of electrolyzers or hydrogen pipelines to build. These techniques ensure model tractability while capturing the complex, non-linear relationships inherent in energy systems.

Modeling hydrogen integration into national energy systems requires a combination of complementary approaches. Energy system models, power grid simulations, sector coupling frameworks, and advanced optimization techniques collectively enable comprehensive assessments of hydrogen's technical, economic, and environmental implications. Each modeling approach addresses different aspects of hydrogen integration, from high-level policy analysis to detailed operational planning. As hydrogen technologies evolve and their deployment scales up, continued advancements in modeling methodologies will be essential for designing robust, efficient, and resilient hydrogen-based energy systems.

2.3 Key Factors in Model Development

Developing robust and effective models for hydrogen integration into national energy systems requires careful consideration of several interrelated technical, economic, environmental, and regulatory factors as shown in figure 2. Each of these dimensions influences the assumptions, structure, and outputs of hydrogen-related models, ultimately shaping their utility in policy-making and investment decisions (Huijts*et al.*, 2016). A comprehensive approach to model development must incorporate these factors to ensure realistic and actionable insights into hydrogen's role in future energy systems.

Technical considerations are central to hydrogen modeling, particularly given the unique operational characteristics of hydrogen technologies. One of the primary technical challenges is ensuring grid flexibility and balancing. As renewable energy penetration increases, variability in power supply creates a need for additional balancing resources. Hydrogen production via electrolysis can provide a flexible demand-side resource by absorbing excess electricity during periods of surplus and reducing demand during shortages. Models must account for the ability of electrolyzers to ramp up or down quickly, their operational constraints, and their interaction with grid stability services such as frequency regulation and voltage control (Wang *et al.*, 2018; Ayivor, 2018). Failure to capture these dynamics could result in inaccurate assessments of hydrogen's value in balancing electricity systems.

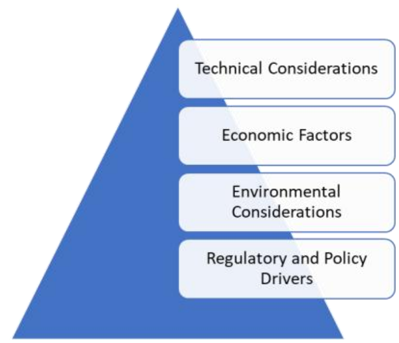

Figure 2: Key Factors in Model Development

Another essential technical factor is storage duration, which determines the role hydrogen plays relative to other storage technologies. Hydrogen is uniquely suited for long-term and seasonal storage, enabling the system to shift excess renewable generation from high-production seasons (e.g., summer) to high-demand seasons (e.g., winter). In contrast, technologies such as batteries are generally optimized for short-duration, high-frequency cycling. Models must accurately distinguish between these storage durations to optimize technology portfolios. Additionally, assumptions about hydrogen conversion efficiencies—covering electrolysis, compression or liquefaction, storage, and fuel cell reconversion—are critical. Electrolysis efficiencies typically range from 60% to 70%, while subsequent storage and reconversion losses can further reduce overall round-trip efficiency (Mulder *et al.*, 2017; Tuller, 2017). Models must reflect these conversion losses realistically to prevent overestimating hydrogen's net energy contribution.

Economic factors also play a significant role in hydrogen model development. The cost of hydrogen production and infrastructure—including electrolyzers, fuel cells, storage systems, pipelines, and fueling stations—has a direct impact on model outcomes. Capital costs for electrolyzers remain high, although they are expected to decrease with technological learning and economies of scale. Additionally, hydrogen transportation methods, such as liquefaction or pipeline retrofitting, add significant costs that models must incorporate. Infrastructure investment costs must be paired with realistic operational and maintenance expenditures to assess the total cost of hydrogen deployment accurately (Hirsch *et al*., 2018; Ardo *et al*., 2018).

In parallel, market mechanisms such as subsidies, carbon pricing, and renewable energy credits can drastically influence hydrogen economics. Models must simulate the effects of these mechanisms on hydrogen competitiveness. For example, carbon pricing can make green hydrogen more attractive by penalizing fossil-based alternatives, while subsidies for electrolyzer deployment or renewable power procurement can lower the effective cost of green hydrogen production. Incorporating dynamic market mechanisms allows models to capture how hydrogen deployment might evolve under different policy scenarios and market conditions (Pinson *et al*., 2017; Cherp*et al*., 2018).

Environmental considerations are another crucial aspect of hydrogen modeling, particularly in assessing the sustainability of hydrogen pathways. Lifecycle emissions analysis is essential to evaluate the full environmental footprint of hydrogen production and use. While green hydrogen has negligible operational emissions, upstream emissions associated with equipment manufacturing, electricity generation, and water use can still be significant. In contrast, blue hydrogen depends heavily on the effectiveness of carbon capture and storage (CCS) technologies to limit emissions. Models must capture these lifecycle differences to inform decisions on which hydrogen pathways offer the greatest emissions reductions.

Moreover, models should explore renewable integration synergies. Hydrogen production can enhance renewable utilization by absorbing excess generation that would otherwise be curtailed. This creates a feedback loop wherein hydrogen enables greater renewable penetration, which in turn supplies more low-cost electricity for hydrogen production. Capturing this dynamic requires models to co-optimize electricity and hydrogen systems over multiple time scales, including sub-hourly operations and long-term planning horizons (Milligan *et al*., 2016; Ela *et al*., 2018; Barrows *et al*., 2018).

Finally, regulatory and policy drivers are indispensable in shaping hydrogen models. Many countries have published hydrogen strategies and national roadmaps that establish targets for hydrogen production capacity, market development, and infrastructure deployment. Incorporating these roadmaps ensures that models align with policy priorities and provide actionable guidance to decision-makers. Additionally, grid codes and hydrogen blending limits—which dictate the allowable proportion of hydrogen in natural gas networks—can significantly affect modeling assumptions (Panfilov, 2016; Guandalini*et al*., 2017). For example, some jurisdictions allow up to 20% hydrogen blending, while others impose stricter limits due to material compatibility and safety concerns. Models must incorporate these technical regulations to realistically assess hydrogen's near-term integration potential.

The development of hydrogen integration models requires a multidisciplinary approach that balances technical realism with economic feasibility, environmental integrity, and regulatory compliance. By incorporating grid flexibility, storage duration, and conversion efficiencies, models can effectively simulate hydrogen's technical role in energy systems. Simultaneously, economic factors such as production costs and market mechanisms, along with environmental considerations including lifecycle emissions and renewable synergies, are essential for robust analysis. Regulatory frameworks and national strategies further refine model assumptions, ensuring alignment with current and emerging policies (Werbeloff and Brown, 2016; Brown *et al*., 2017). Together, these factors enable the creation of integrated, accurate, and policy-relevant hydrogen models that can inform strategic energy planning and drive effective decarbonization strategies.

2.4 Applications

The integration of hydrogen into national and regional energy systems has moved beyond theoretical modeling into practical application through several high-profile case studies and pilot projects worldwide (Levidow and Upham, 2017; Oteman*et al*., 2017).

These real-world examples provide empirical data and strategic insights that inform and validate modeling efforts. They also reveal the opportunities and challenges associated with infrastructure development, sector coupling, and cross-border coordination. Among the most notable case studies are the European Hydrogen Backbone Initiative, Japan's Hydrogen Energy Supply Chain (HESC), and localized grid-hydrogen integration pilots in the United States and Australia. Each of these cases demonstrates distinct modeling approaches and implementation strategies tailored to different geographic, economic, and energy system contexts.

The European Hydrogen Backbone Initiative (EHB) represents one of the most ambitious efforts to establish a transnational hydrogen infrastructure. Launched by a consortium of European gas transmission system operators (TSOs), the initiative envisions a 53,000 km hydrogen pipeline network across 28 countries by 2040, largely built on repurposed natural gas pipelines. This vision is underpinned by sophisticated cross-border pipeline modeling, which accounts for demand centers, renewable energy availability, terrain constraints, pipeline capacity, and geostrategic considerations. The EHB relies on integrated energy system models that couple electricity and hydrogen networks to assess the optimal deployment of electrolyzers and pipelines, including considerations for hydrogen storage in salt caverns and balancing intermittent renewable energy generation. These models evaluate the impact of cross-border hydrogen flows on national energy balances, grid flexibility, and investment planning. Furthermore, they simulate hydrogen blending limits and separation technologies at pipeline interfaces. The EHB demonstrates how large-scale infrastructure modeling can inform both EU-wide policy and national hydrogen strategies, providing a blueprint for regional hydrogen markets.

In contrast to Europe's regional integration approach, Japan's Hydrogen Energy Supply Chain (HESC) is focused on establishing a robust, import-based hydrogen system to compensate for the country's limited domestic renewable resources. Japan aims to import liquefied hydrogen produced overseas—initially from brown coal gasification with carbon capture in Australia, with future plans for green hydrogen from renewable-rich regions such as the Middle East and Latin America. The HESC project involves highly detailed logistics and supply chain modeling, covering hydrogen production, liquefaction, maritime transport, regasification, and end-use in power generation and mobility. These models address technical parameters such as boil-off losses during transport, liquefaction efficiency, ship storage constraints, and docking infrastructure. Economic modeling of the HESC also integrates fuel cost scenarios, currency exchange risks, and carbon pricing impacts. Moreover, the project emphasizes the security of energy supply, incorporating stochastic simulations that account for geopolitical and environmental risks. The HESC case highlights the critical role of supply chain modeling in enabling hydrogen import strategies, especially for resource-constrained nations seeking energy diversification and decarbonization.

In the United States, several pilot projects have tested the feasibility of localized grid-hydrogen integration, with a focus on decarbonizing electricity and mobility sectors. Notable examples include the Los Angeles Department of Water and Power (LADWP)'s Intermountain Power Project in Utah, which plans to blend hydrogen with natural gas in a newly constructed gas turbine, eventually transitioning to 100% hydrogen. This project involves detailed capacity expansion modeling and power flow analysis to assess the grid impacts of hydrogen combustion, including emissions reduction, turbine efficiency, and system reliability. In California, hydrogen refueling infrastructure is being modeled and deployed in parallel with renewable-powered electrolysis, using urban energy models that optimize location selection based on traffic density, grid availability, and emission hotspots (Grimoldi, 2017; Ornetzeder*et al.*, 2018). These pilots are supported by multi-objective optimization frameworks that balance cost, emissions, and energy access objectives.

Australia, another key player in the global hydrogen landscape, has also launched a series of pilot projects focusing on green hydrogen production and export readiness. For example, the Hydrogen Energy Supply Chain project in Victoria (linked to Japan's HESC) and the Hydrogen Park South Australia are exploring local electrolysis powered by wind and solar energy.

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These projects utilize sector coupling models to integrate hydrogen into residential heating, electricity balancing, and industrial applications. In addition, Australia's National Hydrogen Strategy has prompted the development of spatially resolved models that map renewable resource availability, water access, and grid infrastructure to determine optimal hydrogen hub locations. These models incorporate climate variables, desalination needs, and transmission costs to ensure environmental sustainability and economic viability. Pilot data from these hubs inform larger-scale modeling efforts on hydrogen exports, domestic usage patterns, and grid load implications.

Together, these case studies offer a comprehensive view of the diverse modeling applications required for successful hydrogen integration. The European Hydrogen Backbone emphasizes long-distance pipeline modeling and regulatory coordination, Japan's HESC underscores supply chain resilience and import logistics, and pilot projects in the U.S. and Australia focus on localized integration, sector coupling, and renewable optimization. By grounding theoretical models in real-world data and operational constraints, these initiatives provide essential feedback loops that refine and enhance model accuracy and relevance. Importantly, they also highlight the need for collaborative policy frameworks, investment in infrastructure, and flexible regulatory environments to support hydrogen's role in clean energy transitions (Moore and Shabani, 2016; Markard and Hoffmann, 2016).

2.5 Challenges and Limitations

Despite its growing potential as a key enabler of decarbonization and energy system flexibility, the integration of hydrogen into national energy systems faces several challenges and limitations, particularly within the context of energy modeling and planning. These challenges stem from inherent model complexity and uncertainty, data availability constraints, interoperability issues with existing systems, and wider socioeconomic impacts as shown in figure 3. Addressing these limitations is essential to develop realistic and actionable hydrogen deployment strategies.

One of the foremost challenges is the complexity and uncertainty of modeling hydrogen technologies and markets, especially in long-term energy system forecasts (Bevrani*et al*., 2017; Verdolini*et al*., 2018). Hydrogen modeling involves multiple interrelated technologies, including production methods (electrolysis, reforming, and gasification), storage options (compressed gas, liquefaction, and chemical carriers), transportation modes (pipelines, shipping, and blending), and diverse end-use applications in power, transport, heating, and industry. These layers of complexity make it difficult to capture system-wide interactions accurately. Additionally, many hydrogen technologies are still evolving, with significant uncertainty surrounding future performance metrics, costs, and deployment rates. For example, electrolysis costs are projected to decrease with technological innovation and economies of scale, but the pace and extent of these reductions remain highly uncertain. Similarly, assumptions about carbon capture effectiveness for blue hydrogen or the efficiency of new storage methods introduce long-term variability into model outputs. Forecasting hydrogen demand also depends on external factors such as renewable energy costs, policy support, and global market dynamics, all of which are difficult to predict with high precision. Consequently, hydrogen models often require simplifying assumptions, which may limit their predictive accuracy and policy relevance.

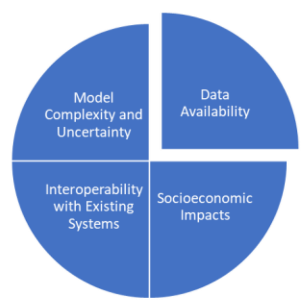

Figure 3: Challenges and Limitations

Another major limitation is the lack of high-quality, granular data on hydrogen infrastructure, costs, and operational performance. Many hydrogen projects are still in early demonstration or pilot phases, meaning that real-world operational data are scarce. Information on capital expenditures (CAPEX), operating expenditures (OPEX), and maintenance costs for electrolysis, storage, and distribution systems remains highly variable and often proprietary. Additionally, regional variations in resource availability, infrastructure conditions, and market characteristics make it difficult to generalize findings across different geographic contexts (Banwo*et al*., 2017; Nicotra *et al*., 2018). For example, models that rely on aggregated or outdated cost assumptions may fail to reflect actual deployment feasibility in specific countries or regions. Similarly, data on hydrogen blending limits, material degradation in pipelines, and long-term storage behavior in salt caverns or other geological formations are often incomplete. This data scarcity constrains model calibration and validation efforts, reducing confidence in model predictions and potentially leading to suboptimal investment or policy decisions.

Interoperability with existing systems poses another significant technical and operational barrier. Integrating hydrogen into national energy systems requires compatibility with current infrastructure, including natural gas grids, electricity transmission networks, and industrial facilities. However, many legacy systems were not designed to accommodate hydrogen, leading to technical integration challenges. For example, hydrogen's small molecular size and high reactivity can cause embrittlement and leakage in pipelines and storage tanks, requiring retrofitting or replacement of components. Furthermore, the introduction of hydrogen into existing gas grids is often limited by safety regulations and technical standards, typically capping blending ratios at relatively low levels (e.g., 10–20%). These limitations constrain the speed and scale of hydrogen deployment, complicating long-term system planning. Additionally, hydrogen's role in grid balancing introduces new operational complexities, such as coordinating electrolyzer operation with variable renewable energy inputs while maintaining power quality and system stability. Models must account for these technical constraints, but many existing tools lack the detailed representation of infrastructure interoperability needed to accurately simulate such interactions.

Beyond technical and operational issues, hydrogen integration also raises significant socioeconomic challenges that are often underrepresented in modeling exercises. One key issue is energy equity and access. Hydrogen infrastructure development may concentrate in regions with abundant renewable resources, existing industrial hubs, or favorable policy environments, potentially exacerbating disparities in energy access between regions or social groups. For example, rural or low-income communities may face higher energy costs or delayed access to hydrogen-based solutions if investment priorities focus on high-demand urban centers or export-oriented projects. Furthermore, public acceptance remains an uncertain variable, particularly regarding safety concerns related to hydrogen storage and transportation (Zaunbrecher *et al*., 2016; Bögel *et al*., 2018). Historical incidents involving gas leaks or explosions may heighten public resistance to hydrogen infrastructure projects, especially in densely populated areas. Models that fail to incorporate social acceptance dynamics may overestimate the speed of hydrogen deployment and understate potential barriers to adoption.

In addition, the wider economic impacts of large-scale hydrogen transitions—such as job creation, industrial competitiveness, and trade dynamics—are rarely incorporated into techno-economic models but can have significant policy implications. The risks of stranded assets, especially in legacy natural gas infrastructure or carbon-intensive industries, also warrant closer examination within hydrogen modeling frameworks.

While hydrogen holds considerable promise for advancing energy transitions, significant challenges and limitations must be addressed to fully realize its potential. Model complexity and technological uncertainty, data limitations, technical interoperability barriers, and socioeconomic concerns all constrain current modeling approaches and decision-making processes (Agostinho *et al*., 2016; Haroon *et al*., 2016; Ryan and Watson, 2017). Overcoming these limitations will require more transparent, interdisciplinary, and adaptive modeling practices, alongside improved data collection, stakeholder engagement, and regulatory frameworks that reflect both technical feasibility and social realities. Only through such holistic approaches can hydrogen's role in sustainable, equitable, and resilient energy systems be effectively harnessed.

2.6 Future Directions

As the global energy transition accelerates, the role of hydrogen as a secondary energy carrier continues to gain prominence (Rosen and Koohi-Fayegh, 2016; Filippov, 2018). To fully unlock hydrogen's potential for decarbonization and energy system flexibility, future research and development must focus on advancing modeling techniques, promoting cross-sectoral integration, enhancing policy-informed scenario analysis, and fostering global collaboration. These directions are crucial for designing robust and adaptive hydrogen deployment strategies that align with technological, economic, and social objectives.

One of the most promising future directions lies in the advancement of modeling techniques, particularly through the integration of artificial intelligence (AI) and machine learning. AI-driven forecasting tools can significantly enhance the predictive capabilities of hydrogen models by analyzing large, complex datasets that traditional methods struggle to process. These tools can optimize hydrogen production, storage, and distribution schedules based on dynamic variables such as renewable energy availability, market prices, and grid conditions. Machine learning algorithms can also improve the accuracy of techno-economic assessments by identifying nonlinear relationships between technology parameters and system performance. For instance, AI models can dynamically predict electrolyzer degradation, optimize hydrogen blending ratios, and forecast sectoral hydrogen demand under various policy scenarios. Additionally, optimization algorithms powered by AI can solve large-scale, multi-objective problems involving cost, emissions, and system reliability more efficiently than conventional optimization methods.

Another emerging technique is the use of digital twins for hydrogen systems. Digital twins are virtual replicas of physical assets or systems that enable real-time monitoring, simulation, and control. In the context of hydrogen, digital twins can simulate the entire value chain—from production and storage to transport and end-use—under varying operational conditions. These models can integrate real-time sensor data from hydrogen facilities to continuously calibrate and refine system models, enabling predictive maintenance, fault detection, and performance optimization. Digital twins can also facilitate scenario testing for emergency response, grid balancing, and market operations, providing valuable decision support for operators and regulators alike (Motlagh *et al*., 2016; Glachant*et al*., 2017). By bridging the gap between simulation and real-world operations, digital twins represent a transformative tool for risk management and system optimization in hydrogen infrastructure.

A key priority for future hydrogen modeling is deepening cross-sectoral integration, especially with the industrial and transport sectors. While existing models often focus on the electricity-hydrogen nexus, a more holistic approach is required to fully capture hydrogen's role in decarbonizing hard-to-abate sectors such as steel, cement, chemicals, shipping, and aviation. Advanced sector coupling models can simulate the interplay between hydrogen production and industrial heat demand, fuel switching in freight transport, and hydrogen-based synthetic fuels for aviation and maritime applications. These models must also incorporate the temporal and spatial variability of both supply and demand, enabling the design of integrated energy hubs where hydrogen acts as a bridging vector between multiple sectors. Improved cross-sectoral models will allow policymakers and investors to identify synergies, avoid redundancies, and optimize the allocation of renewable resources and infrastructure investments.

Policy-informed scenario analysis will be increasingly essential for guiding hydrogen development strategies. Many countries and regions have adopted ambitious carbon neutrality targets and are implementing green hydrogen mandates to accelerate the energy transition. Future models must integrate these policy objectives to evaluate how different regulatory frameworks, incentive mechanisms, and compliance pathways affect hydrogen deployment. Scenario analyses should incorporate the evolving landscape of carbon pricing, renewable portfolio standards, and fuel blending mandates, along with technological learning curves and supply chain constraints. This approach will enable the identification of least-cost decarbonization pathways and policy trade-offs, providing governments with actionable roadmaps for achieving net-zero goals while maintaining energy security and economic competitiveness.

Lastly, global collaboration is vital for accelerating hydrogen innovation and deployment, particularly through knowledge-sharing platforms and joint demonstration projects. Hydrogen development faces common challenges worldwide, including infrastructure costs, safety standards, and regulatory barriers (Hardman *et al*., 2017; Khan, 2017). International partnerships can facilitate the exchange of best practices, harmonization of technical standards, and co-development of infrastructure across borders. Initiatives such as the Clean Energy Ministerial's Hydrogen Initiative and the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) offer collaborative platforms for countries to align research agendas, share modeling tools, and jointly fund pilot projects. Large-scale demonstration projects involving multiple countries can validate new technologies, de-risk investment, and accelerate market formation. Examples include cross-border hydrogen corridors, joint electrolysis projects, and shared storage infrastructure, which collectively provide valuable data for improving models and informing future investments.

The future of hydrogen modeling and integration is poised for significant advancements driven by technological innovation, cross-sectoral synergies, policy alignment, and global cooperation. AI-powered forecasting, digital twins, and advanced optimization methods will enhance model accuracy and operational decision-making. Deeper sector coupling with industry and transport will broaden hydrogen's role in decarbonization strategies, while policy-informed scenario analysis will ensure that models reflect evolving regulatory landscapes and carbon neutrality goals. Global collaboration will facilitate knowledge sharing, standardization, and joint investments, creating a more coordinated and efficient hydrogen economy (Brandon and Kurban, 2017; Kupecki*et al*., 2018). Together, these future directions will enable the development of more resilient, adaptive, and sustainable hydrogen-based energy systems worldwide.

CONCLUSION

Hydrogen holds significant promise as a flexible, decarbonized energy carrier capable of transforming national energy systems. Its versatility across multiple sectors—including power generation, transportation, heating, and industry—enables it to serve as a critical bridge in the global transition toward low-carbon, resilient, and integrated energy infrastructures. Hydrogen's ability to store large amounts of energy over varying time scales, from hours to entire seasons, makes it uniquely suited for balancing renewable energy variability and enhancing grid flexibility. Furthermore, its potential to decarbonize hard-to-abate sectors positions hydrogen as a key pillar for achieving national and international climate goals.

However, realizing hydrogen's full potential requires robust and sophisticated modeling approaches. Detailed models are essential for guiding investment planning, ensuring that hydrogen infrastructure—such as electrolyzers, pipelines, and storage systems—is deployed efficiently and cost-effectively. Additionally, modeling tools are critical for policy design, enabling governments to evaluate the effectiveness of different incentives, regulatory frameworks, and carbon pricing mechanisms. Models also play a vital role in risk mitigation by identifying technological uncertainties, operational bottlenecks, and market vulnerabilities before large-scale investments are made.

Moving forward, there is an urgent need for coordinated research and policy action to address the remaining challenges and uncertainties surrounding hydrogen integration. Policymakers, researchers, and industry stakeholders must adopt integrated, cross-sectoral approaches that combine advanced modeling techniques with empirical data from real-world projects. Greater international collaboration, improved data transparency, and standardized modeling frameworks will be essential to fully unlock hydrogen's value in future energy systems. By fostering such multidisciplinary efforts, the global energy community can harness hydrogen's unique capabilities to build sustainable, inclusive, and secure energy systems for the coming decades.

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