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Hydrogen Industry 4.0: A Review on Digital Twin Approaches

[1] Delaram Ghofrani, [2] Narges Fallah

[1] Department of Chemical Engineering, Politecnico di Milano, Italy
[2] Department of Chemical Engineering, Amirkabir University of Technology, Iran
Corresponding Author Email: [1] Delaram.ghofrani@gmail.com, [2] Nfallah2001@aut.ac.ir

Abstract*— Hydrogen is a clean, versatile energy carrier and is considered one of the most favored ways of transitioning into a more sustainable energy future. However, it confronts major industry obstacles that hinder large-scale adoption, particularly in the areas of manufacturing, storage, and distribution. On the other hand, Industry 4.0 is expected to lead to advanced new tools and techniques that can solve most of these challenges, with the most promising solution being the digital twin. Digital twins are real-time virtual representation of actual physical systems and allow real-time monitoring, simulating, and optimizing processes relevant to hydrogen. This review will, therefore, present a compact analysis of digital twins' applicability within the hydrogen industry. Building on a brief review of the role of hydrogen in the energy transition and its associated challenges, and introducing the principles and technologies that underpin digital twins and their application to enhancing the efficiency, safety, and reliability of hydrogen systems, A detailed case study is presented where the implementation of digital twins was performed for a hydrogen production facility. The main aim of this review is to reveal the potential of digital twins in this sector, and bring up the main concerns and shortcomings for future research directions.

***Keywords*— "Hydrogen Industry 4.0", "Digital Twin Technology", "Energy Transition", "Sustainable Energy".**

I. INTRODUCTION

A key energy carrier in the transition to sustainable energy systems is hydrogen. Its adaptability enables it to store, carry, and distribute energy in a variety of industries, including manufacturing, transportation, and power generation [1]. When used, hydrogen emits just water as a byproduct, making it a more ecologically friendly alternative to fossil fuels. These characteristics make hydrogen an important component in attempts to reduce greenhouse gas emissions and prevent climate change [2]. The use of hydrogen into energy systems has several benefits. In industries where direct electrification is challenging, such as heavy industry and long-distance transportation, it makes it possible to decarbonize these sectors [3]. Furthermore, hydrogen is used to store excess renewable energy, improving grid stability and allowing for greater use of intermittent renewable sources such as wind and solar power [4]. Hydrogen's potential as a clean energy carrier has fuelled the expansion of a comprehensive hydrogen industry that comprises production, storage, distribution, and consumption. This business is critical to the worldwide energy transition, providing options for decarbonizing industries where direct electrification is difficult [5]. Advances in hydrogen generation technology, such as renewable-energy-powered electrolysis, have made large-scale hydrogen deployment more feasible [6]. Furthermore, developments in storage and distribution systems are addressing logistical challenges, making it easier to integrate hydrogen into existing energy infrastructure. The hydrogen industry's growth is aided by worldwide regulations and investments targeted at reaching net-zero emissions, emphasizing its importance in future energy systems [7]. Despite its promise, hydrogen's broad use as an energy carrier faces hurdles such as production prices, storage technologies, and infrastructural development [8]. Ongoing research and technical breakthroughs seek to solve these challenges, opening the path for hydrogen to play an important role in future energy systems [9]. These problems include efficiency restrictions in production and usage, safety concerns due to hydrogen's flammability, and scaling issues associated with infrastructure development [10]. Addressing these challenges is critical to incorporating hydrogen into the global energy grid. Industry 4.0 technologies, such as digital twins, the Internet of Things (IoT), and artificial intelligence (AI), address these issues by improving process optimization, predictive maintenance, and real-time monitoring [11]. Implementing these modern technologies may increase efficiency, assure safety, and simplify the scale deployment of hydrogen infrastructure, thereby speeding up the transition to a sustainable energy future [12]. Digital twin technology is crucial for addressing the challenges of efficiency, safety, and scalability in the hydrogen sector. A digital twin is a virtual version of a physical system, allowing real-time monitoring, simulation, and optimization [11]. In hydrogen production and distribution, digital twins enable the modelling of hydrogen production processes, resulting in the discovery and implementation of optimal operating conditions [13]. Production becomes more economical and sustainable as a result of the increased energy efficiency and decreased operating expenses. Digital twins also make it easier to identify possible equipment faults early through ongoing monitoring, allowing for proactive maintenance that reduces downtime and improves overall reliability [14] Additionally, by simulating various scenarios, digital twins help assess risks, enabling the development of strategies to mitigate potential hazards, thus contributing significantly to the safety of hydrogen handling and storage [14]. By combining data from several sources, digital twins offer a reliable way to manage complex systems as the hydrogen sector grows. Due to their ability to provide coordinated control across the whole hydrogen value chain, digital twins are a crucial tool in the search for scalable hydrogen solutions [15]. This article reviews the use of digital twin approaches in the hydrogen sector, highlighting how they might help solve current problems and promote the development of a sustainable energy future.

1.1. Hydrogen Production

The creation of hydrogen is the foundation of the hydrogen industry and is essential to its broad adoption in other industries. There are a number of ways to produce hydrogen, each with its own advantages and disadvantages, such as biomass gasification, electrolysis, and steam methane reforming (SMR) [17]. However, the complexity and scale of these processes introduce several key challenges that must be addressed to ensure efficiency, safety, and sustainability across the industry. Achieving the highest possible energy efficiency is one of the main obstacles in the manufacture of hydrogen. For example, electrolysis, which uses electricity to divide water into hydrogen and oxygen, is a very energy-intensive process. [18]. It is crucial to reduce energy use without sacrificing output, particularly when producing "green hydrogen" with renewable energy sources. Optimizing production parameters is essential for lowering energy consumption and overall expenses, but maintaining maximum efficiency frequently necessitates ongoing monitoring and modification [19]. Another challenge involves emissions management. Steam methane reforming (SMR), currently the most widely used hydrogen production method, releases a significant amount of carbon dioxide as a byproduct [20]. To align with global climate goals, SMR operations must implement effective carbon capture and reduction strategies [21]. To ensure that emissions remain below permissible limits, this calls for the capacity to measure emissions precisely and in real-time, as well as the flexibility to quickly adapt to new regulations when they are introduced. Because facilities that produce hydrogen rely on complex and often sensitive machinery, issues with production equipment maintenance and dependability might arise [22]. Mechanical failures not only lead to costly downtime but can also compromise safety due to the high pressure and reactivity of hydrogen. It is crucial to implement proactive maintenance procedures, which include ongoing equipment health monitoring to identify wear or potential breakdowns before they interfere with operations [23]. Since hydrogen is extremely flammable, safety is a key concern in the manufacture of hydrogen. Hydrogen is prone to leakage due to its small molecule size, which might result in dangerous conditions if not detected promptly. Since even little changes can have an influence on safety, thorough, real-time monitoring of operational and environmental factors is necessary to ensure the safe handling, storage, and processing of hydrogen [24]. Finally, a major obstacle to the broad use of hydrogen as an energy carrier is still scalability. To meet the increasing demand, the hydrogen industry needs to move from small-scale demonstration projects to big, commercially viable production facilities. In order to accomplish this shift, production output must be balanced with cost, efficiency, and safety all of which call for exact control and flexibility within production systems [25]. The energy efficiency, emissions control, equipment reliability, safety, and scalability issues that the hydrogen manufacturing industry faces are interrelated. To overcome these obstacles and develop a more robust and effective hydrogen production process, sophisticated monitoring, optimization, and predictive skills will be needed. The efficiency, safety, and scalability of hydrogen production processes can be greatly improved by implementing automated control systems, real-time data analytics, and predictive maintenance algorithms. Continuous monitoring of energy use and emissions is possible by real-time data analytics, which also allows for dynamic modifications to maximize efficiency and save operating expenses [12]. This method guarantees constant performance and adherence to environmental regulations by enabling quick reactions to changes in production parameters. By using predictive maintenance algorithms, unexpected downtime and related expenses are reduced since equipment faults are predicted before they happen [26]. By analysing data from many sensors and operational inputs, these algorithms are able to predict potential issues and enable timely maintenance interventions. Automated control systems increase safety by monitoring critical factors including temperature, pressure, and potential gas escapes. By promptly detecting anomalies and initiating corrective actions, these systems can lessen the risks associated with hydrogen's flammability and offer a safer production environment [27]. Advanced control systems and data-driven optimization make it easier to handle bigger and more complicated operations without sacrificing effectiveness or safety [12].

1.2. Hydrogen Storage

Since hydrogen is naturally low in density, storing large amounts of it is extremely difficult. The density of hydrogen at normal air conditions is around 0.09 kg/m³, significantly less than that of traditional fuels. Because of its low density, hydrogen requires a lot of volume to store, making it impossible to transport or store without specific techniques that raise its density [28]. The hydrogen storage techniques include liquefied hydrogen storage, compressed gas storage, chemical carriers such as ammonia, and storage by adsorbents such as metal hydrides. Every storage technique has different issues that need to be resolved to guarantee effectiveness, security, and scalability [29]. Compressed Gas

Storage involves storing hydrogen at high pressures, typically between 350 and 700 bar. This method faces challenges related to safety and energy consumption. Hydrogen's small molecular size increases the risk of leaks, which necessitates continuous monitoring to prevent potential hazards. Additionally, compressing hydrogen to such high pressures is energy-intensive, impacting overall efficiency and operational costs [30]. In liquefied hydrogen storage, where hydrogen is stored at cryogenic temperatures around -253°C, thermal management is a critical challenge. Minor increases in temperature can lead to boil-off, causing hydrogen loss and reducing overall storage efficiency. Maintaining stable temperatures requires sophisticated cooling systems that can adapt dynamically to changing conditions within storage tanks. Additionally, ensuring robust insulation is essential to prevent energy losses and maintain the hydrogen in its liquefied state [31]. By chemically binding hydrogen, chemical carriers like ammonia and liquid organic hydrogen carriers (LOHCs) provide substitute storage options. However, energy losses occur by the conversion processes used to store and release hydrogen, which requires careful control to preserve efficiency. It is needed to guarantee the purity of the hydrogen discharged by these carriers, particularly for fuel cell applications where contaminants may harm the system [32]. In solid-state storage using metal hydrides, challenges come from the material degradation that can occur over repeated absorption and release cycles. Monitoring the condition of storage materials is necessary to anticipate maintenance needs and replace components before they affect storage efficiency. Additionally, temperature control is essential since hydrogen release from metal hydrides is an exothermic process, which, if unmanaged, can lead to overheating and reduced storage capacity [33]. Scaling hydrogen storage systems to meet growing demand also involves managing operational complexities without sacrificing safety or efficiency [34]. An economic strategy to scaling is made possible by analysing storage data from the equipment's lifecycle, including material performance and energy consumption. This aids storage facilities in better resource management and well-informed infrastructure investments.

1.3. Hydrogen Transportation

Hydrogen transportation is an essential link in the hydrogen value chain, allowing for the movement of hydrogen from production facilities to various end-use sites. Hydrogen’s transportation requires specialized methods to ensure both efficiency and safety, because of its low density and unique properties [35]. Current transportation methods include pipelines, compressed gas trucks, liquefied hydrogen tankers, and chemical carriers, each facing unique challenges that need to be addressed for effective large-scale distribution[36]. Pipeline transportation, where pipelines are dedicated to transporting hydrogen over medium to long distances, is often the most efficient means of large-volume transport. However, this method comes with significant technical challenges [37]. Due to hydrogen’s small molecular size, it is highly prone to leakage, which poses a safety risk because of its flammability [37]. Continuous monitoring is required to detect leaks and maintain the pipeline’s integrity. Additionally, hydrogen can cause embrittlement in certain metals, increasing the risk of fractures or pipeline failures. Monitoring the structural health of pipelines and identifying early signs of embrittlement are critical for safe, long-term operation [38]. Transporting compressed hydrogen gas by truck provides more flexibility, especially in regions without established pipeline infrastructure. However, this method faces limitations related to payload and energy consumption. Compressing hydrogen gas is highly energy-intensive and requires advanced containment systems to maintain high-pressure levels without compromising safety [39]. During transit, high-pressure hydrogen tanks are exposed to vibrations and temperature changes, which can affect storage conditions. Monitoring these factors ensures safe transit and reduces the risk of leaks. Optimizing compression and transport efficiency is essential to mitigate these energy and logistical challenges [40]. For large-scale distribution, liquefied hydrogen tankers offer a higher energy density compared to compressed gas. However, transporting liquefied hydrogen is technically challenging because it must be maintained at cryogenic temperatures around -253°C to remain in liquid form. Keeping hydrogen at this temperature requires sophisticated insulation and cooling systems to prevent boil-off losses. Small temperature increases can lead to hydrogen vaporization, which decreases storage efficiency and poses additional safety risks [41]. Moreover, cryogenic temperatures can weaken storage tank materials over time, necessitating continuous monitoring of structural integrity to prevent potential failures during long-distance transport [42]. Chemical carriers such as ammonia and liquid organic hydrogen carriers (LOHCs) are alternative approaches to hydrogen transport. By chemically binding hydrogen, these carriers allow for safer storage and transport under less difficult conditions than direct hydrogen transport. However, releasing hydrogen from these carriers requires a chemical conversion process, which causes additional energy costs and potential efficiency losses [43]. Maintaining overall cost-effectiveness requires ensuring high conversion, and precise control over reaction conditions minimizes these losses. Furthermore, the hydrogen released from carriers must be of high purity, especially for applications like fuel cells. Ensuring purity through real-time quality monitoring is essential for immediate usability [43].

1.4. End-Use Applications

Hydrogen utilization, or the end-use applications of hydrogen, represents a critical sector in the hydrogen industry. This sector encompasses a wide range of applications, including industrial processes, power generation, transportation, and even residential and commercial heating [44]. Ensuring effective, secure, and scalable use in these many applications is crucial as hydrogen becomes more popular as a sustainable energy source. To optimize hydrogen's potential in the energy transition, however, some issues arising from its use must be resolved [45]. In industrial applications, hydrogen can be used as an important input in processes such as steel production and ammonia synthesis. In steelmaking, hydrogen acts as a reducing agent, resulting in a low-carbon alternative to traditional coke-based methods. However, achieving consistent hydrogen supply and quality is necessary, as process efficiency depends heavily on hydrogen purity and availability [46]. Hydrogen's quality instability can impact the final product and reduce operational efficiency. Continuous quality monitoring and predictive assessments of demand will prevent disruptions and maintain product consistency in industrial applications. For power generation, hydrogen can be used in fuel cells [47] or combustion turbines[48] to produce electricity. One of the primary challenges in power generation occurs in balancing hydrogen input with varying electricity demand. Fuel cells, for example, are sensitive to hydrogen purity and operational conditions, so any inconsistency in hydrogen supply or quality can reduce efficiency or cause damage to the cells [47]. Efficient load management and continuous monitoring of fuel quality ensure that hydrogen systems are responsive to variations in power demands without risking efficiency losses. Transportation is another important sector for hydrogen applications, particularly through fuel cell vehicles (FCVs) for both light-duty and heavy-duty applications. While hydrogen fuel cells offer promising zero-emission solutions, it is needed to work on safe, high-quality hydrogen refuelling infrastructure. FCVs require high-purity hydrogen, as impurities can damage fuel cells and reduce vehicle efficiency [49]. Further complexity is present because of the need for a robust and widely available refuelling network, as hydrogen stations must consistently manage fuel quality and monitor equipment to avoid failures. Additionally, as FCVs operate across varying locations and weather conditions, real-time monitoring of hydrogen usage and vehicle performance can enhance efficiency and safety [50]. For residential and commercial heating, hydrogen is an alternative to natural gas for reducing carbon emissions in heating applications. However, hydrogen's use in heating requires safe handling and control, especially when blended with natural gas. Hydrogen's low ignition energy (on a volume basis) and high diffusivity raise safety concerns. Therefore, leak detection and risk assessment are critical [51]. Monitoring hydrogen distribution systems for leaks, ensuring consistent blending, and adjusting for fluctuations in demand are all necessary to maintain safe and reliable heating. Across these end-use applications, the challenges of hydrogen utilization includes ensuring purity, supply consistency, efficient load management, safety, and real-time monitoring. Addressing these issues requires robust monitoring systems, predictive maintenance, and adaptive controls to ensure hydrogen's efficient and safe application across sectors. Table 1 summarizes the critical information mentioned in this section. This table highlights the critical need for advanced technological improvements within the hydrogen industry. Each sector, from production and storage to transportation and end-use applications, faces unique challenges that can significantly impact efficiency, safety, and scalability. In hydrogen production, for instance, achieving optimal energy efficiency and emissions control is essential to make processes like electrolysis and steam methane reforming sustainable and cost-effective. Similarly, in hydrogen storage, managing high-pressure environments, cryogenic conditions, and maintaining material integrity for chemical carriers and metal hydrides requires real-time monitoring and adaptive control to ensure safety and prevent losses.

Table I. The challenges within the hydrogen industry

Hydrogen Industry Sector	Method	Challenge
Production	Steam Methane Reforming (SMR)	Need for precise CO2 monitoring and adaptive strategies to align with emissions standards
	Electrolysis	Optimization of energy consumption to achieve efficient and sustainable operations
	Biomass Gasification	Balancing complexity and efficiency to maintain high production output at lower costs
Storage	Compressed Gas Storage	Continuous leak detection and pressure monitoring to ensure safe high-pressure storage
	Liquefied Hydrogen Storage	Thermal management to prevent boil-off and maintain stability under cryogenic conditions
	Chemical Carriers	Efficiency in hydrogen release and purity assurance to meet application standards

Hydrogen Industry Sector	Method	Challenge
	Metal Hydrides	Monitoring material condition to manage wear and ensure stable hydrogen release
Transportation	Pipeline Transportation	Early detection of structural degradation and leak prevention for safe pipeline transport
	Compressed Gas Trucks	Real-time adjustment to manage vibration impacts and temperature variations during transport
	Liquefied Hydrogen Tankers	Maintaining cryogenic conditions and structural health for safe, efficient long-haul transport
	Chemical Carriers	Consistent hydrogen quality assurance and efficiency in release processes
End-Use Applications	Industrial Processes	Ensuring supply consistency and quality control to maintain process efficiency
	Power Generation	Balancing energy demand with fuel quality requirements for reliable power output
	Transportation	High-precision monitoring for fuel quality and infrastructure reliability
	Residential and Commercial Heating	Real-time tracking and blending control for safe, consistent heating applications

Accordingly, transporting hydrogen, whether via pipelines or cryogenic tankers, faces risks of leaks, structural degradation, and operational inconsistencies, all of which demand sophisticated systems for early detection, condition monitoring, and rapid response. End-use applications, spanning from industrial processes to fuel cell vehicles and residential heating, require precise quality control, supply consistency, and safety protocols to maintain reliable performance and ensure user safety. Together, these challenges demonstrate the importance of integrating advanced technologies capable of supporting predictive maintenance, real-time monitoring, and optimization across the hydrogen value chain. To grow sustainably and satisfy the world's energy demands, the hydrogen sector must be able to predict failures, adjust to changing operating circumstances, and uphold strict quality requirements. As a result, the table provides a clear example of the urgent need for improved technological solutions, which are essential for the safe, effective, and strong growth of hydrogen as a basis for the shift to a low-carbon economy.

1.5. Digital Twin Technology and Its Role in Industry 4.0

Industry 4.0, known as the fourth industrial revolution, represents the integration of digital and physical systems, characterized by real-time data exchange and interconnected smart technologies [52]. Through advanced technologies like the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing, Industry 4.0 aims to transform traditional industries by enhancing automation, improving efficiency, and enabling data-driven decision-making. This digital transformation creates "smart" systems where physical assets, production lines, and entire supply chains can communicate, adapt, and optimize processes autonomously [53]. One of the most innovative and practical tools in Industry 4.0 is digital twin technology. A digital twin is a virtual counterpart of a physical object or system, continuously updating based on real-time data from the physical entity. This technology allows companies to replicate and monitor physical processes in a digital environment, where adjustments, analyses, and predictions can be conducted without interrupting actual operations [54]. Digital twins leverage data from IoT sensors, advanced analytics, and real-time simulations to provide a comprehensive view of the asset's condition, performance, and potential areas for optimization [55].

1.6. Digital Twin Structure

A digital twin is structured around three main components that work together to create a dynamic, real-time representation of a physical asset or process. These components include the physical entity, the digital model, and data connectivity between them. This structure enables continuous synchronization between the digital and physical worlds, providing insights that enable monitoring, optimization, and predictive capabilities. The Physical Entity: The physical entity is the real-world asset, process, or system that the digital twin is designed to replicate. These physical assets are equipped with a network of sensors and IoT devices that continuously collect data on operational parameters such as temperature, pressure, vibration, and energy usage. This data is essential for creating a precise virtual counterpart that mirrors the current state and behaviour of the physical asset, enabling accurate analysis and monitoring [56].

The Digital Model: The digital model is a virtual replica of the physical entity that simulates its structure, dynamics, and performance. This model is built using advanced simulation tools and modelling techniques, ranging from simple geometric representations to highly complex, physics-based simulations [57]. The digital model uses real-time data from the physical entity, enabling dynamic updates. This synchronization allows operators to interact with a current virtual representation of the asset, providing a framework for process optimization and predictive analysis[58]. Advanced digital twins may incorporate machine learning algorithms and predictive analytics, which can simulate various operational conditions, test hypothetical scenarios, and provide insights into potential outcomes. This functionality makes digital twins particularly valuable for complex processes that require precise control, such as sectors within hydrogen industry [59].

Data Connectivity and Integration: Data connectivity is the important link between the physical and digital components of a digital twin, facilitated through IoT devices, cloud infrastructure, and data integration platforms. The continuous data stream from the physical entity to the digital model enables real-time updates and accurate reflection of the asset's current conditions. Data integration provides a solid communication, enabling feedback loops in which insights from the digital model can inform operational decisions and adjustments in the physical system [60]. Data connectivity also supports extensive data analytics, combining historical and live data to reveal trends, patterns, and potential performance issues. In complex industrial settings, such as hydrogen industry facilities, robust data integration and connectivity will maintain efficiency and safety across interconnected sectors [61].

1.7. Advanced Functionalities in Digital Twin Structure

A well-structured digital twin often includes additional advanced functionalities, such as predictive analytics, scenario simulation, and performance optimization: Predictive Analytics: By analysing patterns and trends from operational data, digital twins can predict issues before they occur, such as equipment wear or process inefficiencies. This proactive approach to maintenance minimizes downtime and extends asset lifespan, which is essential in energy-intensive industries like hydrogen industry [62]. Scenario Simulation: Digital twins enable scenario testing by simulating various operational conditions and responses to potential disruptions. For instance, operators can test how a hydrogen production system might respond to extreme temperatures or pressure swings. This capability is invaluable for risk assessment and safety planning, allowing for rapid response planning without risking actual equipment [63]. Performance Optimization: By continuously adjusting operational parameters based on real-time data, digital twins help optimize system performance. In energy-intensive processes, such as hydrogen industry sectors, digital twins can dynamically adjust settings to reduce energy consumption, improve efficiency, and minimize costs [64].

1.8. Operational Mechanism of Digital Twins

As mentioned before, digital twin technology creates a synchronized virtual counterpart of a physical asset or process, enabling continuous interaction between the physical and digital realms. This dynamic system operates through several core steps:

1.8.1.Data Collection from Physical Assets

The process begins with the collection of real-time data from the physical asset via sensors and Internet of Things (IoT) devices, capturing parameters such as temperature, pressure, and operational metrics. This data provides a continuous flow of information that mirrors the asset's real-time state [65].

1.8.2.Data Transmission and Integration

Collected data is securely transmitted to digital platforms, often via cloud infrastructure, where it is processed and integrated into the digital twin model. This integration enables seamless updating of the digital twin, ensuring accurate, real-time representation [66].

1.8.3.Digital Model Creation

A digital twin is constructed using simulation tools, ranging from basic geometry to complex, physics-based simulations, depending on the application. This model will continuously be updated with live data, creating a dynamic virtual environment that reflects the physical asset's exact state and behaviour [67].

1.8.4.Real-Time Analysis and Visualization

Operators interact with the digital twin model through intuitive interfaces that provide visualizations and operational insights. This real-time analysis helps in decision-making, as users can view critical parameters and trends, enabling swift, data-driven adjustments [68].

1.8.5.Simulation and Scenario Testing

Digital twins enable the simulation of hypothetical scenarios to predict how an asset might respond under different conditions, such as extreme temperatures or increased demand. This feature is invaluable for risk assessment and optimization without interrupting real-world operations [54].

1.8.6.Predictive Maintenance and Optimization

Through data analysis, digital twins detect trends indicating potential failures or inefficiencies, which is helpful for proactive maintenance. Predictive algorithms analyse usage patterns and environmental factors to optimize maintenance schedules, minimizing unplanned downtime [66].

1.8.7. Feedback Loop and Real-Time Adjustments

A key feature of digital twins is their feedback loop, which allows insights from the digital model to influence real-time operations. Adjustments to operating parameters are fed back to the physical asset, enabling automated optimization and fine-tuning of performance [67]. In this structured approach, digital twins provide robust control and insight into complex systems, making them highly valuable for optimizing productivity, reducing risks, and advancing sustainable practices in industries like hydrogen.

II. APPLICATIONS OF DIGITAL TWINS IN THE HYDROGEN INDUSTRY

By considering the challenges outlined in Section 2 and the operational mechanisms of digital twins discussed in Section 3, this section examines how digital twins can transform hydrogen industry practices through targeted applications. The hydrogen sector, with its complex requirements in production, storage, distribution, and applications can benefit from the capabilities of digital twins, which facilitate real-time data integration, predictive maintenance, and system-wide optimization. By leveraging digital twins, hydrogen facilities can address operational inefficiencies and safety concerns while paving the way for scalable, sustainable growth.

2.1. The Need for Digital Twins in the Hydrogen Industry

The hydrogen industry's advancements towards scalability and safety, requires new and more responsive approaches to managing complex processes. Digital twin technology exhibits a unique opportunity to meet these needs by a real-time, data-driven method for optimizing each stage of the hydrogen value chain. As digital twins integrate with IoT and data analytics, they provide the ability to monitor, predict, and adjust operations dynamically something traditional methods struggle to achieve at scale.

2.1.1. Enhancing Efficiency and Operational Control

Digital twins enable hydrogen facilities to maintain precise control over production parameters, leading to higher operational efficiency. By creating a virtual replica of production systems, digital twins support real-time adjustments to optimize energy use and output. This fine-tuning reduces waste and lowers costs, while also helping to identify optimal operating conditions, which can improve overall productivity and resource utilization [69].

2.1.2. Proactive Risk Management and Safety Enhancement

The real-time monitoring capability of digital twins leads to early detection of operational anomalies, an essential feature in managing the safety risks associated with hydrogen handling. Through predictive analytics, digital twins can anticipate potential safety issues, such as pressure irregularities or equipment wear, before they escalate. This proactive risk management reduces the likelihood of accidents, which makes facilities to respond to emerging issues without disrupting operations [70].

2.1.3. Scalability and System Integration

As the hydrogen sector grows to meet rising energy demand, digital twins aid scalability by coordinating complex systems from production, storage, and transportation networks to end-use applications. Digital twins provide a comprehensive perspective of operations by combining data from several areas into a unified digital platform. This system-wide perspective enables coordinated control, assuring efficient energy use and optimized workflows across facilities of all sizes [71].

2.1.4. Enabling Sustainability and Long-Term Cost Efficiency

Digital twins contribute to sustainability by constantly analysing and improving resource utilization, hence lowering the environmental impact of hydrogen industry. By modelling various running situations, digital twins can discover the most sustainable practices, guaranteeing that energy consumption is low while operational efficiency is high. Furthermore, predictive maintenance powered by digital twins extends equipment lifespan and reduces waste, connecting the hydrogen industry's operations with environmental goals [70].

2.2. Case Studies: Applications of Digital Twins

Across the Hydrogen Industry Numerous investigations have been carried out to examine the use of digital twin technology in various sectors of the hydrogen industry. According to these studies, digital twins have the ability to solve the particular problems in each industry's sector, whether they are related to production process optimization, storage and transportation safety protocols, or end-use application performance and efficiency. A more sustainable and effective hydrogen economy is being introduced by digital twins, which are revolutionizing hydrogen operations by offering scalability, predictive maintenance, and real-time monitoring. The following case studies show how digital twins are being used practically in these important domains and demonstrate how they have revolutionized the hydrogen sector.

2.2.1. Hydrogen Production Facilities

One of the most promising areas for digital twin application is hydrogen production, particularly in optimizing electrolyser operations. In a study by Alsharif et al. [71], a Fleet Twin model was developed to manage a large-scale electrolyser fleet. By aggregating real-time data from multiple units, the Fleet Twin enables predictive maintenance and prognostic health management (PHM) to reduce downtime and optimize performance. Three architectural approaches Data Lake, Separated Twins, and

Federated Twins were evaluated to ensure scalability, reliability, and data ownership, with the Federated Twins model as a balanced solution for fleet-wide data integration and privacy. Gerard et al.[72] focused on using a digital twin-driven framework to design green hydrogen facilities under economic uncertainty. This study employs stochastic simulations to assess investment risks and optimize system design through different redundancy configurations. By balancing capital investment and system availability, this approach provides stakeholders with insights into the financial viability and operational stability of green hydrogen production, ensuring economic sustainability for large-scale production facilities. Together, these studies demonstrate the scalability and economic viability of digital twin applications in hydrogen production, offering a foundation for sustainable industry growth.

2.2.2. Hydrogen Storage

Hydrogen storage is under safety risks due to hydrogen's flammability and reactivity. The study by Jaribion et al. [14] explores the application of a digital twin for a high-pressure hydrogen storage vessel. Through real-time monitoring and predictive analytics, this digital twin detects deviations in pressure, temperature, and gas concentration, enabling early warning and preventive actions to mitigate potential hazards. Using action design research methodology, the study developed a prototype that incorporates sensors and wireless communication, allowing remote monitoring and control. Ferrari et al. [73] extended digital twin applications in hydrogen storage by creating a twin for a cold-adsorbed hydrogen tank using advanced materials like Activated Carbons (ACs) and Metal-Organic Frameworks (MOFs). This digital twin evaluates adsorption efficiency under different material configurations and operational conditions, optimizing hydrogen storage at lower pressures and temperatures. This model aids in selecting efficient materials, reducing storage energy costs, and enhancing overall storage safety. These studies show how digital twins enhance both safety and efficiency in hydrogen storage by providing real-time tracking, predictive maintenance, and operational insights necessary for high-risk applications.

2.2.3. End-Use Applications

In the context of hydrogen-powered fuel cell vehicles (FCVs), digital twins enable real-time performance monitoring and optimization of complex systems. Bartolucci et al. [74] developed a digital twin for a Fuel Cell Hybrid Electric Vehicle (FCHEV) that models the hydrogen powertrain and auxiliary systems. This digital twin simulates driving cycles under various environmental conditions, assessing the impact of factors like ambient temperature on energy consumption and driving range. Benchenina et al. [75] expanded on vehicle-focused digital twin technology by developing a twin for a Proton Exchange Membrane (PEM) fuel cell to enhance efficiency and facilitate predictive maintenance. Using MATLAB Simscape, the model simulates various load profiles and captures key performance metrics like current-voltage characteristics, reactant utilization, and thermal efficiency. This digital twin helps in identifying and addressing potential performance issues, optimizing the fuel cell system's energy efficiency, and reducing operational downtime. Donato et al. [76] developed a self-updating digital twin for a hydrogen-powered furnace, using data assimilation to adjust predictions based on real-time sensor data. This twin employs the Kalman filter to continuously update temperature and emission profiles, achieving highly accurate predictions even with variations in fuel composition and operating conditions. The research highlights the importance of self-updating digital twins in hydrogen combustion, which enable real-time modifications to preserve safety and peak performance. This feature is particularly important for systems that use hydrogen-methane mixtures, as the fuel composition greatly affects the combustion characteristics. Table 2 provides a summary of these case studies' main ideas.

Table 2. Comparison of Digital Twin Applications Across Hydrogen Industry Sectors

Study	Hydrogen Industry Sector	Objective	Key Features	Outcomes	Significance
Fleet Twin for Electrolysers (Alsharif et al., 2024)	Production	Optimize fleet management and scalability	Fleet-wide data aggregation, predictive maintenance, three architecture models for scalability	Enhanced scalability, reduced maintenance costs, improved operational insights	Provides a scalable model for large hydrogen production facilities, supporting industry growth and economic viability
Digital Twin-Driven Green Hydrogen Facility Design (Gerard et al., 2022)	Production	Optimize design under economic uncertainty	Stochastic simulation, redundancy configurations, investment risk assessment	Balanced system availability and capital investment, improved financial viability	Supports economically sustainable design choices for hydrogen production, essential for scaling up the industry

Study	Hydrogen Industry Sector	Objective	Key Features	Outcomes	Significance
Digital Twin for High-Pressure Vessel (Jaribion et al., 2020)	Storage	Improve safety and risk management	Real-time monitoring, predictive analytics, remote control via wireless sensors	Early warning for failures, enhanced storage safety	Demonstrates a scalable approach to safety management for hydrogen storage, crucial for high-risk applications
Digital Twin for Adsorbed Hydrogen Tank (Ferrari et al., 2024)	Storage	Optimize storage through material selection and operational adjustments	Cold adsorption modeling, real-time simulation of adsorption and material properties	Enhanced storage efficiency, cost-effective material selection	Advances low-pressure hydrogen storage by enabling optimized material use and energy-efficient storage solutions
Digital Twin of FCHEV (Bartolucci et al., 2022)	End-Use Applications	Optimize energy distribution and driving range	Real-time simulation of driving cycles, control strategy for power distribution between fuel cell and battery	Increased efficiency, optimized power use, improved driving range	Supports the advancement of hydrogen fuel cell vehicles by improving energy efficiency under variable conditions
Digital Twin of PEM Fuel Cell (Benchenina et al., 2024)	End-Use Applications	Enhance fuel cell efficiency and enable predictive maintenance	Current-voltage tracking, reactant utilization, Matlab Simscape simulation	Improved energy efficiency, predictive maintenance, optimized performance	Supports efficient, reliable hydrogen fuel cell operations, aiding in the development of sustainable transportation solutions
Self-Updating Digital Twin for Furnace (Donato et al., 2024)	End-Use Applications	Maintain accuracy under variable conditions	Data assimilation with Kalman filter, real-time temperature and emission updates based on sensor data	Accurate predictions, stable combustion, enhanced safety and efficiency	Shows the potential of self-updating twins for dynamic hydrogen applications, improving control and stability

III. CHALLENGES AND FUTURE DIRECTIONS

To reach its full potential, a number of issues need to be resolved as digital twin technology becomes more and more integrated into the hydrogen industry. By talking about these issues, we can investigate potential avenues for future research to improve the use and efficiency of digital twins in the hydrogen sector.

3.1. Challenges in Implementing Digital Twins in the Hydrogen Industry

3.1.1. Interoperability and Data Integration

It is quite difficult to achieve smooth interoperability across various devices and systems in hydrogen infrastructure. A cohesive digital twin ecosystem cannot be developed because of the complexity of data integration and exchange caused by the absence of established protocols. The Digital Twin Consortium highlights that in order to promote interoperability across different platforms, standardized frameworks are necessary [77].

3.1.2. Scalability for Large-Scale Hydrogen Infrastructure

Complex simulations and large datasets must be handled when scaling digital twins to operate huge hydrogen infrastructure. This scalability is frequently constrained by data management and processing power. Digital twin scaling in industrial settings presents difficulties, as discussed by Liu et al. [78], who emphasize the necessity of strong architectures to accommodate large-scale applications.

3.1.3. Cybersecurity and Data Privacy

Concerns regarding data privacy and cybersecurity are raised by the incorporation of digital twins into hydrogen infrastructure. It is crucial to defend sensitive operational data from online attacks in order to guarantee system dependability and integrity. The importance of putting advanced cybersecurity measures in place to protect digital twin applications in the energy sector is emphasized by Sheveleva and Solomos [11].

3.1.4. High Initial Costs and Resource Requirements

Implementing digital twins requires substantial initial investments in technology, infrastructure, and skilled personnel. These high costs can be a barrier, especially for small and medium-sized enterprises within the hydrogen industry. Choi et al. [79] highlight the economic challenges associated with deploying digital twins, suggesting the need for cost-effective solutions to promote wider adoption.

3.2. Future Directions for Research and Development

3.2.1. Enhanced AI-Driven Adaptive Digital Twins

Digital twins that incorporate machine learning and artificial intelligence (AI) can become adaptive systems that react to changing operational circumstances. These developments can optimize performance and enhance predictive maintenance. The potential of AI-enhanced digital twins in the energy industry is examined by Zhang et al. [80], who highlight how these tools might help create self-optimizing systems.

3.2.2. Lifecycle Assessment and Environmental Impact Modelling

The environmental impact of hydrogen technologies can be assessed and reduced with the use of digital twins that integrate lifecycle assessment (LCA) capabilities. These models can help guide sustainable practices across the hydrogen value chain by modelling different situations [81].

3.2.3. Standardization Efforts for Digital Twin Protocols

For digital twins in the hydrogen sector to be interoperable and scalable, common protocols and frameworks must be established. In order to streamline digital twin applications across several sectors, the National Institute of Standards and Technology (NIST) highlights the necessity of uniform standards [82].

3.2.4. Advanced Cybersecurity Frameworks and Blockchain for Data Integrity

Implementing robust cybersecurity frameworks, potentially incorporating blockchain technology, can enhance data integrity and protect digital twins from cyber threats. Liu et al. [78] discuss the application of blockchain in securing digital twin data exchanges, highlighting its potential to improve security in industrial applications.

IV. CONCLUSION

The hydrogen industry has seen a significant breakthrough with digital twin technology, which offers a flexible, data-driven answer to some of the most important problems facing the sector. Hydrogen has become a promising clean energy carrier as the world moves toward sustainable energy systems, but issues with production, storage, distribution, and end-use applications pose logistical, safety, and technical challenges to its broad adoption. These issues can be resolved by digital twins, which are virtual representations of physical systems that allow for simulation, real-time monitoring, and predictive analytics. Through their integration, digital twins offer a strong framework for improving safety, minimizing environmental impact, and maximizing operational efficiency in every aspect of the hydrogen sector. Digital twins in manufacturing provide a technique to maximize energy efficiency and minimize emissions, especially with improved electrolysis and steam. By enabling real-time condition monitoring and early defect detection, digital twins improve safety in storage and transportation by reducing the dangers associated with cryogenic and high-pressure storage techniques as well as complicated transportation needs. Furthermore, digital twins ensure continuous and effective hydrogen consumption in end-use applications by offering precise quality control and predictive maintenance, particularly in fuel cell technologies, industrial processes, and domestic heating. Regardless of the benefits, there are obstacles to overcome before digital twins are widely adopted in the hydrogen sector. Data interoperability, the requirement for scalable systems to accommodate large-scale applications, cybersecurity issues, and the high upfront deployment costs are some of the main challenges. For hydrogen infrastructure to support interoperability and smooth data integration across many systems, standardized protocols and frameworks must be developed. Advances in AI-driven adaptive digital twins should be the main focus of future research since they have the potential to react to operating situations on their own and improve predictive maintenance skills. Furthermore, life-cycle assessment and environmental effect modelling in digital twin frameworks can promote more environmentally friendly procedures, bringing hydrogen technology into line with international decarbonization objectives. As digital twin technology develops further, its application to the hydrogen sector could revolutionize the production, storage, transportation, and use of hydrogen, creating an industry that can satisfy environmental and financial requirements. Digital twins have the potential to revolutionize the hydrogen industry and propel it toward a sustainable, scalable, and resilient energy future by overcoming present constraints through innovation in AI, cybersecurity, and standards. This shift places digital twins at the forefront of the worldwide movement for sustainable energy transitions and represents a significant step toward achieving Hydrogen Industry 4.0 and its promise of a cleaner, more efficient energy landscape.

REFERENCES

[1] Züttel, A., A. Remhof, A. Borgschulte, and O. Friedrichs, *Hydrogen: the future energy carrier*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2010. **368**(1923): p. 3329-3342.

[2] Rosen, M.A. and S. Koohi-Fayegh, *The prospects for hydrogen as an energy carrier: an overview of hydrogen energy and hydrogen energy systems*. Energy, Ecology and Environment, 2016. **1**: p. 10-29.

[3] Griffiths, S., et al., *Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options*. Energy Research & Social Science, 2021. **80**: p. 102208.

[4] Hassan, Q., et al., *Hydrogen as an energy carrier: properties, storage methods, challenges, and future implications*. Environment Systems and Decisions, 2024. **44**(2): p. 327-350.

[5] Qureshi, F., et al., *Contemporary avenues of the Hydrogen industry: Opportunities and challenges in the eco-friendly approach*. Environmental Research, 2023. **229**: p. 115963.

[6] Alamiery, A., *Advancements in materials for hydrogen production: A review of cutting-edge technologies*. ChemPhysMater, 2024. **3**(1): p. 64-73.

[7] Sher, F., *Advanced approaches towards policy making for net zero emissions*. Current Opinion in Green and Sustainable Chemistry, 2024: p. 100951.

[8] Salehi, K., M. Rahmani, and S. Atashrouz, *Machine learning assisted predictions for hydrogen storage in metal-organic frameworks*. International Journal of Hydrogen Energy, 2023. **48**(85): p. 33260-33275.

[9] Armaroli, N., E. Bandini, and A. Barbieri, *Hydrogen as an energy carrier: constraints and opportunities*. Pure and Applied Chemistry, 2024. **96**(4): p. 479-485.

[10] Ahad, M.T., et al., *An overview of challenges for the future of hydrogen*. Materials, 2023. **16**(20): p. 6680.

[11] Sheveleva, A.V. and V.I. Solomos, *Digital Technologies in the Development of Hydrogen Energy*, in *Smart Green Innovations in Industry 4.0: New Opportunities for Climate Change Risk Management in the "Decade of Action"*. 2023, Springer. p. 257-264.

[12] Yavari, A., C.J. Harrison, S.A. Gorji, and M. Shafiei, *Hydrogen 4.0: A Cyber–Physical System for Renewable Hydrogen Energy Plants*. Sensors, 2024. **24**(10): p. 3239.

[13] Feng, Z., et al., *Review of digital twin technology applications in hydrogen energy*. Chain, 2024. **1**(1): p. 54-74.

[14] Jaribion, A., et al. *A digital twin for safety and risk management: A prototype for a hydrogen high-pressure vessel*. in *International Conference on Design Science Research in Information Systems and Technology*. 2020. Springer.

[15] Krug, T., O. Veledar, and G. Macher. *Leveraging Digital Twins for Smart Hydropower: A Pathway to Industry 4.0*. in *European Conference on Software Process Improvement*. 2024. Springer.

[16] Osman, A.I., et al., *Hydrogen production, storage, utilisation and environmental impacts: a review*. Environmental Chemistry Letters, 2022: p. 1-36.

[17] Chelvam, K., M.M. Hanafiah, K.S. Woon, and K. Al Ali, *A review on the environmental performance of various hydrogen production technologies: An approach towards hydrogen economy*. Energy Reports, 2024. **11**: p. 369-383.

[18] Pashchenko, D., *Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization?* Renewable Energy, 2024: p. 120033.

[19] Adeli, K., et al., *A deep learning-enhanced framework for sustainable hydrogen production from solar and wind energy in the Moroccan Sahara: Coastal regions focus*. Energy Conversion and Management, 2024. **302**: p. 118084.

[20] Bhat, S.A. and J. Sadhukhan, *Process intensification aspects for steam methane reforming: an overview*. AIChE Journal, 2009. **55**(2): p. 408-422.

[21] Maleki, F., M.B. Ledari, and M. Fani, *Sustainable hydrogen supply chain development for low-carbon transportation in a fossil-based port region: A case study in a tourism hub*. International Journal of Hydrogen Energy, 2024. **65**: p. 95-111.

[22] Gusev, A.L., et al., *Some aspects of reliability prediction of chemical industry and hydrogen energy facilities (vessels, machinery and equipment) operated in emergency situations and extreme conditions*. International Journal of Hydrogen Energy, 2024. **86**: p. 482-510.

[23] Groth, K.M. and A. Al-Douri, *Hydrogen safety, risk, and reliability analysis*, in *Hydrogen Economy*. 2023, Elsevier. p. 487-510.

[24] Chau, K., A. Djire, and F. Khan, *Review and analysis of the hydrogen production technologies from a safety perspective*. International Journal of Hydrogen Energy, 2022. **47**(29): p. 13990-14007.

[25] Zheng, Y., M. Ma, and H. Shao, *Recent advances in efficient and scalable solar hydrogen production through water splitting*. Carbon Neutrality, 2023. **2**(1): p. 23.

[26] Calabrese, M., et al., *Hydrogen safety challenges: a comprehensive review on production, storage, transport, utilization, and CFD-based consequence and risk assessment*. Energies, 2024. **17**(6): p. 1350.

[27] Moroz, V.V., S.S. Gavriushin, M.V. Murashov, and L.V. Baulina. *Industrial Automation for Regulating the Technological Process of High-Pressure Hydrogen Generation*. in *2024 IEEE 25th International Conference of Young Professionals in Electron Devices and Materials (EDM)*. 2024. IEEE.

[28] Felderhoff, M., C. Weidenthaler, R. von Helmolt, and U. Eberle, *Hydrogen storage: the remaining scientific and technological challenges*. Physical Chemistry Chemical Physics, 2007. **9**(21): p. 2643-2653.

[29] Langmi, H.W., N. Engelbrecht, P.M. Modisha, and D. Bessarabov, *Hydrogen storage*, in *Electrochemical power sources: Fundamentals, systems, and applications*. 2022, Elsevier. p. 455-486.

[30] Alves, M.P., W. Gul, C.A. Cimini Junior, and S.K. Ha, *A review on industrial perspectives and challenges on material, manufacturing, design and development of compressed hydrogen storage tanks for the transportation sector*. Energies, 2022. **15**(14): p. 5152.

[31] Naquash, A., N. Agarwal, and M. Lee, *A Review on Liquid Hydrogen Storage: Current Status, Challenges and Future Directions*. Sustainability, 2024. **16**(18): p. 8270.

[32] Pawelczyk, E., et al., *Recent progress on hydrogen storage and production using chemical hydrogen carriers*. Energies, 2022. **15**(14): p. 4964.

[33] Nivedhitha, K., et al., *Advances in hydrogen storage with metal hydrides: mechanisms, materials, and challenges*. International Journal of Hydrogen Energy, 2024. **61**: p. 1259-1273.

[34] Raza, A., et al., *A holistic overview of underground hydrogen storage: Influencing factors, current understanding, and outlook*. Fuel, 2022. **330**: p. 125636.

[35] Faye, O., J. Szpunar, and U. Eduok, *A critical review on the current technologies for the generation, storage, and transportation of hydrogen*. International Journal of Hydrogen Energy, 2022. **47**(29): p. 13771-13802.

[36] Li, H., et al., *Safety of hydrogen storage and transportation:*

An overview on mechanisms, techniques, and challenges. Energy Reports, 2022. **8**: p. 6258-6269.

[37] Witkowski, A., A. Rusin, M. Majkut, and K. Stolecka, *Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects*. Energy, 2017. **141**: p. 2508-2518.

[38] Cai, L., et al., *Experimental investigation on the hydrogen embrittlement characteristics and mechanism of natural gas-hydrogen transportation pipeline steels*. Materials Research Express, 2022. **9**(4): p. 046512.

[39] Lahnaoui, A., C. Wulf, H. Heinrichs, and D. Dalmazzone, *Optimizing hydrogen transportation system for mobility by minimizing the cost of transportation via compressed gas truck in North Rhine-Westphalia*. Applied energy, 2018. **223**: p. 317-328.

[40] Lahnaoui, A., C. Wulf, H. Heinrichs, and D. Dalmazzone, *Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks*. International journal of hydrogen energy, 2019. **44**(35): p. 19302-19312.

[41] Ahn, J., H. You, J. Ryu, and D. Chang, *Strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker*. International journal of hydrogen energy, 2017. **42**(8): p. 5366-5380.

[42] Lowesmith, B., G. Hankinson, and S. Chynoweth, *Safety issues of the liquefaction, storage and transportation of liquid hydrogen: An analysis of incidents and HAZIDS*. International journal of hydrogen energy, 2014. **39**(35): p. 20516-20521.

[43] Otto, M., et al., *Optimal hydrogen carrier: Holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation*. Journal of Energy Storage, 2022. **55**: p. 105714.

[44] Kamran, M. and M. Turzyński, *Exploring hydrogen energy systems: A comprehensive review of technologies, applications, prevailing trends, and associated challenges*. Journal of Energy Storage, 2024. **96**: p. 112601.

[45] Sareen, K., A.K. Rajput, and S. Suman, *End-use applications of green hydrogen: A case study*. Water and Energy International, 2023. **66**(8): p. 31-35.

[46] Rosner, F., et al., *Green steel: design and cost analysis of hydrogen-based direct iron reduction*. Energy & Environmental Science, 2023. **16**(10): p. 4121-4134.

[47] Felseghi, R.-A., et al., *Hydrogen fuel cell technology for the sustainable future of stationary applications*. Energies, 2019. **12**(23): p. 4593.

[48] Boretti, A., *Towards hydrogen gas turbine engines aviation: A review of production, infrastructure, storage, aircraft design and combustion technologies*. International Journal of Hydrogen Energy, 2024. **88**: p. 279-288.

[49] Halder, P., et al., *Performance, emissions and economic analyses of hydrogen fuel cell vehicles*. Renewable and Sustainable Energy Reviews, 2024. **199**: p. 114543.

[50] Li, B., J. Li, Z. Li, and M.A. Sotelo, *Real-Time Hydrogen Refuelling of the Fuel Cell Electric Vehicle Through the Coupled Transportation Network and Power System*. IEEE Transactions on Intelligent Transportation Systems, 2024.

[51] Wang, L., et al., *Cooperative operation of industrial/commercial/residential integrated energy system with hydrogen energy based on Nash bargaining theory*. Energy, 2024. **288**: p. 129868.

[52] Kumar, K., D. Zindani, and J.P. Davim, *Industry 4.0: developments towards the fourth industrial revolution*. 2019: Springer.

[53] Romero, M., W. Guédria, H. Panetto, and B. Barafort, *Towards a characterisation of smart systems: A systematic literature review*. Computers in industry, 2020. **120**: p. 103224.

[54] Tao, F., et al., *Digital twin modeling*. Journal of Manufacturing Systems, 2022. **64**: p. 372-389.

[55] Barricelli, B.R., E. Casiraghi, and D. Fogli, *A survey on digital twin: Definitions, characteristics, applications, and design implications*. IEEE access, 2019. **7**: p. 167653-167671.

[56] Fuller, A., Z. Fan, C. Day, and C. Barlow, *Digital twin: Enabling technologies, challenges and open research*. IEEE access, 2020. **8**: p. 108952-108971.

[57] Boschert, S. and R. Rosen, *Digital twin—the simulation aspect*. Mechatronic futures: Challenges and solutions for mechatronic systems and their designers, 2016: p. 59-74.

[58] Zipper, H. and C. Diedrich. *Synchronization of industrial plant and digital twin*. in *2019 24th IEEE international conference on emerging technologies and factory automation (ETFA)*. 2019. IEEE.

[59] Tao, F., H. Zhang, A. Liu, and A.Y. Nee, *Digital twin in industry: State-of-the-art*. IEEE Transactions on industrial informatics, 2018. **15**(4): p. 2405-2415.

[60] Kang, T.W. and Y. Mo, *A comprehensive digital twin framework for building environment monitoring with emphasis on real-time data connectivity and predictability*. Developments in the Built Environment, 2024. **17**: p. 100309.

[61] Liu, Q., et al., *Digital twin-based designing of the configuration, motion, control, and optimization model of a flow-type smart manufacturing system*. Journal of Manufacturing Systems, 2021. **58**: p. 52-64.

[62] Unal, P., Ö. Albayrak, M. Jomâa, and A.J. Berre, *Data-driven artificial intelligence and predictive analytics for the maintenance of industrial machinery with hybrid and cognitive digital twins*, in *Technologies and Applications for Big Data Value*. 2022, Springer. p. 299-319.

[63] Jia, W., W. Wang, and Z. Zhang, *From simple digital twin to complex digital twin Part I: A novel modeling method for multi-scale and multi-scenario digital twin*. Advanced Engineering Informatics, 2022. **53**: p. 101706.

[64] Grieves, M. and J. Vickers, *Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems*. Transdisciplinary perspectives on complex systems: New findings and approaches, 2017: p. 85-113.

[65] Tao, F., et al., *Digital twin-driven product design, manufacturing and service with big data*. The International Journal of Advanced Manufacturing Technology, 2018. **94**: p. 3563-3576.

[66] Qi, Q. and F. Tao, *Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison*. Ieee Access, 2018. **6**: p. 3585-3593.

[67] Dietz, M. and G. Pernul, *Digital twin: Empowering enterprises towards a system-of-systems approach*. Business & Information Systems Engineering, 2020. **62**: p. 179-184.

[68] Uhlemann, T.H.-J., C. Lehmann, and R. Steinhilper, *The digital twin: Realizing the cyber-physical production system for industry 4.0*. Procedia Cirp, 2017. **61**: p. 335-340.

[69] Colmenares-Quintero, R.F., et al. *Methodology for creating digital twins for green hydrogen production based on simulation and gamification*. in *2023 World Engineering Education Forum-Global Engineering Deans Council*

(WEEF-GEDC). 2023. IEEE.

[70] Hashmi, R., H. Liu, and A. Yavari, *Digital Twins for Enhancing Efficiency and Assuring Safety in Renewable Energy Systems: A Systematic Literature Review*. Energies, 2024. **17**(11): p. 2456.

[71] Alsharif, S., et al., *Digital Twin concept and architecture for fleets of hydrogen electrolysers*. Frontiers in Energy Efficiency, 2024. **2**: p. 1437214.

[72] Gerard, B., E. Carrera, O. Bernard, and D. Lun. *Smart design of green hydrogen facilities: A digital twin-driven approach*. in *E3S web of conferences*. 2022. EDP Sciences.

[73] Ferrari, L., D. Melideo, E. Morelli, and P.T. Pardelli, *Digital Twins of a cold-adsorbed Hydrogen tank by Activated Carbons and Metal Organic Frameworks*. Entropy. **3080**: p. 2541.5.

[74] Bartolucci, L., et al. *Digital Twin of Fuel Cell Hybrid Electric Vehicle: a detailed modelling approach of the hydrogen powertrain and the auxiliary systems*. in *E3S Web of Conferences*. 2022. EDP Sciences.

[75] Benchenina, Y., A. Zemmit, and M.M. Bouzaki, *Enhancing fuel cell efficiency through advanced digital twin modeling*. Studies in Engineering and Exact Sciences, 2024. **5**(1): p. 2102-2114.

[76] Donato, L., C. Galletti, and A. Parente, *Self-updating digital twin of a hydrogen-powered furnace using data assimilation*. Applied Thermal Engineering, 2024. **236**: p. 121431.

[77] Budiardjo, A. and D. Migliori, *Digital twin system interoperability framework*. 2021, Tech. rep. Digital Twin Consortium, East Lansing, Michigan.

[78] Liu, S., P. Zheng, and J. Bao, *Digital Twin-based manufacturing system: A survey based on a novel reference model*. Journal of Intelligent Manufacturing, 2024. **35**(6): p. 2517-2546.

[79] Choi, W., et al., *Digital twin in the power generation industry*. JMST Advances, 2024. **6**(1): p. 103-119.

[80] Zhang, M., et al., *Self-adaptive digital twin of fuel cell for remaining useful lifetime prediction*. International Journal of Hydrogen Energy, 2024. **89**: p. 634-647.

[81] Hojas, L.H., E. García-Del-Toro, and I.M. López. *DIGITAL TWIN AS A TOOL FOR SOCIAL PARTICIPATION IN ENVIRONMENTAL IMPACT ASSESSMENT*. in *INTED2024 Proceedings*. 2024. IATED.

[82] Heluany, J.B. and V. Gkioulos, *A review on digital twins for power generation and distribution*. International Journal of Information Security, 2024. **23**(2): p. 1171-1195.