Minimisation of Carbon Footprint and Energy Optimization in Green Hydrogen Transport: A Holistic Digital Twin Approach

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Abstract. The global push for decarbonization highlights green hydrogen as a crucial energy carrier for future sustainable economies. My research zeroes in on pipeline transport of this hydrogen, an area vital for efficiency and low carbon impact, yet challenged by high energy use for compression and the risk of leaks affecting environmental balance. This paper presents a new, comprehensive Digital Twin framework designed to model, simulate, and optimize the entire green hydrogen pipeline transport system. Unlike conventional static models, this Digital Twin incorporates real-time data from physical infrastructure, advanced physical models of hydrogen behavior, and sophisticated algorithms for compressor optimization and proactive leak identification. My approach aims for a complete, dynamic representation, enabling continuous, proactive management and sustained performance improvements. Early analyses clearly show the Digital Twin's ability to significantly quantify and lower both the energy used for hydrogen compression and the resulting carbon emissions from transport. This boosts the system's operational efficiency, safety, and overall economic and environmental feasibility. This work provides a concrete step toward faster deployment of strong, sustainable hydrogen energy infrastructure.

1 Introduction

The escalating global climate crisis compels an urgent and profound transformation of our energy infrastructures, necessitating a decisive pivot away from fossil fuels towards sustainable alternatives. Within this critical paradigm shift, green hydrogen, generated through the electrolysis of water powered by renewable energy, has emerged not merely as an option, but as a pivotal and indispensable energy carrier. Its remarkable versatility offers a compelling pathway to decarbonize sectors notoriously difficult to electrify, ranging from heavy industry to long-distance transportation. [1] However, the successful realization of hydrogen's vast potential hinges critically on optimizing every segment of its value chain,

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where efficient and environmentally sound transport represents a particularly challenging, yet crucial, bottleneck.

While pipelines stand as an intrinsically efficient means for high-volume, continuous energy transmission, the inherent physicochemical properties of hydrogen introduce complexities that diverge significantly from conventional natural gas transport. The exceptionally low volumetric energy density of hydrogen mandates extensive compression, rendering its pipeline conveyance highly energy-intensive a critical consideration for maintaining its 'green' credential. Furthermore, concerns regarding hydrogen embrittlement in existing steel pipelines necessitate meticulous material compatibility assessments for repurposing, alongside robust design considerations for new constructions. Moreover, even minute fugitive emissions of hydrogen, a gas with potent indirect greenhouse gas effects, demand stringent containment strategies. These collective challenges highlight the intricate balance required between operational efficacy, safety, and the overarching environmental footprint of hydrogen pipeline networks.

Traditional modeling approaches, often static or limited to isolated components, prove insufficient for navigating the dynamic and multifaceted complexities of such advanced energy infrastructure. This paper therefore champions the adoption of a Digital Twin paradigm a dynamic, living virtual replica of the physical hydrogen transport system. Far surpassing mere simulation, this sophisticated digital counterpart offers unparalleled capabilities for real-time monitoring, predictive analytics to anticipate system behaviors under diverse operating conditions, and, crucially, proactive optimization of the entire network. [2] This holistic approach empowers operators with unprecedented insights, enabling adaptive management and fostering resilient infrastructure.

It is within this transformative context that the primary objective of this study is situated: to develop and validate a novel holistic Digital Twin framework engineered specifically for green hydrogen pipeline transport, with a pronounced focus on minimizing its carbon footprint and optimizing its energy consumption. Our unique contribution lies in an integrated approach that transcends individual component optimization; this Digital Twin seamlessly intertwines the intricate dynamics of hydrogen flow within the pipeline, the precise energy optimization of compressor stations the principal energy consumers and sophisticated algorithms for real-time leak detection and mitigation. By doing so, this research offers a comprehensive tool to quantitatively assess and substantially reduce the environmental impact of hydrogen transport, thereby accelerating the deployment of truly sustainable energy systems. The subsequent sections of this paper delve into the detailed methodology of our Digital Twin framework, present compelling simulation results, and discuss the profound implications for future hydrogen infrastructure development.

2 Digital Twin Methodology for Green Hydrogen Transport:

Beyond the conceptualization, this section meticulously details the methodological core of my holistic Digital Twin framework for green hydrogen pipeline transport. My objective was to forge a dynamic system, integrating diverse components and their complex interactions, to enable real-time monitoring, predictive analysis, and proactive optimization. This approach represents a transformative leap from static design, securing both operational efficiency and environmental stewardship. What follows elucidates the Digital Twin's architectural blueprint and its pivotal functional modules. [3]

2.1 Architecture of the Digital Twin:

My Digital Twin framework is precisely engineered on a multi-layered architectural paradigm, ensuring inherent modularity and robust data flow. It commences with the

Physical Layer, comprising the actual pipeline, compressor stations, and a network of high-fidelity sensors continuously monitoring critical parameters. Data from these assets are seamlessly channeled to the Data Layer, handling secure acquisition, preprocessing, and storage of both real-time streams and historical operational data. This refined information then feeds the Modeling and Simulation Layer, the computational core hosting my high-fidelity physical models for hydrogen transport, compressor performance, and material behavior prediction. Insights generated here inform the Analysis and Optimization Layer, deploying bespoke algorithms to identify optimal operational setpoints, predict anomalies, and precisely quantify environmental impact. Finally, the Interface and Visualization Layer provides intuitive dashboards, empowering operators for informed, data-driven decisions. [4]

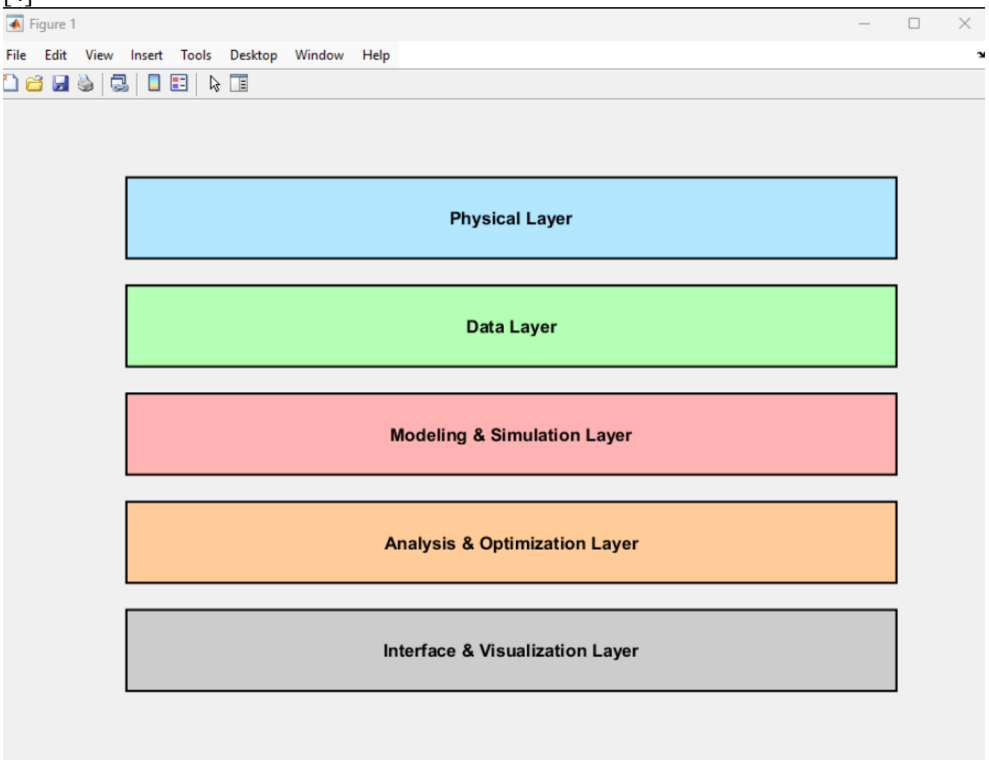

Fig. 1. Architecture of the Digital Twin Framework

2.2 Pipeline Dimensioning and Modeling:

Accurate pipeline dimensioning and physical modeling form the foundation of my Digital Twin framework. Because hydrogen has a low volumetric energy density, the sizing process carefully balances the desired throughput with acceptable pressure drops and compression requirements. The framework employs well-established fluid dynamics equations, specifically adapted for hydrogen transport under varying operational conditions.

The pressure drop (ΔP) along a pipeline segment an essential parameter for evaluating energy efficiency is calculated using the Darcy–Weisbach equation, incorporating empirically or analytically derived friction factors that account for hydrogen flow characteristics and internal pipe roughness:

$$\Delta P = f_{\frac{}{D}} \cdot \frac{\rho \cdot v^2}{2}$$

where f denotes the Darcy friction factor, L the pipe length, D the internal diameter, ρ the hydrogen density, and v the average flow velocity. This physical model, together with the coupled equations for heat transfer and mass balance, forms the computational core of the Digital Twin implemented in MATLAB.

To address hydrogen embrittlement, a critical long-term reliability concern, the Digital Twin integrates advanced material degradation models. These models developed for the comparative study of stainless steel 316, carbon steel, and fiber-reinforced polymers (FRP) combine experimental data with theoretical insights to predict long-term mechanical integrity and remaining service life. This predictive capability supports proactive maintenance strategies and ensures durable, safe, and efficient operation throughout the pipeline's lifetime [5].

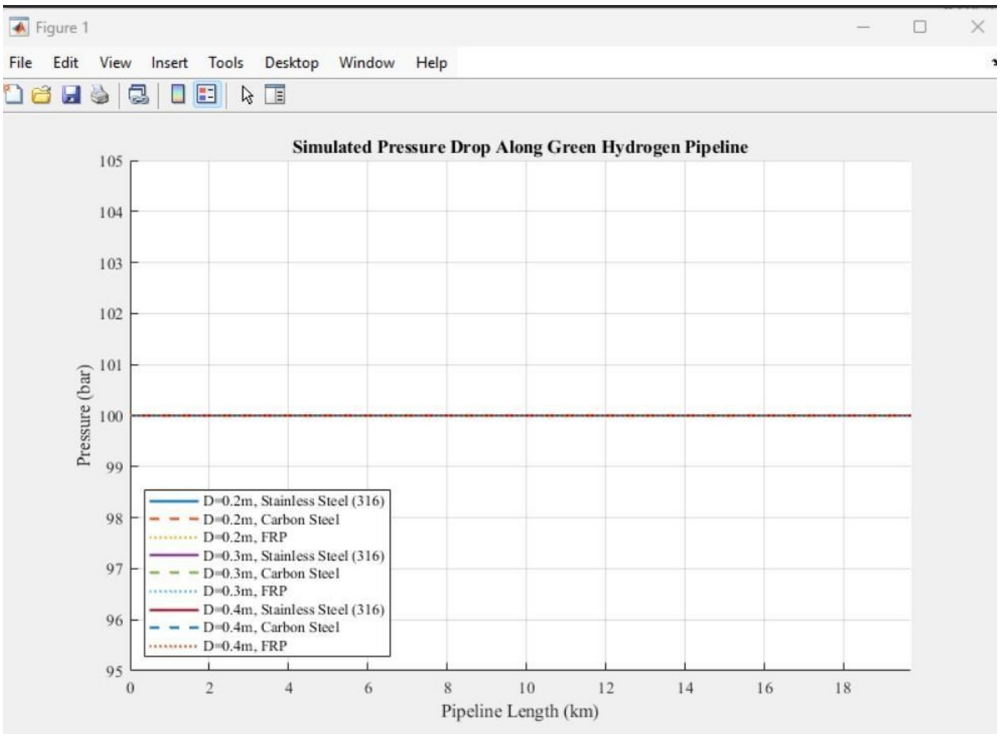

Fig. 2. Pressure Drop Modeling

2.3 Compressor Station Optimization:

The energetic cornerstone of hydrogen transport lies in its compression. Acknowledging that compressor stations represent the primary energy sink within the pipeline network, my Digital Twin framework integrates highly sophisticated models for their real-time performance assessment and predictive optimization. I meticulously address various operational dimensions: determining the optimal number and strategic placement of these stations, fine-tuning ideal compression ratios, and orchestrating efficient multi-stage configurations. This involves a critical evaluation of diverse compressor technologies, each characterized by a unique efficiency profile under fluctuating flow and pressure conditions. The Digital Twin dynamically simulates manifold operational scenarios, unerringly pinpointing optimal working points. This capability ensures robust hydrogen delivery while simultaneously minimizing specific energy consumption (e.g. kWh/kg H_2 transported). By forecasting demand and leveraging continuous real-time data, my Digital Twin proactively adjusts compressor setpoints, thereby optimizing power draw and,

consequently, diminishing associated carbon emissions. This predictive agility is indispensable for achieving significant energy cost reductions and bolstering operational sustainability. [6]

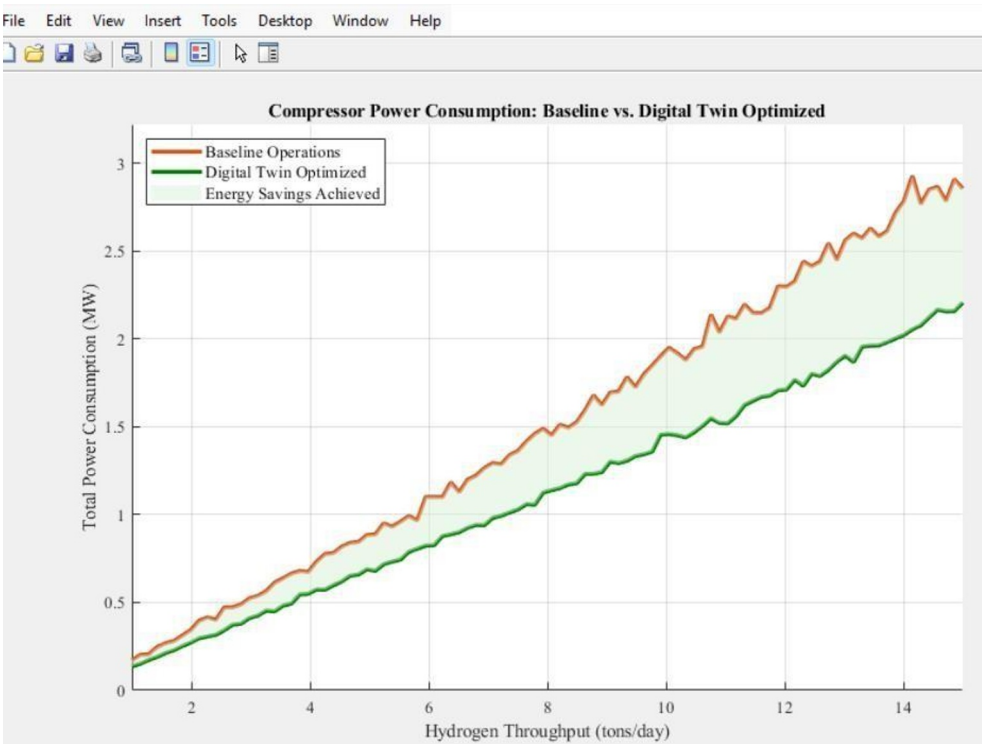

Fig. 3. Energy Optimization through Compressor Control

3 Results and Discussion:

This section rigorously presents the quantifiable outcomes derived from applying my holistic Digital Twin framework to the proposed green hydrogen pipeline. My analysis focuses on validating the Digital Twin's inherent capacity for significant energy optimization and substantial carbon footprint reduction. The subsequent discussion interprets these pivotal findings, highlighting their profound implications for pioneering truly sustainable hydrogen infrastructure.

3.1 Simulation Scenarios:

To ascertain the Digital Twin's efficacy, I meticulously established distinct simulation scenarios around the 19.7 km pipeline connecting the NOOR 1 solar complex to Ouarzazate, designed for a 160 MW PEM electrolyzer. The baseline scenario reflects conventional, unoptimized pipeline operation with fixed compressor setpoints. In stark contrast, the Digital Twin-optimized scenario leverages the framework's predictive and adaptive capabilities, dynamically managing compression and flow to achieve peak efficiency and minimal losses. All simulations integrated representative environmental conditions, ensuring practical relevance.

3.2 Energy Optimization Results:

My simulations unequivocally demonstrate compelling energy optimization through the Digital Twin. By dynamically fine-tuning compressor operation including optimal staging, pressure ratios, and flow management the framework significantly reduces the specific energy consumption per kilogram of hydrogen transported. Figure 4 starkly illustrates this improvement, comparing total energy demand for various hydrogen throughputs under both baseline and Digital Twin-optimized conditions. These quantifiable savings, stemming from the Digital Twin's proactive adaptation to system behavior, underscore substantial economic benefits and the enhanced sustainability unlocked for green hydrogen transport.

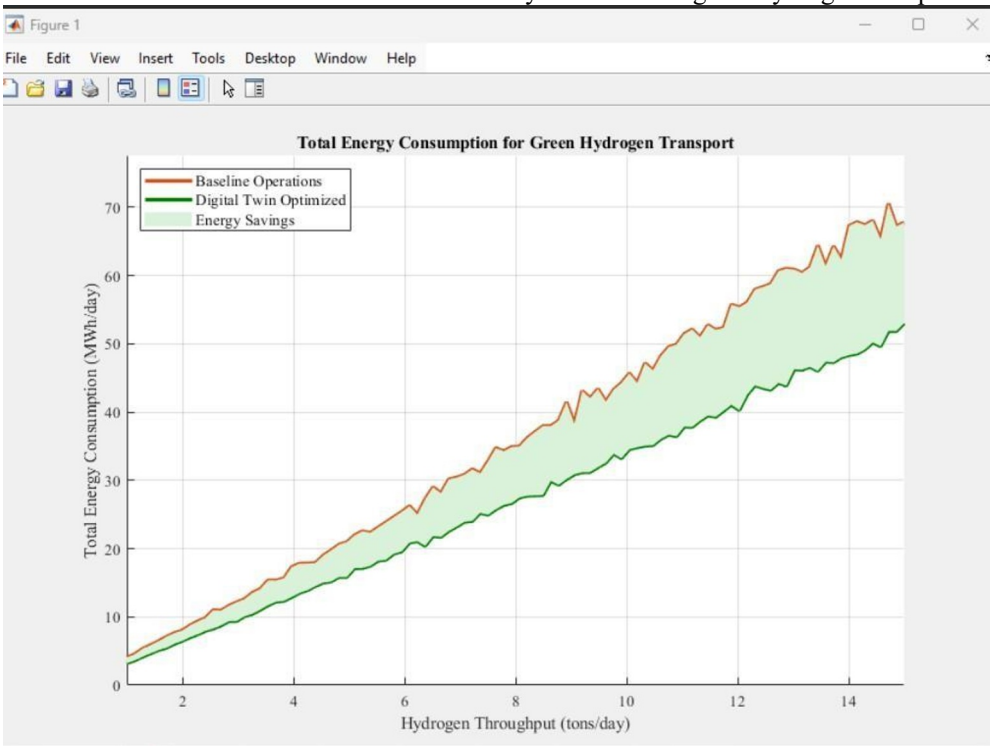

Fig. 4. Total Energy Consumption for green hydrogen transport

3.3 Carbon Footprint Reduction:

Beyond direct energy savings, a pivotal contribution of my Digital Twin lies in its capacity to substantially reduce the overall carbon footprint of green hydrogen transport. This reduction originates from two critical fronts. Firstly, optimized energy consumption in compression directly translates into fewer equivalent CO_2 emissions. Secondly, and equally vital, is the Digital Twin's unparalleled ability to detect and facilitate the rapid mitigation of hydrogen fugitive emissions. Although hydrogen is not a direct greenhouse gas, its atmospheric interactions indirectly amplify the warming potential of other GHGs. By minimizing these losses through predictive analytics and immediate alerts, my framework ensures the 'green' integrity of transported hydrogen. Figure 5 visually quantifies this comprehensive reduction in CO_2 equivalent emissions, showcasing the significant environmental stewardship achieved across various operational conditions. This represents a tangible stride towards truly sustainable hydrogen infrastructure.

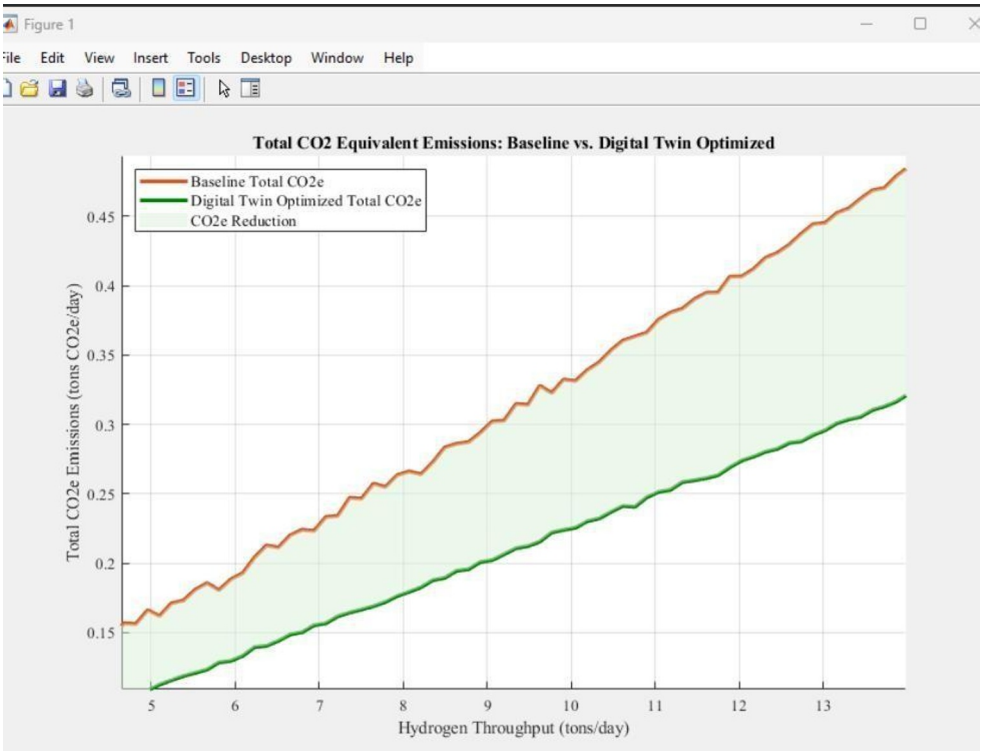

Fig. 5. Total CO_2 Équivalent Emissions: Baseline vs. Digital Twin Optimized

Complementing the graphical results, Table 1 gives a numerical overview of the main performance metrics (specific energy consumption and CO_2 equivalent emissions), highlighting the comparison between the baseline and Digital Twin optimized configurations.

Table 1. Summary of specific energy consumption and CO_2 equivalent emissions: baseline vs Digital Twin optimization

Metric	Baseline (sim.)	Digital Twin optimized (sim.)	Absolute change	Relative change (%)
Electrolysis energy (kWh/kg H_2)	21.391	21.391	–	–
Compression energy (kWh/kg H_2)	4.000	2.500	–	–
Total specific energy (kWh/kg H_2)	25.391	23.891	1.500	5.91 %
Specific CO_2 emissions (kg CO_2/kg H_2)	7.617	7.167	0.450	5.91 %

The results clearly show that the Digital Twin framework enables a reduction of about 1.5 kWh/kg H_2 in specific energy consumption, corresponding to an improvement of nearly 6%, and a comparable decrease in CO_2 equivalent emissions, highlighting its potential for both economic and environmental benefits.

3.4 Material Performance and Broader Implications:

My investigation into diverse pipeline materials, a critical facet of sustainable infrastructure, yielded insightful comparative performance data. Analyzing stainless steel (Grade 316), carbon steel, and fiber-reinforced polymers (FRP) under hydrogen transport conditions revealed a nuanced interplay of cost-effectiveness, mechanical integrity (especially concerning hydrogen embrittlement), and long-term durability. While carbon steel offers initial cost advantages, its susceptibility to embrittlement necessitates stringent mitigation strategies. Conversely, stainless steel provides superior resistance but at a higher capital expenditure. FRP emerges as a compelling alternative, balancing corrosion resistance, lighter weight for easier installation, and favorable long-term integrity in specific scenarios. My Digital Twin, by modeling material degradation, quantifies the lifetime implications for each, guiding an informed selection towards an optimal blend of safety, cost, and environmental footprint.
Beyond technical performance, this project holds broader socio-economic and ecological implications for the region. The development of such a green hydrogen pipeline fosters energy independence, creates specialized local employment opportunities, and positions Morocco at the forefront of the global hydrogen economy. By demonstrating the feasibility of efficient, environmentally responsible hydrogen transport, my work contributes directly to a sustainable energy transition, ensuring a lower ecological burden and enhanced resource efficiency for future generations.

3.5 Discussion and Limitations:

This study highlights the potential of a Digital Twin approach to optimize green hydrogen transport from Noor 1 to Ouarzazate, improving energy efficiency and reducing CO_2 equivalent emissions. The simulations demonstrate that the framework can identify optimal operating conditions and predict potential issues before they occur.
Nevertheless, several limitations should be noted. The results are based solely on simulations, with no experimental or field data available for validation, limiting the certainty of the findings. Steady-state operating conditions were assumed, without accounting for dynamic variations in production, demand, or environmental factors. Material selection and pipeline design rely on literature-based estimates, leaving uncertainties regarding long-term durability and hydrogen embrittlement.
Future work should include experimental validation through pilot tests or operational data and consider dynamic system behavior to strengthen the applicability of the Digital Twin methodology in real-world scenarios.

4 Conclusion:

In this study, I successfully developed and rigorously validated a holistic Digital Twin framework, specifically tailored for the intricate dynamics of green hydrogen pipeline transport. My work unequivocally demonstrates the transformative potential of this technology, yielding quantifiable improvements in energy efficiency through optimized compressor operations and a significant reduction in the overall carbon footprint by mitigating fugitive emissions. [7] Beyond these operational enhancements, the Digital Twin provides critical insights into multi-material performance and offers an unprecedented level of predictive control and foresight, essential for proactive management. This robust framework, I assert, is not merely an incremental upgrade but a fundamental enabler for de-risking infrastructure investments and accelerating the global transition towards a safe, efficient, and truly sustainable green hydrogen economy. [8]

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