Evaluation of the Hydrogen Value Chain: Integrating Production with Distribution Networks

Introduction

The transition to renewable energy sources requires the development of efficient and reliable large-scale energy distribution and storage solutions, primarily to balance fluctuations and ensure a safe supply. Hydrogen is garnering significant attention as a clean energy carrier due to its physiochemical properties and high calorific value. It stands out among potential future fuels, mainly because it can be produced from renewable sources, aligning with the expected future energy landscape. For hydrogen transport, two key components, namely the pipeline system and thermal turbomachinery, play a central role in the efficient distribution of hydrogen. Yet the optimal design and operational parameters are still subjects of ongoing research. Additionally, the optimization of underground hydrogen storage (UHS) sites, which offer significant capacity for long-term storage, presents a challenge due to the influence of geological characteristics, storage technology selection, and operational parameters on storage capacity, efficiency, and safety. Existing studies often fail to consider the integration and interaction of different system components within the hydrogen network, overlooking the complexity of the overall system. This knowledge gap impedes the development of strategies to improve the efficiency and cost-effectiveness of hydrogen networks, thus slowing progress toward a more sustainable future.

We aim to bridge these gaps by proposing simulation approaches for the effective integration of UHS and hydrogen networks. By examining the interactions between UHS, pipeline systems, and thermal turbomachinery, the research seeks to enhance the understanding of complex system integration and develop strategies to optimize the efficiency, reliability, and cost-effectiveness of the future hydrogen economy.

Materials and Methods

We developed an integrated simulation model for hydrogen networks to enable comprehensive evaluation, and economic analysis of the various components within the hydrogen network such as production, transmission pipelines, intermediate compressor stations, surface facilities, underground storage, and finally a holistic economic assessment of the entire system. The individual modules are as follows:

Production module: facilitates the evaluation of hydrogen production methods, such as electrolysis or steam methane reforming (SMR). It provides options to calculate hydrogen production rates and energy requirements. The production method mainly serves as input for energy consumption as can be seen below.

Table 1: *Average specific energy consumption (ASEC) for different hydrogen production methods*

Production Method	Average Specific Energy Consumption (ASEC) [kWh/kg H2]
Alkaline Electrolysis (AEL)	45
Proton Exchange Membrane (PEM)	60
Steam Methane Reforming (SMR)	45
High-Temperature Electrolysis (HTEL)	40
Pyrolysis	8
Arbitrary	55

What should be noted is that the ASEC values found in literature vary and that practical values may diverge significantly from theoretical values.

Transmission and compression module: It provides functionality for calculating flow performance and pressure drops within the transmission lines of the hydrogen network. It allows us to determine optimal pipe diameters and visualize pressure profiles and flow rates along the transmission network. Compression along the transmission lines is also considered in the simulation. This includes estimating the required number and locations of compressor stations within the network. By considering input parameters such as flow rates, pressure differentials, and system constraints, the module can optimize compressor station characteristics to minimize energy consumption while ensuring desired performance. Input parameters are the pipeline dimensions, length, and pipe roughness factor.

UHS module: When the hydrogen is transported over the defined distance, the hydrogen will be introduced into an underground storage facility where it will remain there for a predefined period. Thus, the UHS module focuses on the assessment of UHS utilization and its impact on the re-production of stored hydrogen, especially in terms of purity and production rate. It calculates storage capacity requirements based on system dynamics and also evaluates the effects of storage utilization on network performance and the economic viability of the project. A realistic seasonal storage pattern for different injection rates is available. With that, the implications on extracted hydrogen purity and remaining amounts in the subsurface can be assessed.

Distribution module: After producing hydrogen back from the subsurface storage facility, the chemistry of the gas will not be identical to the purely injected hydrogen. Thus, the parameters of the gas mixture will differ from those of pure hydrogen. This module analyses the distribution network, especially its effect on economics by selecting optimal pipeline routes and considering factors such as distance, pipe lifetime, and infrastructure availability.

Economic evaluation module: The economic evaluation module provides functionality for the comprehensive economic analysis of the entire hydrogen network. It calculates the overall cost of the network, considering capital investments, operational expenses, both non-energy-related and energy-related, and maintenance costs. Furthermore, the cost distribution of the transmission system, distribution system, and sensitivity analysis can be performed.

Simulation Results

During the research, a real planned case was taken as a basis and was extended to assess the resulting levelized costs of delivered hydrogen for long-distance pipeline transport to Central Europe. A distance of 5,140 km of a 48” hydrogen pipeline transporting the considerable energy content of 100 TWh of hydrogen annually from Qatar to southern Bavaria (**Figure 1**).

Figure 1*: Investigated case for simulation of trans-continental large-scale hydrogen transport in pipelines (Google Maps, 2024)*

Seasonal Storage Performance: In the considered case, the minimum purity of hydrogen occurs at the end of the production cycle, reaching 48.57%. This is important to consider for the subsequent transport and processing of hydrogen due to potential differences in physio-chemical properties compared to pure hydrogen. Over multiple cycles, an increase in bottomhole pressure could be observed. This increase in pressure with each storage cycle is attributed to hydrogen accumulation in the reservoir and the absence of significant CO_2 impurities in the subsurface model. The presence of CO_2 would potentially cause a pressure drop due to methanation processes. The assumption of a homogeneous and isotropic reservoir leads to initially high and stable hydrogen production, followed by a decline to lower values. A significant amount of trapped hydrogen remains in the subsurface after the second production cycle, approximately 5,251,438 kg. This poses challenges to project profitability and resilience. However, over time, the purity of extracted hydrogen increases, and the co-production of other gases, such as methane, decreases significantly.

Economic System Performance: Labor costs represent the largest portion of costs in the pipeline system, particularly in the distribution system. The difference in pipeline dimensions and distance explains the variation in miscellaneous and material costs between the two systems. Energy-related operating expenses for compression contribute significantly to the overall compression costs per kilogram of transported hydrogen. Results from the integrated simulation, encompassing inlet compression, transmission pipelines and compression, and distribution pipelines and compression, indicate a levelized cost of delivered hydrogen (LCODH) ranging from 2.78 €/kg to 10.54 €/kg. The specific LCODH value depends on the selected production method and the observed period. The levelized costs of delivered green hydrogen range between 4.30 €/kg and 10.54 €/kg whereas for grey hydrogen the costs lay between 2.78 €/kg and 4.64 €/kg.

From the sensitivity analysis, it can be seen that the inlet and transport temperature of hydrogen in the pipelines had a significant effect on the final costs of hydrogen. Also, the suction and compression pressure which are operational parameters of the enroute compressor stations had a significant impact on the overall cost structure of the system. These parameters also greatly influence the flow velocity through the pipelines which in turn will impact the longevity of the system components, particularly the pipelines.

Conclusions

The research conducted in this study has successfully demonstrated the effectiveness of an integrated simulation approach in determining plausible results for the levelized costs of hydrogen. These results align with existing findings in the literature. Moreover, the integrated simulation approach offers numerous advantages over analyzing individual components of the future hydrogen network in isolation.

The primary outcome of this study is the development of a standalone application capable of representing a generic hydrogen network, encompassing the production, transmission, storage, and extraction of hydrogen for final use. The simulation results obtained from this application serve as the foundation for an integrated economic analysis, providing insights into the projected costs of hydrogen projects.

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