Holistic Demand driven Hydrogen Supply Chain Design Optimisation

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Introduction

The implementation of the Paris Agreement on 4th November, 2016 has set in motion a global energy exodus towards a low-carbon economy. Governments and key stakeholders are on the mission to reduce emissions without jeopardising economic growth (Li et al., 2019). Hydrogen as an energy carrier has been deliberated since 1970s, initially considered to power the transportation sector, and have since evolved to transform other industries such as chemical, heating, and steel. Hydrogen is emerging as one of the major energy carriers of the future energy system, and currently 95% of all hydrogen produced is through the steam methane reformation (SMR) of natural gas ((IRENA), 2019). SMR requires methane and emits carbon dioxide as its byproduct both of which are potent greenhouse gas and far from an ideal solution to a low-carbon economy. On the contrary, renewable-powered electrolysis producing green hydrogen is viewed as a key production method to help decarbonise numerous sectors (Riera et al., 2023), however the scarcity of the present infrastructure to form an efficient and robust hydrogen supply chain (HSC) is considered to be one of the main barriers towards boosting the hydrogen economy, primarily green hydrogen generation facilities, storage, and transportation of hydrogen (Li et al., 2019, Riera et al., 2023). The primary challenge for investors and policymakers alike with regards to the aforementioned issue is the formulation of strategy to satisfy the "4 w questions" that is, the spatial and temporal decisions to build hydrogen infrastructures- when, where, what size, and with which technologies (Lin et al., 2008). These decisions are notoriously difficult to make given the multifaceted factors involved such as demand projection, resource availability, technological maturity, sector integration, logistics, and regulatory frameworks. Hydrogen supply chain design (HSCD) focuses on tackling the challenges associated with implementing hydrogen infrastructure and optimization is a central component of systematic methodologies to support hydrogen expansion. Despite recent developments within the sphere of multi-period optimisation of HSCD (De-León Almaraz et al., 2015, Carrera and Azzaro-Pantel, 2021), there is a lack of research underpinning demand projections from multiple sectors and their respective uncertainties (Riera et al., 2023). It is therefore necessary to develop an accurate and reliable HSCD optimisation framework by incorporating these factors, aiding the advancement of the hydrogen economy.

Research Questions:

1. What are the factors affecting current and projected supply and demands for hydrogen and their related uncertainties?
2. How can hybrid modelling improve the accuracy and reliability of hydrogen demand projections across multiple sectors?
3. What factors influence the optimal spatial and temporal deployment of green hydrogen generation infrastructure, and how can these be quantified within a robust network model?

Aims and Objectives:

The overall aim of this research is to develop a novel multi-period spatio-temporal optimisation methodology by integrating a holistic hydrogen demand projection within the framework to facilitate the deployment of hydrogen infrastructure across a hydrogen supply chain (HSC). To achieve the aim, five objectives are developed as follows:

1. Conduct comprehensive sectoral analysis on a regional and national scale through market and academic research to understand the factors affecting supply and demand for hydrogen.
2. Develop a novel holistic hydrogen demand projection framework by integrating multiple demand forecast simulation modelling techniques through the concept of hybrid modelling.

3. To integrate evaluation results with centrality theory and ArcGIS to develop a robust weighted network representation of the investigated HSC.
4. To develop a MILP optimisation model that determines the optimal deployment of centralised green hydrogen generators across the HSC based on the spatio-temporal constraints and desired objectives.
5. To validate the model by comparing its outputs with historical data and expert knowledge and conduct sensitivity analysis to assess the robustness of the model developed to changes in input parameters.

Literature Review:

In order to obtain a more realistic results for the configuration of the hydrogen economy it is first vital to gain a holistic view of the hydrogen demand projections from various sectors (Bloomberg, 2020), (Riera et al., 2023). The International Energy Agency (IEA) estimates by the year 2030 demand for hydrogen in a net-zero CO_2 emissions scenario (NZE) is likely to rise to 210 million tons (Mt) and to 540 (Mt) by 2050 (Oesingmann et al., 2024). Most of the HSC optimisation papers considered and modelled hydrogen demand from the market penetration of Hydrogen Fuel Cell Vehicles (HFCV's) which just one of the elements under the transportation sector. Thus, considering the need for hydrogen across the other elements within transportation (Aviation, Shipping and Rail); the energy sector (employing hydrogen for energy storage or power generation); and industrial applications (such as steel, paper, and cement production), among others, will provide a more reliable demand forecast thus enhancing the HSCD optimisation model (Maryam, 2017, Riera et al., 2023).

Theoretical Framework:

The theoretical framework for this research integrates multiple concepts and methodologies to address the complex challenge of hydrogen supply chain design optimization. It combines elements of systems theory, demand forecasting, network analysis, and multi-objective optimization. This integrative approach allows for the incorporation of market dynamics, technological advancements, and geographical constraints into a cohesive decision-making tool. The framework leverages centrality theory and GIS techniques to develop a robust network representation of the hydrogen supply chain, which serves as the foundation for a Mixed Integer Linear Programming (MILP) optimization model. This multi-faceted theoretical structure enables a more nuanced and realistic approach to hydrogen supply chain design, accounting for the complexities and uncertainties inherent in emerging energy systems.

Research Design:

The research design for this study adopts a mixed-methods approach, combining quantitative and qualitative techniques within a multi-stage process. Initially, a comprehensive literature review and market analysis will be conducted to identify key factors influencing hydrogen supply and demand across various sectors. This will inform the development of a novel hybrid simulation model for demand projection, integrating multiple forecasting techniques to enhance accuracy and reliability. The study will then employ GIS and centrality theory to create a weighted network representation of the hydrogen supply chain. This network model will serve as the foundation for a Mixed Integer Linear Programming (MILP) optimization framework, designed to determine optimal spatial and temporal deployment of green hydrogen infrastructure. The optimization model will incorporate the demand projections and network analysis results, along with various constraints and objectives. To ensure robustness and validity, the model will be calibrated using historical data and expert knowledge, followed by sensitivity analyses to assess its responsiveness to parameter changes. This multi-faceted research design allows for a holistic approach to hydrogen supply chain optimization, addressing the complex interplay between demand dynamics, geographical constraints, and infrastructure deployment strategies.

Relevance and/or practical importance of the study:

This study is highly relevant and practically important as it addresses the urgent need for sustainable energy solutions in the transition to a low-carbon economy. By focusing on green hydrogen, it contributes to global efforts to reduce greenhouse gas emissions. The research provides essential insights for policymakers and investors regarding the optimal deployment of hydrogen infrastructure, thus aiding in informed decision-making and reducing financial risks. The development of a novel hybrid simulation model for demand forecasting enhances the accuracy of projections, facilitating efficient planning and implementation of hydrogen technologies. Additionally, the holistic approach considers various factors such as resource availability and technological maturity, informing evidence-based policymaking to support hydrogen economy growth. This interdisciplinary research not only impacts the energy sector but also serves as a practical tool for industry stakeholders to assess and plan their investments. Ultimately, this study fills a critical gap in understanding hydrogen supply chain design and optimization, with significant implications for regional development and sustainable energy practices.

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