Report of the techno-economic analysis

Deliverable 5.1. Report of the techno-economic analysis

Authors: Umur Hasturk, Ece Kayacik, Evrim Ursavas with contributions by Arjen T. Veenstra, Albert H. Schrotenboer, Frank Hagedoorn, Stef ter Bekke, Feiko Smid, Hidde Scholten, Michiel A J Uit het Broek, Stuart Zhu, Nicky van Foreest, Iris Vis, Kees Jan Roodbergen, Tatiana Block, Enrique Troncoso

Clean Hydrogen Partnership

Co-funded by the European Union

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 875090. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

Table of contents

1 Introduction 3

1.1 Background 3

1.2 Overview and Summary 3

1.2.1 Identifying the Technical, Regulatory, and Market Barriers Inhibiting the Commercialization of an Integrated Hydrogen Economy in the Northern Netherlands 4

1.2.2 Green Hydrogen Plant: Optimal control strategies for integrated hydrogen storage and power generation with wind energy 4

1.2.3 Towards Low-carbon Power Networks: Optimal Integration of Renewable Energy Sources and Hydrogen Storage 5

1.2.4 Green Hydrogen Distribution Planning in the Northern Netherlands: Stochastic Cyclic Inventory Routing with Supply Uncertainty 5

1.2.5 Structuring the Hydrogen Refueling Station Network to accommodate Fuel Cell Electric Trucks: A study in the Northern Netherlands. 6

1.2.6 Laying the foundation for a hydrogen refueling network for inland cargo ships in the Netherlands and Germany: A roadmap to 2050 7

1.2.7 Infrastructure development for green hydrogen use in railway transport – a case study in the Northern Netherlands 7

2 Appendix 9

1 Introduction

1.1 Background

With the objective of establishing the market framework and developing regional business models adapted to the Northern Netherlands, studies considering the economic conditions for wide-scale commercialization of green H2 and for optimum operation of an integrated H2 Valley in the Northern Netherlands have been developed. The main tasks performed are as follows:

1. Establishing the framework for the production, distribution, and end-use of H2 across the Northern Netherlands.
2. Identification of the technical and economic parameters, constraints, and barriers towards full-scale commercialization, including RCS and other legal & policy barriers, end-user acceptance (e.g., safety aspects, social barriers).
3. Analyzing current market and techno-economic conditions for the development of the regional H2 ecosystem in the region.
4. Building scenarios and performing scenario analysis to analyze interactions between these markets and assess the effects of policy measures on market outcomes.

Multiple projects have been worked on on the market and techno-economic studies, considering the current and envisaged developments over a timeframe (linked to WP6). The objective is to lay out the framework conditions for developing specific business cases. Techno-economic analysis and computational studies are provided to obtain insights into the development of integrated business models. Close interaction with WP6 is realized by providing a strong link among tasks, for example, providing input for the roadmap WP6 -Task 6.8 and using data from the techno-economic studies focus on infrastructure for mobility as input in WP6 -Task 6.7. In particular, the output from the assessments of techno-economic and RCS barriers in heavy-duty road, maritime, and railway applications has been provided as input to deliverable 6.7 “Hydrogen Applications in Heavy Duty Transportation”. Studies reported here also involve roadmap analysis, and they are already reported within this deliverable for completeness.

1.2 Overview and Summary

The report is structured around studies focusing on the techno-economic analysis and development of integrated H2V business models. Furthermore, market and techno-economic barriers toward wide-scale commercialization of green H2 in NN are carefully analyzed. We hereby provide a short summary of the studies. The full texts are given in Appendix.

1.2.1 Identifying the Technical, Regulatory, and Market Barriers Inhibiting the Commercialization of an Integrated Hydrogen Economy in the Northern Netherlands

We focused on the technological, market, and regulatory barriers toward the development of an integrated hydrogen economy in the Northern Netherlands and interactions between the different parts of the value chain (e.g. regional supply of green hydrogen, distribution, and delivery to end-user applications). The goal is to establish a framework for the development of regional business models and specific business cases, aiming toward the commercialization of green hydrogen in the Northern Netherlands. Based on the 12 interviews conducted with managers, industry experts, and local governments, 29 techno-economic and system-wide barriers are identified across the hydrogen supply chain. The study showed that the barriers are highly interrelated and interdependent indicating the complexity of developing a hydrogen economy. Besides, social acceptance barriers proved crucial to the commercialization of specific technologies. Based on the results, a framework with mitigation strategies was provided, which can help practitioners to better understand when and how the identified barriers should be addressed. The framework can be considered as a blueprint on which future research can be based and which practitioners can use to better plan for the development of an integrated hydrogen economy.

1.2.2 Green Hydrogen Plant: Optimal control strategies for integrated hydrogen storage and power generation with wind energy

We examined the optimal strategies on the supply side for operating integrated energy systems consisting of green hydrogen supply and storage. The work carried out in this study involved constructing optimal policies for day-to-day decisions on how to operate renewable power plants, for instance, how much energy to store as hydrogen, buy from or sell to the electricity market, and how much hydrogen to sell for use as gas to the industry. Special emphasis has been paid to practical settings, such as contractually binding power purchase agreements, varying electricity prices, different distribution channels, green hydrogen offtake agreements, and hydrogen market price uncertainties. Extensive experiments and analysis were performed in the context of the Northern Netherlands, where Europe’s first Hydrogen Valley is being formed. Results show that important gains in operational revenues are possible by introducing hydrogen storage units and competitive hydrogen market prices. The results also indicate that hydrogen offtake agreements will be crucial in keeping the energy transition on track.

1.2.3 Towards Low-carbon Power Networks: Optimal Integration of Renewable Energy Sources and Hydrogen Storage

We analyzed how hydrogen can be used to provide flexibility to the highly volatile energy market and be used to alleviate the congestion problems in the power network. The focus was on the integration of the H2 market into the power systems. The increased integration of renewables into power networks disrupts electricity supply-demand matching because of the intermittency and uncertainty of renewable energy output. The use of green hydrogen is a high-potential solution to this problem; it can be used to store renewable energy to mitigate supply-demand imbalances of electricity. Besides, it can be sold outside of the network to satisfy increasing green hydrogen demand from various sectors, including industry, mobility, and heat. Interactions of hydrogen storage, renewables, and power networks at a regional scale are being analyzed, in order to design low-carbon energy networks efficiently. Specifically, a techno-economic analysis for this segment of the value chain (i.e. supply of green hydrogen) was conducted to investigate how different levels of hydrogen-related economic and technical parameters affect the commercialization of green hydrogen, considering both capital and operational costs. The results show that the integration of hydrogen storage significantly reduces the operational cost of the power system. Besides, the added value of selling hydrogen on a functioning hydrogen market will not only increase the return on investment but also accelerate the adoption of hydrogen storage.

1.2.4 Green Hydrogen Distribution Planning in the Northern Netherlands: Stochastic Cyclic Inventory Routing with Supply Uncertainty

Distribution of hydrogen requires special attention considering the characteristics of green hydrogen supply and also the uncertainty of demand. An analysis is done to identify the challenges arising from the uncertainty of supply and demand of green hydrogen. The focus is on the distribution of H2, considering the inventory levels of H2 at both customers and the producers, taking into account the uncertainty that derives from the production of green hydrogen and the uncertainty in demand. This is especially important in the early transition states and the uncertainties are higher due to low volumes and intermittency of green hydrogen production. Subsequently, the distribution of green H2 from producers to customers will be simulated via mathematical models and associated solution methodologies, assuming that an inventory of the product is kept both at the producer and at each customer. While the customer inventories are gradually depleted, the producer inventory is filled with a random amount of production. The goal is to determine an efficient schedule for deliveries to the customers while ensuring that there is sufficient inventory for each customer. A case study for 2030, 2040, and 2050 is studied for replenishing end users. The results show that it is more cost-effective to replenish multiple locations together since the major costs derive from the distance. Moreover, the parameters and model elements are analyzed for these case studies. It is shown that including production uncertainty is significantly reducing costs. Finally, a cost analysis is done on storage capacities. The insights taken from these studies and analyses are crucial for the wide-scale commercialization of green H2 distribution in the NN towards 2050.

1.2.5 Structuring the Hydrogen Refueling Station Network to accommodate Fuel Cell Electric Trucks: A study in the Northern Netherlands.

Fuel Cell Electric Trucks (FCET) have short refueling times and a long vehicle range when compared to Battery Electric Trucks (BET). Using green hydrogen from renewable energy sources significantly reduces Well-to-Wheel (WTW) emissions for heavy-duty trucks (HDT). However, for a large FCET market to become a reality, enormous efforts are yet to be taken. Investors in hydrogen refueling infrastructure (HRS) are waiting for more FCETs to enter the road. On the other end of the spectrum, companies are not inclined to invest in FCETs as long as there is no widespread refueling infrastructure. This study focuses on the latter by evaluating how the HRS infrastructure should be structured to accommodate different percentages of FCET market penetration shares in the heavy-duty transportation sector. A flow refueling location model (FRLM) has been developed, which determines where to locate HRS facilities depending on vehicle flow intensity on the roads considering HRS cost aspects and including a temporal analysis. This model is applied to an in-depth case study in the Northern Netherlands. The results show that the HRS network expands as the FCET market grows, from 8 HRS facilities in 2030 to 17 stations in 2050. Especially in the early adoption years, it is more cost-efficient to put in place fewer stations with high capacity rather than numerous small HRS facilities. Finally, the results obtained from these economic analyses as a whole in the Northern Netherlands indicate that financial government stimulation, along with collaboration and transparency in the sector is essential to accommodate an increasing number of FCETs on the road.

1.2.6 Laying the foundation for a hydrogen refueling network for inland cargo ships in the Netherlands and Germany: A roadmap to 2050

The transport sector is notoriously heavy in emissions and the need to make this sector more sustainable is growing. A transition from a fossilized-fueled to a hydrogen-fueled inland shipping sector can potentially contribute to the solution. To make this transition two important steps need to be taken. One step is that an infrastructure capable of refueling hydrogen-fueled ships need to be built. The second step is to make hydrogen-fueled maritime transport commercially feasible. Technical, economic, and political/legal barriers have been identified that can hinder the transition towards hydrogen-fueled inland cargo vessels. To create a new infrastructure it is important to find optimal locations for refueling stations. For this, a refueling location model has been developed to fit the characteristics of hydrogen-fueled ships. In this model, the differences between slow and fast refueling locations and hydrogen characteristics have been incorporated. The model has been validated by doing a case study with interviews in parts of the Netherlands and Germany. Scenarios for 2030, 2040, and 2050 are simulated with the model and the results are combined in a comprehensible roadmap to 2050. The results show that the percentage of early adaptation is expected to be low in 2030, resulting in the need for governmental aid for development in the future years. Furthermore, from 2040, with more adaptation levels and consumers willing to pay the green tag, it is possible to successfully operate hydrogen refueling locations with minimal to no governmental aid, depending on the transition towards the green hydrogen economy.

1.2.7 Infrastructure development for green hydrogen use in railway transport – a case study in the Northern Netherlands

In the railway industry, green hydrogen can be used as an alternative to the expensive electrification of railway lines. To develop a hydrogen railway infrastructure, a flow-interception location model (FILM) has been reformulated to analyze optimal locations for hydrogen refueling stations (HRS), taking the capacity of an HRS into account. The developed model minimizes the distribution costs of hydrogen to an HRS to achieve a cost-efficient network. Linked to the roadmap studies three future scenarios for 2030, 2040, and 2050 are drawn up, using real-life railway data from the Northern Netherlands. The scenarios assume increased adoption of hydrogen trains and take future developments into account. Developments entail fuel cell efficiency, train range, distribution methods, and the price of hydrogen. In addition, interviews with industry experts have also been completed. The results showed that future HRSs in Groningen and Leeuwarden require less capacity than current plans indicate. It is also concluded that there are still a number of uncertainties regarding regulations that may influence the implementation of hydrogen in the railway industry.

2 Appendix

1. Identifying the Technical, Regulatory, and Market Barriers Inhibiting the Commercialization of an Integrated Hydrogen Economy in the Northern Netherlands
2. Green Hydrogen Plant: Optimal control strategies for integrated hydrogen storage and power generation with wind energy
3. Towards Low-carbon Power Networks: Optimal Integration of Renewable Energy Sources and Hydrogen Storage
4. Green Hydrogen Distribution Planning in the Northern Netherlands: Stochastic Cyclic Inventory Routing with Supply Uncertainty
5. Structuring the Hydrogen Refueling Station Network to accommodate Fuel Cell Electric Trucks: A study in the Northern Netherlands.
6. Laying the foundation for a hydrogen refueling network for inland cargo ships in the Netherlands and Germany: A roadmap to 2050
7. Infrastructure development for green hydrogen use in railway transport – a case study in the Northern Netherlands