FINAL REPORT

NETWORK-H2
CALL 1 - ECONOMIC FEASIBILITY OF HYDROGEN FUELLED TRANSPORTATION

PROJECT DETAILS

Grant number

NH2-001

Award holding organisation

Organisation	University of Kent

Title of research project

Techno-economic feasibility study of hydrogen-fuelled freight transport

Investigators

Role	Name	Organisation
Principal investigator	Dr Ramin Raeesi	University of Kent
Co-investigator	Prof. Philip Greening	Heriot-Watt University
Co-investigator	Dr Mi Tian	University of Exeter
Co-investigator	Dr Nazmiye Ozkan	Cranfield University

Grant number

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Final Project Report

1. Project Overview

Freight transportation accounts for more than 40% of transport-related emissions, and 65% of this is due to road freight transport only [1]. Between 1990 and 2010 Heavy Duty Vehicles (HDV) emissions increased by 36% and they are projected to grow to 40% by 2030 [2]. Shifting from fossil fuels to clean alternative fuel options such as hydrogen is an essential step in decarbonising road freight transport sector and facilitating an efficient transition towards zero-emissions goods distribution of the future.

As an alternative to petroleum-based fuels for transport, hydrogen is an energy carrier that is approximately 2.5 times more efficient than gasoline [3], and can be produced from conventional primary energy sources (e.g., natural gas, coal and petroleum), as well as renewables (e.g., solar and wind energy), and as such contributes also to improving energy security [4].

Transition to a hydrogen-based energy system to support and accelerate the widespread adoption of hydrogen-powered freight HDVs is, however, significantly hindered by the lack of the infrastructure required for producing, storing, transporting and distributing hydrogen. Designing an economically viable and competitive Hydrogen Supply Chain (HSC) to meet the end-user demand is a significant challenge and relies primarily on the optimal configuration and sizing of required facilities and infrastructure [4]. In essence, the ultimate price of hydrogen at pump which in turn implies its economic feasibility against conventional fuel options, relies greatly on the optimal determination of production and storage facilities location, technology and capacity given their required capital investment and operational costs, and connecting them using cost-effective, sufficient and appropriate transport links.

The research project “techno-economic feasibility study of hydrogen-fuelled freight transport” was supported by the UK's Engineering and Physical Sciences Research Council (EPSRC) through the Programme Grant EP/S032134/1 “a network for hydrogen-fuelled transportation (Network-H2)”. The project kicked-off officially on 15/05/2021 and was completed on 14/02/2022. The work carried out over the duration of the project originally aimed at building a techno-economic model for understanding the economics of hydrogen utilisation for land-based freight transport in Great Britain (GB) through the course of the following three Work Packages (WPs):

- WP1 Model development and demand scenarios generation
- WP2 Supply scenarios generation
- WP3 Tecno-economic scenarios analysis

WP2 was dedicated to developing techno-economic and spatially-explicit scenarios representing situations with hydrogen production and storage in GB. Existing, as well as future hydrogen production and storage technologies and their expected capital investment and operations costs were identified and data on existing hydrogen production and storage sites in GB were collected as part of this WP. Demand-side scenarios representing HDV demand (size and location) for hydrogen, and the potential network of hydrogen refuelling stations, on the other hand, were investigated as part of WP1. Over the course of WP3, all generated scenarios (demand and supply sides) were exercised against a two-stage optimisation-based model developed through WP1 for linking road freight demand to HSC. The proposed methodology captures the complex interactions among various HSC entities and identifies optimal strategic and operational configurations of the chain within the boundaries of each scenario constraints to satisfy road freight demand such that the ultimate £/kg cost of getting hydrogen to the downstream of HSC (i.e., hydrogen pumps) is minimised. A key distinctive feature of the proposed methodology pertains to its unique capability to integrate centralised and on-site hydrogen production decisions within a unified demand-driven optimisation framework. Using this tool, first-hand insights regarding hydrogen utilisation by the road freight sector in GB are generated which will be presented in this report.

In what follows, in section 2 a clear statement of the project added value and its key contribution and outcomes is presented. Section 3 elaborates on project outcomes and findings including a discussion on the proposed methodology, the collected data, and the analysis and scenarios set up. Finally concluding remarks and potentials for a follow-on work are presented in section 4.

2. Project added value and key contributions

Spatially-explicit optimisation models that consider the entire HSC and run at a national or regional scale [5] are key to addressing the need for optimal deployment of hydrogen infrastructure and strategic HSC design. Such models integrate multiple HSC components pertaining to production, storage, and transportation within a single Mixed-Integer Linear Programming (MILP) framework and output optimal number and location of the required facilities with their adopted technology and size, as well as the transportation infrastructure needed while minimising the capital and operating costs of the HSC. In most of these models, hydrogen production is assumed to be "centralised" and off-site, and ironically, a key finding from almost all of them pertains to the fact that by far the largest proportion of HSC cost is dominated by the capital and operating cost of hydrogen storage, transport and distribution rather than that of hydrogen production. This may imply considerable cost-saving opportunities at the consideration of distributed "on-site" small-scale hydrogen production in HSC design to eliminate the need for hydrogen storage and transport where possible.

While there is a dedicated stream of research focusing on the economies of on-site hydrogen production [6, 7], we are not aware of any existing HSC optimisation model that is capable of incorporating both on-site and centralised production decisions into an integrated modelling framework. At the same time, the HSC network design decided through these models is essentially "demand-driven" [8]. That is, the entire design of the HSC and the deployment of hydrogen facilities and infrastructure (and thus, the ultimate hydrogen price at pump) primarily depend on the size and the geographical distribution of hydrogen "demand" at the downstream of the chain. Demand, on the other hand, will be limited to fleet vehicles with daily routes and regular refuelling intervals during the introductory stage of a hydrogen economy [9], and therefore designing a demand-driven HSC to fuel the road freight sector with the lion's share of the overall freight-related emissions is of prime relevance, although largely missing from the existing literature. To tackle these limitations this project made the following key contributions:

- To provide fist-hand managerial and policy making insights for a phased transition to a hydrogen-based economy for the road freight sector, this project developed a two-stage demand-driven supply chain design for hydrogen-fuelled road freight transport of the future, unifying centralised and on-site production decisions into a single optimisation framework.
- Existing and anticipated techno-economic hydrogen production and storage scenarios in Great Britain (GB) were identified and exercised against the proposed methodology to provide important and unprecedented empirical insights for the GB market.
- State-of-the-art and futuristic technologies for blue and green hydrogen production comprising: (i) Steam Methane Reformer with Carbon Capture, Usage and Storage (SMR with CCUS), (ii) Autothermal Reformer with Carbon Capture and Storage (ATR with CCUS), (iii) Autothermal Reformer with Gas Heated Reformer with Carbon Capture, Usage and Storage (ATR+GHR with CCUS), (iv) Alkaline Electrolysis (A-E), (v) Proton Exchange Membrane Electrolysis (PEM-E) and (vi) Solid Oxide Electrolysis (SO-E) were considered.
- Cost-effective underground hydrogen storage technologies including: (i) Underground Pipe Storage (UG-PS), (ii) Underground Lined Rock Cavern (UG-LRC), and (iii) Underground Salt Cavern (UG-SC) alongside conventional overground storage technologies corresponding to Overground Compressed hydrogen gas tank at 700 MPa (OG-CH2 GT) were included in scenarios.

Details on the proposed methodology, data and results are provided next.

3. Project outcomes and findings

As was discussed above, a two-stage demand-driven supply chain design for hydrogen-fuelled road freight transport is developed that distinctively unifies centralised and on-site production decisions. The proposed model is a very useful tool for deriving important managerial and policy making insights and can be simply adapted to incorporate many different scenarios and demand settings. In this section we present the method and data, and the key findings and takeaways from its application in understanding the economics of hydrogen utilisation for land-based freight transport in GB.

3.1. Setting the problem

The centralised HSC is composed of four key elements corresponding to production, storage, transportation and distribution. Hydrogen can be produced from non-renewable energy sources such as natural gas, coal and petroleum through technologies like SMR, or from renewables such as electricity generated from solar and wind for water electrolysis. Hydrogen production can take place at the site of the primary energy source required, or away from it, and in the latter case the required energy source must be transported to the production site. While production from renewable sources can be assumed net-zero, hydrogen production through non-renewables contributes significantly to carbon emissions, and as such Carbon Capture and Storage (CCS) technologies are required at the production point. Produced hydrogen at the production site can be in Liquid Hydrogen (LH2) or Compressed-gaseous Hydrogen (CH2) physical forms, or if required, it can be conditioned to a preferred physical form for its transportation and storage. The production capacity and cost vary with production technology, but currently hydrogen SMR is the most mature technology for hydrogen production at scale.

Once centrally produced, hydrogen must be transported to a local or regional hydrogen storage site, where it is stored to address immediate local and regional demand, or to meet demand and supply fluctuations and buffer against plant interruptions [10]. Different underground and overground hydrogen storage technologies can be established depending on the physical form of the hydrogen to be stored (i.e., LH2 or CH2). The size of the storage facility, on the other hand, depends on the size of the demand that the facility must satisfy and the assumed period for accommodating demand and supply fluctuations. Hydrogen transportation between feedstock, production, storage and Refuelling Stations (RSs), on the other hand, can take place using different transportation modes such as tube trailers, railway tube cars, pipeline, tanker trucks and railway tanker trucks [11] depending on the physical form of hydrogen, infrastructure availability and transportation distances. Each transport mode offers different trade-offs between flow rates and capital and operational costs.

The strategic design of central HSC is, therefore, concerned with establishing hydrogen production, storage and transportation infrastructure, such that the entire hydrogen demand is satisfied, and the total cost (capital and operational) of the supply and demand chain is minimised.

Unlike centralised hydrogen production, on the other hand, in on-site hydrogen production, hydrogen is produced where it is demanded (i.e., at an RS) and as such several elements of the centralised HSC discussed above pertaining to bulk storage, transport and distribution are eliminated. The main trade-off between off-site and on-site production is, therefore, due to the production scale and storage and transport costs[1].

Given the above description, the HSC strategic network design is primarily concerned with determining the location, number, technology, and size of different production and storage facilities, establishing sufficient and cost-effective transportation modes to link facilities, and deciding the production rate, average stored inventory, and flow rate of hydrogen [12], such that the total cost (comprising the capital and operational cost) of the entire chain is minimised.

3.1. The methodology

The optimal design of the HSC network is essentially demand-dependent. In the proposed two-stage methodology presented in this section and illustrated graphically in Figure 1, over the first stage of demand modelling, existing HDV fleet data is analysed to derive potential sites for hydrogen refuelling stations, and then a specialised look-ahead set covering optimisation model is developed and used to determine optimally the location and size of hydrogen refuelling stations. This will have significant implications with regard to on-site hydrogen production decisions made in the second stage modelling for HSC network design.

Once optimal site and size of CH2 RSs are identified through the first stage of demand-modelling, the second stage focuses on the optimal configuration of the HSC components pertaining to (centralised/on-site) production, storage, and transportation on the basis of the spatially-explicit demand identified in stage-I which is mapped into the grid structure through an intermediate mapping procedure.

As shown in Figure 1, outputs from the first and the second stage modelling feed into the estimated system wide cost of hydrogen-fuelled road freight (the grey parallelogram in Figure 1). This incorporates all capital and operational costs required to convert the existing HDV fleet into hydrogen powered trucks, establishing RSs, and the required production, storage and transport infrastructure for supplying the realised demand.

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[1] Presentation of the formal description of the model and all mathematical expressions is avoided in this report; these will be, however, available in the first journal paper from the project.

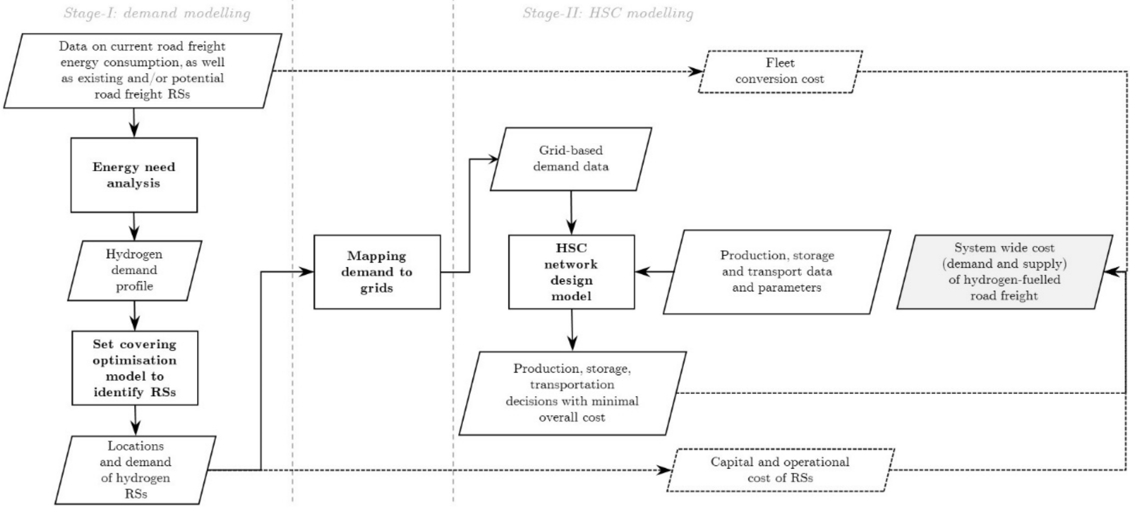


Figure 1 The two-stage optimisation-based methodology

Stage-I of the proposed two-stage optimisation-based methodology consists of two primary phases corresponding to: (i) the HDV energy demand modelling and (ii) the optimal siting of hydrogen RSs. In initiating the first phase, data pertaining to current road freight energy consumption, as well as existing and potential RSs servicing the current diesel HDV fleet are analysed the total potential energy demand for hydrogen in kWh is calculated. HDVs RSs, on the other hand, are predominantly located in warehouses, distribution centres, ports and service stations. Analysing the existing road freight data, a full set of potential RSs, referred to as Candidate Refuelling Facilities (CRFs), is constructed where each CRF is allocated a certain energy demand to be fulfilled over a given period of time, and as illustrated in Figure 1, this is passed onto the second phase of stage-I which entails the optimal siting of hydrogen RSs and their sizing.

Due to the characteristics of the second stage HSC modelling and its interdependence with stage-I, particularly in relation with the on-site production decisions that are made in the second stage, certain complications arise in determining the ‘optimal’ location and size of RSs which are addressed using a look-ahead set covering model for optimal siting and sizing of refuelling stations. This model consolidates CRFs in a way that only an optimal number of RSs are opened from among all CRFs, while the total demand of all these CRFs is satisfied and the cost for potential opening of on-site hydrogen production facilities in the second stage is minimised.

The output from stage-I modelling, is therefore, a set of hydrogen RSs with known locations and demands. These are passed on to the second stage HSC network design, passing through a grid mapping filter. The entire GB is divided into a set of grids of equal sizes (further details in the next subsection) and this procedure determines to which grid each of the identified RSs belongs so that demand-related constraints can be established. These constraints collectively determine the amount of demand within each grid that must be fulfilled through centralised hydrogen production or on-site small scale hydrogen production. These also determine whether centrally supplied demand within each grid is met by local production or through importing hydrogen from other grids.

Production-related constraints, on the other hand, establish mass balance within each grid, ensure that the production rate of each plant is restricted by the number of production facilities established and the minimum and maximum production capacity of the corresponding plant type and size. Storage-related constraints guarantee that safety stock needed to accommodate demand and supply fluctuations is established, and average inventory of hydrogen stored in a storage facility is restricted by the number of storage facilities established and the minimum and maximum storage capacity of the corresponding facility type and size. Finally, transport-related constraints determine the restrictions on the flow rate of hydrogen by each transportation mode between grids.

The objective function of the second stage HSC network optimisation minimises the total daily cost of the chain which is comprised of the capital and operational cost of (on-site/centralised) hydrogen production, storage, and transport.

Next, we discuss the data collected for scenario generation purposes and insight derivation through model application.

3.2. Data

Demand side data analysis procedures, general assumptions and the conversion rates, as well as all data collected and used within the project are available in the Supplementary Document (SD) submitted with this report. This document details the source of the data used and data processing procedures applied for preparing the required modelling data and parameters.

3.3. Analysis set up and optimisation scenarios

The model developed in this research project is quite generic and can accommodate the analysis of many different scenarios to derive important policy making insights. Here, the key influential exogenous decisions that can have a significant impact on the overall configuration of HSC and thus the ultimate cost of getting one kg of hydrogen to RS are presented and a baseline scenario (referred to as SC_0) is put forth. Following this, to analyse the impact of these exogenous decisions, 11 more scenarios are developed for application against the model and insight derivation.

An important parameter in stage-I demand modelling in the proposed two-stage optimisation-based model, which is also a key factor affecting the distribution of demand and the possibility of establishing on-site hydrogen production at RS sites, is the maximal distance that demand allocated to a CRF can be moved and merged with another CRF. This maximal distance value (denoted by MD) determines the coverage of the hydrogen distribution network and has a significant impact on HDVs' ability to refuel. Within the baseline scenario, i.e., SC_0, MD is assumed to be 5 km. Moreover, we assume that the model is operating in its default mode where: (i) both centralised and on-site production options are considered, (ii) full HDV fleet conversion in demand modelling is assumed, (iii) all the 6 production technologies for both blue and green hydrogen production are considered, (iv) decision on where to open facilities is not limited to existing/in-planning hydrogen production and storage sites in GB, and (v) 2050 is considered as the planning year (see Table 1 below). All other scenarios deviate in one or more aspects highlighted in Table 1 from the baseline scenario SC_0. For example, unlike the baseline scenario which considers both on-site and centralised hydrogen production decisions simultaneously, SC_5 only considers centralised hydrogen production, which is the case in most of existing body of research.

Table 1. Scenarios settings against the baseline scenario

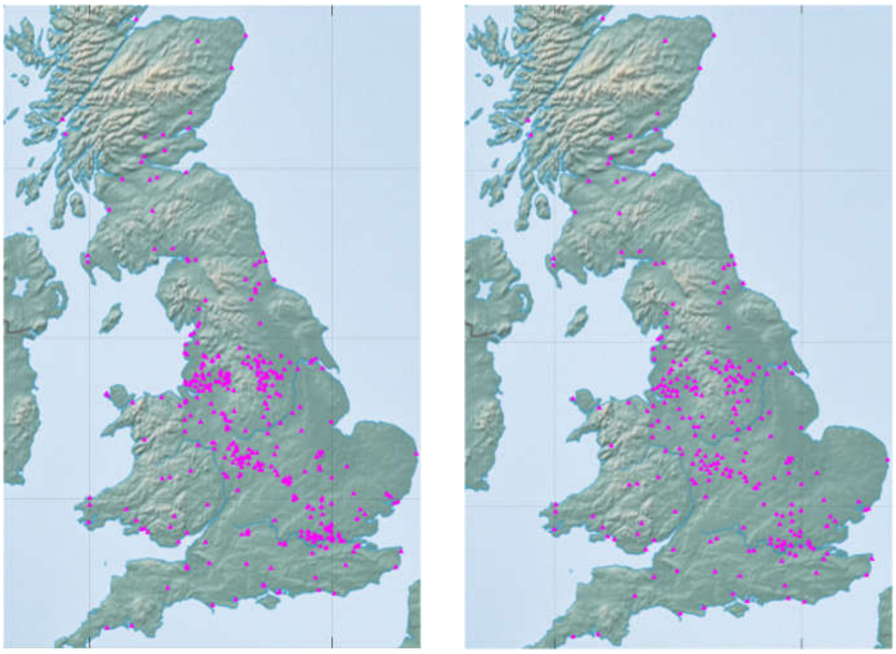
Scenarios	Scenario setting					
	MD	Production options	Fleet conversion	Blue or Green H2?	Site priority	Planning year
SC_0 (baseline)	**5**	**On-site + Centralised**	**100%**	**Both**	**Model decides**	**2050**
SC_1	**2**	On-site + Centralised	100%	Both	Model decides	2050
SC_2	**10**	On-site + Centralised	100%	Both	Model decides	2050
SC_3	**20**	On-site + Centralised	100%	Both	Model decides	2050
SC_4	5	On-site + Centralised	100%	**On-site: Green only – Central: both**	Model decides	2050
SC_5	5	**Centralised only**	100%	Both	Model decides	2050
SC_6	5	On-site + Centralised	100%	**Green only**	Model decides	2050
SC_7	**20**	On-site + Centralised	**20%**	**On-site: Green only – Central: both**	Model decides	2050
SC_8	**20**	On-site + Centralised	**20%**	Both	Model decides	2050
SC_9	5	On-site + Centralised	100%	Both	**Open existing**	2050
SC_10	5	On-site + Centralised	100%	Both	Model decides	**2025**
SC_11	5	On-site + Centralised	100%	Both	Model decides	**2035**

SC_1 to SC_3 allow the investigation of the impact of decreasing RSs coverage by increasing MD. SC_4 enforces that if on-site production is established it should be from a green hydrogen production technology. SC_6, on the other hand, forces the model to pick only green hydrogen production technologies, regardless of whether hydrogen is produced centrally or on-site. SC_7 assumes only 20% penetration of hydrogen HDVs in the fleet with MD = 20. This scenario differs with SC_8 only in terms of on-site production which has to be based on green hydrogen in SC_7. SC_9 is same as the baseline scenario, but here all existing/in-planning hydrogen production and storage sites are first opened. Finally, SC_10 and SC_11 analyse the HSC design for the planning horizons of 2025 and 2035. All these scenarios are exercised against the proposed methodology and results and findings are presented in the next sub-section.

3.4. Results and findings

In this section, we first present the impact of MD selection in demand modelling phase of stage-I in the proposed model, and then results from the baseline scenario are presented. We mainly present a comparison of SC_0 with the scenario that is purely based on centralised hydrogen production, i.e., SC_5 to demonstrate the key added value of the proposed methodology. Following this, results under all other scenarios are briefly discussed.

Figure 3 illustrates the distribution of opened RSs based on the selected MD value. This clearly shows any potential cost reduction due to decreasing MD value deteriorates the network RSs coverage and hence may lead to range anxiety issues in hydrogen HDV operations.



MD = 2
No. RS = 378

MD = 5
No. RS = 275

MD = 10
No. RS = 184

MD = 20
No. RS = 131

Figure 3 impact of MD value on RSs coverage

Under the setting of SC_0, a total capital investment of £3.51 billion is required to establish an HSC that satisfies the total daily demand of 275 RSs for 3,411,259 kg of CH2. Considering the total required investment capital and daily operating cost of the HSC each kg of hydrogen costs the chain £3.13 to be produced, transported, stored, and distributed at an RS pump. Due to the low current output of green hydrogen production technologies, 99% of the produced hydrogen is supplied by blue hydrogen production facilities; particularly 300-MW ATR+GHR with CCUS plants. The remaining 1% is produced by nine 10-MW SO-E facilities. Interestingly, the model decides that 72% of the required hydrogen is produced on-site at RSs and only 28% is centrally produced. In terms of hydrogen storage, the most favourable option turns out to be UG-PS under this scenario which is preferred due to its significantly larger storage capacity compared with overground storage options, although being significantly more costly to establish. In Figure 4, the configuration of the HSC in terms of production facilities and inter-grid transportation is illustrated. In this figure, small blue circles show small on-site blue hydrogen production, and green circles show on-site green hydrogen production. The blue rectangles at the centre of grids 7, 17, 18, 23, 24 and 29 denote centralised blue hydrogen production and arrows going out of these squares to other grids denote inter-grid transportation of the hydrogen produced within these grids.

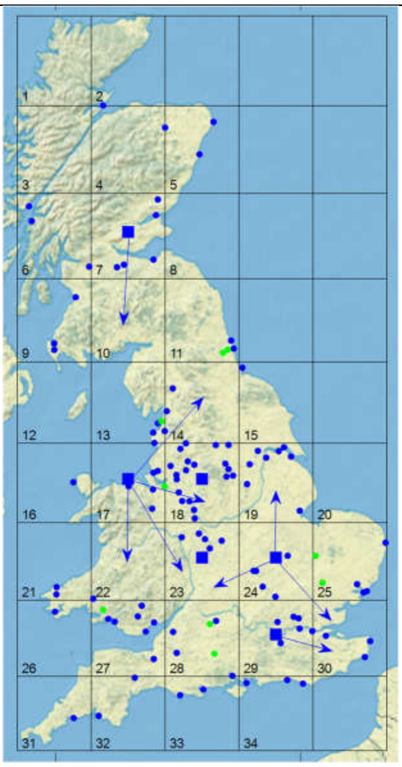


Figure 4 HSC configuration under the setting of SC_0

The optimisation result of all scenarios under different Key Performance Indicators (KPIs) is presented within the SD, in Tables S7 and S8. An interesting comparison from these results would be between the results of scenario S_0 and those of SC_5 which are based on centralised hydrogen production only. Our results suggest that simultaneous consideration of on-site and centralised hydrogen production in HSC network optimisation can lead to over £1.2 billion saving in the total investment capital (i.e., around 27% reduction) and over 17% reduction in the total daily operating cost of the HSC. As was discussed initially and illustrated in Figure 5, this is mainly because of the eliminated need for storage and transport which constitutes a large proportion of capital costs.

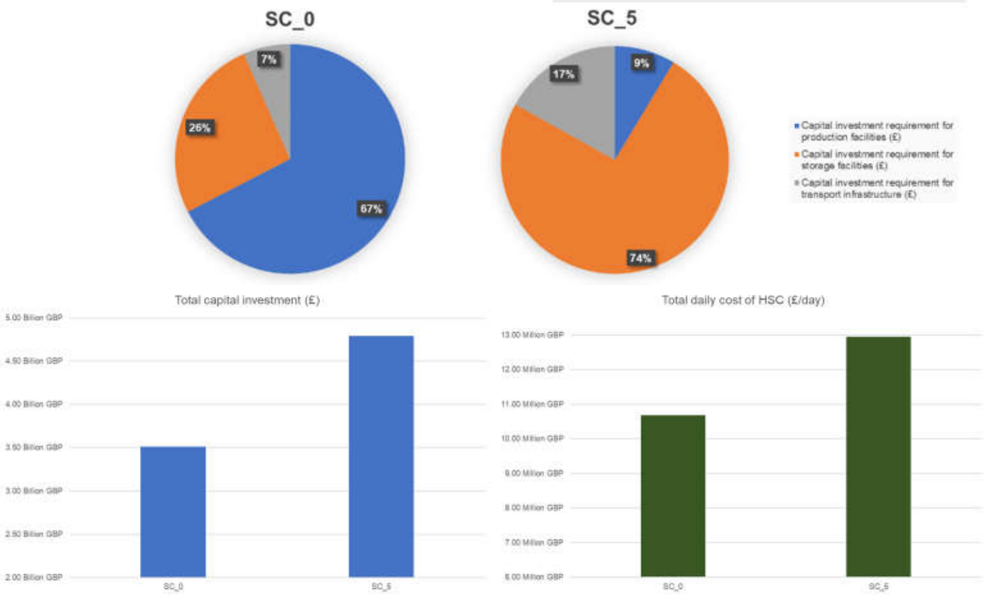


Figure 5 Comparison of results under scenarios SC_0 and SC_5

While our results are significantly sensitive to the assumptions made in our analyses and data, the following summary of insights derived from our optimisation results is worth presenting:

- Assuming the road freight demand for energy figures in 2050 remain similar to that of 2019, with a total capital investment of £3.51 billion the required HSC network to fuel the road freight of the future can be established.

- Converting the total HDV fleet into hydrogen powered HDVs requires around £400 billion investment commitment from freight forwarders. This is the cost for converting a total fleet of 501,500 HDVs[2], each incurring a total cost of ownership of £796,320 [13]. A full conversion of fleet to net zero options, on the other hand, can potentially save trucking companies approximately £2.1 billion in carbon taxes.
- If only 20% of the fleet is converted to hydrogen HDVs by 2050, however, with less than £845 million in capital investment the required HSC can be set up, but this still requires about £80 billion of trucking companies' investment to convert 20% of their fleet.
- In the baseline scenario, 72% of demanded hydrogen is supplied through on-site hydrogen production, and only the remaining 28% is produced centrally and stored and transported to where the need is. On site production, is however, largely based on small blue hydrogen production technologies rather than green hydrogen options.
- Blue hydrogen production is more economically viable in most cases than green hydrogen production due to its current and anticipated economies of scale.
- Producing the total hydrogen required by road freight sector by 2050 through green hydrogen production technologies increases capital cost and total daily cost of the HSC by over 22% and 97%, respectively. This is mainly due to the significantly higher unit production cost of green hydrogen technologies.
- In a centralised HSC network, only 9% of the total capital cost is required for establishing hydrogen production facilities and the rest is spent on bulk hydrogen storage and transportation infrastructure, with bulk storage cost dominating the scene.
- The use of existing UG-LRC and UG-SC can help reduce storage costs significantly.
- 300-MW ATR+GHR with CCUS is the most preferred blue hydrogen production technology, and 10-MW SO-E is the most preferred green hydrogen production technology.

4. Concluding remarks and potentials for follow-on research work

This research project developed a techno-economic model for understanding the economics of hydrogen utilisation for land-based freight transport in GB. Demand-side scenarios representing HDV demand for hydrogen, and the potential network of hydrogen RSs, as well as techno-economic and spatially-explicit scenarios representing situations with hydrogen production and storage in GB were developed and exercised against a two-stage optimisation-based model for linking road freight demand to HSC. The proposed methodology captures the complex interactions among various HSC entities and identifies optimal strategic and operational configurations of the chain within the boundaries of each scenario constraints, and presents a distinctive feature corresponding to the integration of centralised and on-site hydrogen production decisions within a unified framework. Using this tool, first-hand insights regarding hydrogen utilisation by the road freight sector in GB were generated and reported.

Despite the multiple added values and research outcomes generated from the work carried out over this research project, there are some limitations that can be tackled with further related work; below a summary of these limitations and multiple potentials for work in a follow-on project are briefly presented:

- This project made simplifying assumptions with regards to the demand side scenarios pertaining to the refuelling needs of the future hydrogen powered HDV fleet. In the most likely future ecosystem of hydrogen trucks, hydrogen refuelling and battery recharging capabilities must develop hand-in-hand; in the most successful prototype hydrogen truck technologies currently being demonstrated (e.g., Tevva trucks[3]) hydrogen and batteries work in tandem, and fuel cell only operates at a constant, efficient power setting to feed the necessary additional energy needed to supplement the grid-charged battery. A careful development of a network of refuelling facilities (especially at ports) where all these complications are factored in, and demand is accurately identified and planned for is a future research necessity.
- In the analyses carried out in this project, only tube trailers were considered for hydrogen transportation between production, storage and distribution facilities; however, the proposed model can be extended in a follow-on work to include other possible modes of transportation such as railway tube cars, pipeline, tanker trucks and railway tanker trucks. In particular,

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[2] Based on "domestic road freight statistics 2019" data from DfT available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/898747/domestic-road-freight-statistics-2019.pdf

[3] https://www.tevva.com/technologies/

inclusion of scenarios based on the existing pipeline network in the UK and further future investments to exploit the trade-off between flow rate and capital/operational cost could be of great interest.

- Results from this research imply that converting the fleet at the current cost of fuel cell vehicle technologies requires a significantly large level of investment commitment, that unlike HSC infrastructure development decisions cannot be made centrally. This research project was mostly concerned with strategic and high level decision making support, and further research work may be initiated to focus further on the demand side and zoom in on operational level of HDV activities to identify technoeconomic requirements to accelerate hydrogen HDVs adoption by logistics and develop economically viable pathways for gradual conversion of the freight fleet.
- It was assumed that any identified RS can be a candidate site for on-site hydrogen production by setting up a small blue/green hydrogen production plant. Also, it was assumed any hydrogen production technology of any size can be established within any of the grids. Future work can feed further scrutinised and spatially-explicit scenarios into the proposed model for obtaining more reliable outputs.
- In the snapshot model proposed in this work, fleet conversion was assumed with a jump to 20% or 100% conversion ratios; however, conversion and hence increase in demand occur at a much more gradual rate in reality and extending the proposed model to enable planning over a rolling horizon would yet provide further insights.
- Future work can use the proposed methodology to carry out further sensitivity analysis to make more technology and efficiency explicit advice to attain certain levels of incurred capital and operational costs.
- The tool proposed in this research project was coded and implemented in an optimisation software. This can be further tailored and presented to stakeholders and policy makers (e.g., the DfT) in the form of a user-friendly, stand-alone Decision Support System (DSS) dashboard to help reinforce high-level decision making and designing.

References

1. Ng, W.-S., *Enhancing Sustainability of Freight Transport*, in *ESCAP Ninth Meeting of the Working Group on the Asian Highway*. 2021: Bangkok, Thailand.
2. Transport and Environment, *Too big to ignore – truck CO2 emissions in 2030*. 2015: Available at: https://paperzz.com/doc/6837503/too-big-to-ignore-%E2%80%93-truck-co2-emissions-in-2030.
3. Nunes, P., et al., *Design of a hydrogen supply chain with uncertainty.* International Journal of Hydrogen Energy, 2015. 40(46): p. 16408-16418.
4. Kim, M. and J. Kim, *Optimization model for the design and analysis of an integrated renewable hydrogen supply (IRHS) system: Application to Korea's hydrogen economy.* International Journal of Hydrogen Energy, 2016. 41(38): p. 16613-16626.
5. Li, L., H. Manier, and M.A. Manier, *Hydrogen supply chain network design: An optimization-oriented review.* Renewable and Sustainable Energy Reviews, 2019. 103: p. 342-360.
6. Gim, B. and W.L. Yoon, *Analysis of the economy of scale and estimation of the future hydrogen production costs at on-site hydrogen refueling stations in Korea.* International Journal of Hydrogen Energy, 2012. 37(24): p. 19138-19145.
7. Katikaneni, S.P., et al., *On-site hydrogen production from transportation fuels: An overview and techno-economic assessment.* International Journal of Hydrogen Energy, 2014. 39(9): p. 4331-4350.
8. Almansoori, A. and N. Shah, *Design and operation of a future hydrogen supply chain: Snapshot model.* Chemical Engineering Research and Design, 2006. 84(6 A): p. 423-438.
9. Almansoori, A. and N. Shah, *Design and operation of a future hydrogen supply chain: Multi-period model.* International Journal of Hydrogen Energy, 2009. 34(19): p. 7883-7897.
10. Han, J.H., J.H. Ryu, and I.B. Lee, *Multi-objective optimization design of hydrogen infrastructures simultaneously considering economic cost, safety and CO2 emission.* Chemical Engineering Research and Design, 2013. 91(8): p. 1427-1439.
11. Seo, S.K., D.Y. Yun, and C.J. Lee, *Design and optimization of a hydrogen supply chain using a centralized storage model.* Applied Energy, 2020. 262.
12. Almansoori, A. and N. Shah, *Design and operation of a stochastic hydrogen supply chain network under demand uncertainty.* International Journal of Hydrogen Energy, 2012. 37(5): p. 3965-3977.
13. Munshi, S., Garner, G., Theissl, H., Hofer, F., & Raser, B., *Total Cost of Ownership (TCO) Analysis for Heavy Duty Hydrogen Fueled Powertrains.* Online: https://wfsinc.com/file_library/files/wpt-wfsinc/20201225_Westport_AVL_Whitepaper_Hydrogen_HPDI_final.pdf, 2021.