FINAL REPORT

NETWORK-H2
CALL 4 - Analysis of a Strategic Hydrogen Refuelling Infrastructure (ATHENA)

PROJECT DETAILS

Grant number

NH2-002

Award holding organisation

Organisation	Heriot-Watt University

Title of research project

Analysis of a Strategic Hydrogen Refuelling Infrastructure

Investigators

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Grant number

NH2-002

Final Project Report

Executive summary

With the pressured timescale in determining effective and viable net zero solutions within the transport sector, it is important to understand the extend of implementing a new refuelling infrastructure for alternative fuel, such as hydrogen. The purpose of this project is to analyse freight logistics data and determine the geographic location and capacity of the hydrogen refuelling infrastructure required to serve the specified region. The ATHENA framework entails three components which encapsulates the analyses of freight logistics data in estimating the freight refuelling demand and incorporates an optimisation model in determining the hydrogen refuelling network design with an agent-based model simulating the system. The framework is implemented to the NP11 region in Great Britain. During the data analysis phase, the heavy goods vehicle demand is geographically mapped with 14 current refuelling sites identified as possible locations for hydrogen refuelling stations in the rollout phase and 200 current refuelling sites for the mature phase. In the optimisation model, the number of hydrogen refuelling stations with their locations and capacities are provided and for each the supply configuration between on-site and/or off-site hydrogen production supply is determined. Analysis is performed in calibrating parameters and investigating the on-site and off-site production supply alternatives. It is concluded that the system optimality is limited by the feasible number of tube trailer deliveries per day which suggests an opportunity for alternative delivery methods. In the agent-based model, the trade-off between savings and unserved demand is considered when calibrating the required size of a hydrogen refuelling station. The approaches utilised in the study may contribute to further research relating to the deployment of hydrogen refuelling infrastructure. This may serve to inform and support decisions of policy makers, practitioners, technology providers, energy suppliers and other role-players.

1. Introduction

In realising the commitment of the UK towards net zero emissions by 2050, the implementation of cleaner energy sources is critical. The transportation sector is currently the largest emitting sector in the UK and in 2019 it was accountable for 27% of the net greenhouse gas emissions in the country [1]. Within this sector, the advances of innovative fuel solutions, such as hydrogen, biofuels and electricity, therefore plays a significant role. The adoption towards such a strategy, however, is often seen as a challenge in having to consider both the vehicle commercialisation as well as the refuelling infrastructure which may be required to serve the former.

Heavy goods vehicles (HGVs) attributed to an estimated 17% of road transport greenhouse gas emissions in the UK during 2019 [1]. The Road to Zero [2] strategy, as set out by the UK government in 2018, aspires towards the deployment of zero emission HGVs in the long term. The strategy emphasises the value of analysing net zero emission technologies in determining a viable solution for HGVs on the UK road network. Hydrogen fuel cell technologies, although there is a current the lack of infrastructure, may be considered favourable in HGVs when compared to electric battery alternatives due to the advantage of higher driving range and lower refuelling time [3]. In working towards a solution of hydrogen fuel cell HGVs, it is critical to assess the deployment of a hydrogen refuelling structure.

The Northern Powerhouse 11 (NP11) constitutes eleven Local Enterprise Partnerships across Northern England. In 2017, their economy was more carbon intensive than the average for regions in England and the opportunity for developing underutilised assets, such as hydrogen, was identified [4]. With the NP11's aim to transform energy assets in a drive towards clean growth, there is a need to better comprehend the infrastructure requirements for the deployment of hydrogen corridors.

To further the implementation of hydrogen for freight, it is critical to gain an understanding of the investment required for the hydrogen refuelling and distribution networks. Hydrogen cost competitiveness typically depends on various aspects, such as the ability to scale in size and application, as well as the usage of existing pipelines, although it is only considered to reach competitiveness by 2030 [5]. In analysing economic feasibility for hydrogen refuelling corridors, it is necessary to determine the number of hydrogen refuelling stations (HRSs) required to serve the road freight demand along with the capacity per station. Furthermore, various hydrogen delivery and dispensing strategies should be considered.

The research project entitled The ATHENA project: "Analysis of a Strategic Hydrogen Refuelling Infrastructure" was funded by the Engineering and Physical Sciences Research Council under the Network-H2: "A network for hydrogen-refuelled transportation" grant (EP/S032134/1). The research project commenced on 1st August 2021 and was completed on 31 March 2022. The aim of the project is to analyse strategic freight corridors to determine and recommend hydrogen refuelling infrastructure configurations for effective deployment. The geographic focus of the research is primarily on the NP11 region in the north of England.

The framework proposed in this project aims to address the following questions:

- What are the refuelling demands for heavy goods vehicles (HGVs) along the corridors?
- What is the minimum number of hydrogen refuelling stations (HRSs) required to serve the refuelling demand?
- What are the geographic locations and capacities of each of the HRSs required?
- What is the best hydrogen dispense and delivery model to follow?

The key objectives of the project in addressing these questions are as follows:

Objective 1: To clean, synthesise and analyse existing road freight logistics data in mapping the current refuelling demand of HGVs along the strategic corridors

Objective 2: To develop a model with various constraints in determining the minimum number of HRSs and the capacity per station required to serve the refuelling demand for HGVs along the strategic corridors

Objective 3: To perform experiments and scenario analyses considering various hydrogen delivery and dispensing methods for an economic analysis of the hydrogen infrastructure

Finally, the work packages completed in addressing the research questions and fulfilling the objectives are as follows:

Work Package 1: Data analysis in mapping current HGVs refuelling demand
Work Package 2: Design, test and implementation of model
Work Package 3: Model experimentation and analysis
Work Package 4: Economic analysis

Data analysis and quantitative modelling techniques, including optimisation and computer simulation modelling, are applied in achieving these objectives. The remainder of this report encapsulates the proposed ATHENA framework and provides a description of the research performed during each phase of the framework with specific reference to the work packages, which is followed, in a conclusion, by a discussion on the key contributions and the impact of the study.

2. The ATHENA framework

The ATHENA framework, as outlined in Figure 1, illustrates the research methodology exercised in addressing the research questions and objectives in ultimately determining an optimised and validated network design for hydrogen refuelling infrastructure.

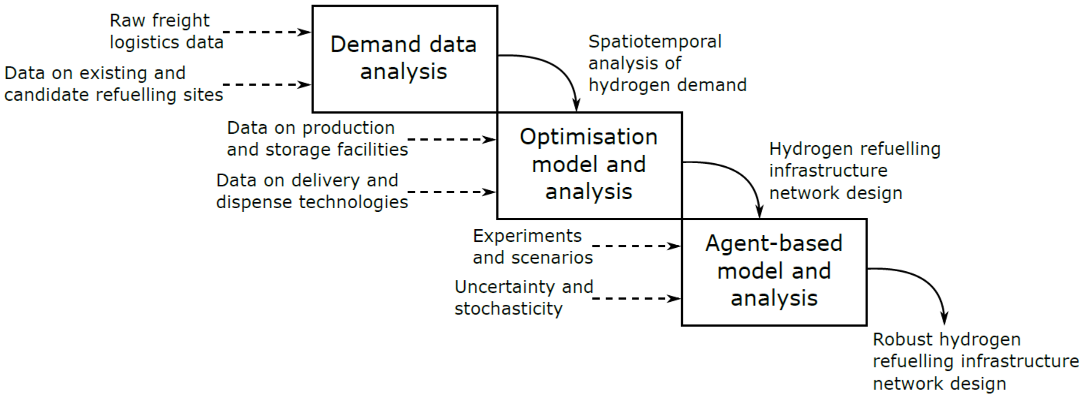


Figure 1: The ATHENA framework.

The first phase, namely *Demand data analysis*, is captured in Work Package 1 in which data pertaining to the freight movement for strategic corridors, such as HGV logistics flow data and historic refuelling trends as well as data on existing and candidate refuelling sites, are utilised as input in developing an analysis of the current fuel demand for HGVs along these corridors. The outcome from this phase is a spatiotemporal analysis of the freight fuel demand in terms of hydrogen. This serves as input to the second phase of the ATHENA framework, *Optimisation model and analysis*, which aligns with Work Packages 2, 3 and 4. An optimisation model based on minimising cost is developed with the ability to minimise the number of HRSs required, while determining the location and capacity of each HRS, as well as the configuration of the supply of hydrogen to each HRS. Input data required relate to the production, storage and delivery of hydrogen with specific consideration to the cost factors. Model analyses are performed which include sensitivity analyses and parameter variation. The outcomes from this phase entail (i) a validated optimisation model for a hydrogen refuelling infrastructure network design underpinned by minimising the costs, (ii) the model output (*i.e.* a hydrogen refuelling infrastructure network design), and (iii) an analysis of the model output. The model output then serves as input to the third and final phase of the ATHENA framework, *Agent-based model and analysis*, which similarly to the second phase, aligns with Work Packages 2, 3 and 4. An agent-based model is developed to test different experiments and perform further analyses in validating the hydrogen refuelling infrastructure network design. The outcomes of the final phase include (i) a validated agent-based model for analysing a hydrogen refuelling infrastructure network design and (ii) a robust hydrogen refuelling infrastructure network design.

3. The ATHENA framework applied to the NP11 region

The NP11 region is the area under investigation in this project and the ATHENA framework is applied in identifying a hydrogen refuelling infrastructure network design. For this project, two instances in time are considered – the rollout phase (estimated at 2027) and a more mature phase (estimated at 2040). A list of further modelling assumptions is provided in Appendix A[1].

3.1 Phase 1: Demand data analysis

The first phase of the ATHENA framework corresponds with Work Package 1 and addresses Objective 1 of the project. Data is collected from various publicly available sources on the total GB fuel demand, the location and sizes of 1765 warehouse facilities in GB [6][2], the locations and types of 291 service stations in GB [7, 8], as well as the locations of 53 ports in the United Kingdom (UK) [9]. It was found that during 2019, the diesel fuel demand for HGVs in the UK was exceeding 5.7 billion litres [10]. This value is translated to an energy demand (in kWh) and finally converted to a hydrogen demand (in kg) which is estimated at 1.599 billion kg, as shown in Table 1.

Table 1: The demand of HGVs in GB as per 2019 data, translated from diesel and hydrogen.

DATA FEATURE	VALUE
GB annual HGV diesel fuel demand (litres)	5,711,150,000
GB annual HGV hydrogen fuel demand (kg)	1,599,281,928

The datasets on the current HGV demand sites, i.e. warehouses, service stations and ports, are cleaned and filtered to only include warehouse facilities greater than a certain size, HGV type service stations and demand sites located in GB. The final combined dataset for GB includes 382 warehouse facilities, 111 service stations and 48 ports. This dataset of 541 demand sites is filtered for the NP11 region and the final combined dataset for the NP11 includes 158 warehouses, 43 service stations and 12 ports.

The annual hydrogen fuel demand in GB is initially distributed amongst all of the GB demand sites based on certain assumptions. First, according to the Petrol Retailers Association [11], it is estimated that 75% of the current diesel demand for HGVs are fulfilled at warehouses. Secondly, a correlation is assumed between the size of a warehouse and its demand. Finally, the remaining 25% of demand is assumed to be equally divided between the set of service stations and ports, and within each set the demand is also equally distributed. The demand distribution is further refined for the NP11 region based on HGV logistics data. Data was provided by Transport for the North [12] on the HGV actual flow on the various corridors in the north of England, as illustrated in Figure 2.

[1] The formal description and mathematical formulation of the model is not included in the report and will be documented within an academic article emanating from the research project.
[2] For the purpose of this project, warehouse facilities, distribution centres and similar facilities are collectively referred to as warehouses.

This dataset is used to calculate a popularity estimate for each demand site based on the actual HGV flow data within a certain radius of the demand site. The popularity estimates are geographically shown in Figure 3.

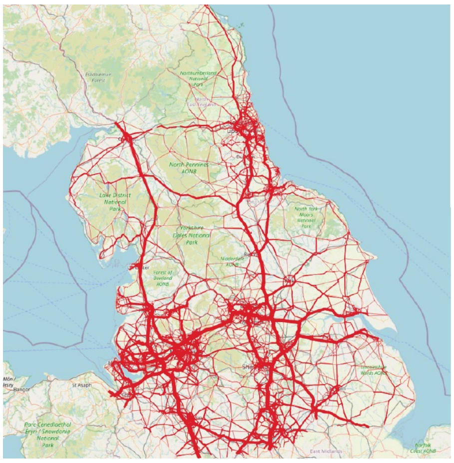


Figure 2: The HGV actual flow data for the NP11 region.

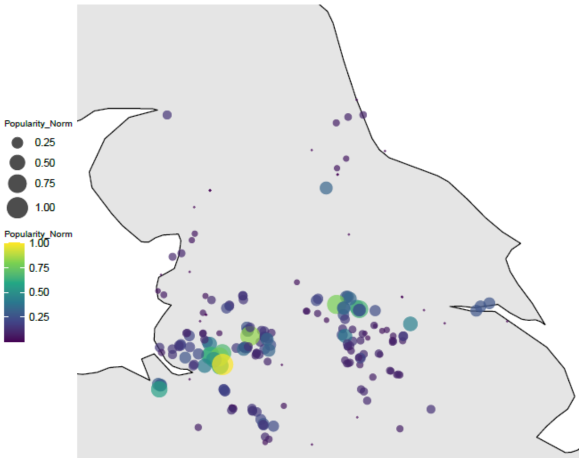


Figure 3: The popularity estimates for the demand sites in the NP11 region.

The demand amongst the demand sites in the NP11 region is redistributed based on the assumptions of correlation with demand and site type, the size and popularity estimate of warehouses, as well as the popularity estimate of service stations and ports. The demand distribution amongst the demand sites in the NP11 region is illustrated in Figure 4 and the value distribution of the daily demand amongst these demand sites are shown in Figure 5. The average daily demand amongst the demand sites is 8,394 kg, with the minimum and maximum daily demand noted as 86 kg and 38,081 kg, respectively.

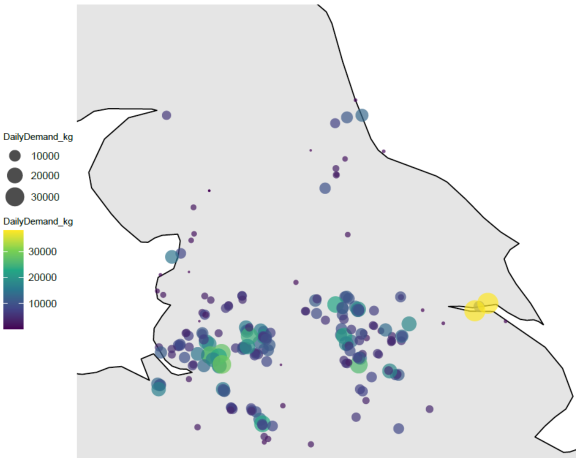


Figure 4: The refined distribution of demand amongst demand sites in the NP11 region.

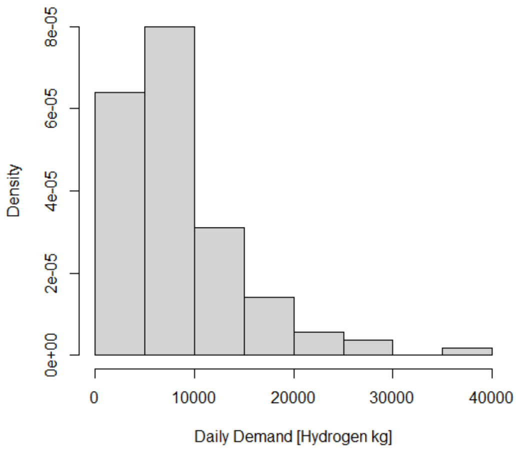


Figure 5: The distribution of the daily demand of hydrogen per refuelling station for the NP11 region.

Note this demand distribution portrays the case where the total HGV demand is converted to hydrogen. For the rollout phase, it is estimated that the demand converted to hydrogen will be 0.1%, whereas in the mature phase, the hydrogen demand will be 50% of the total demand. The demand data is further refined, especially for the rollout phase, where demand is clustered to provide a more realistic representation of the demand at that time. Within the clustered set of demand sites, the rollout phase contains 14 demand sites, while the mature phase contains 200 demand sites.[3]

This concludes the first phase of the ATHENA framework in fulfilment of Work Package 1 and addressing Objective 1 of the project, where an analysis of the HGV freight fuel demand was performed for the specific region under consideration.

3.2 Phase 2: Optimisation model and analysis

The second phase of the ATHENA framework focuses on optimising the number of HRSs required, while determining the location and capacity of these HRSs to fulfil the demand, and optimising the supply of

[3] The set of demand sites refined for input to the optimisation model is included in the Appendix B.

hydrogen to these HRSs. This phase aligns with Work Packages 2, 3 and 4, while addressing Objectives 2 and 3 in the project.

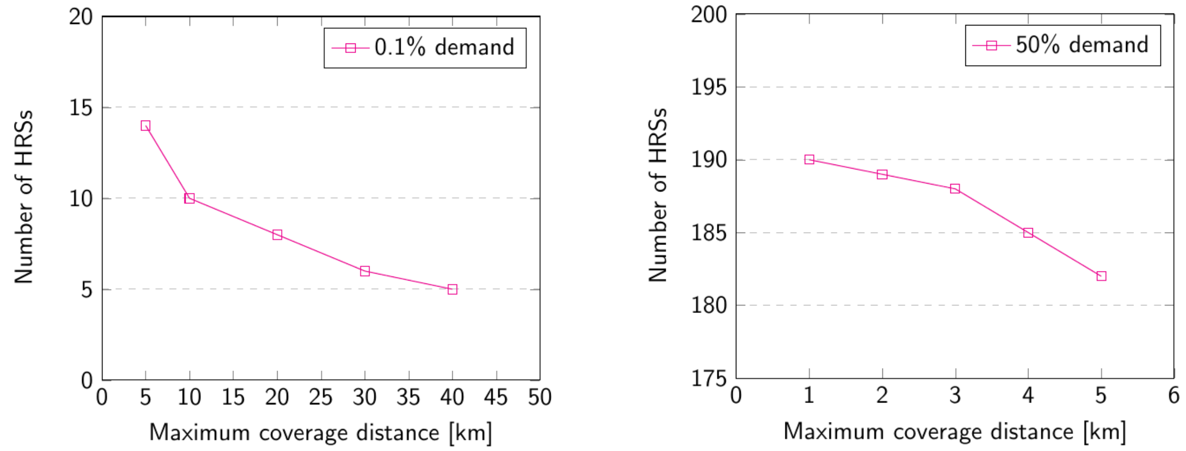
After having identified the location and size of the demand sites within the geographical area under consideration, it is important to consider the layout of the hydrogen refuelling network and the options for supplying of hydrogen to these HRSs. Research has been performed in the configuration of the hydrogen refuelling network and determination of HRS locations, although it remains critical in the deployment of effective hydrogen refuelling infrastructure (refer to Lin et al. [13] for a review of HRS location models). With respect to the supply of hydrogen to HRSs, hydrogen can be produced at a central production from which it may be stored and transported to the HRS (*i.e.* off-site production) or it can be produced locally at the HRS (*i.e.* on-site production) [14]. For the purpose of this project, both off-site and on-site production is considered. In the case of off-site production, the transportation of hydrogen in gaseous from by means of tube trailers are assumed.

The objective of the optimisation model developed is to minimise the overall cost. The cost model includes three primary elements relating to the HRS, as well as the off-site production and on-site production supply of hydrogen. The costs relating to an HRS includes a fixed setup cost and unit cost, while for the off-site production supply of hydrogen the transportation cost and unit production cost is considered, and for the on-site production supply of hydrogen the fixed setup and unit production cost is included. In addition to the objective function, the model consists of a set of decision variables (for which the values of these variables are provided as output by the model) and a set of constraints to which need to be adhered to in determining the decision variables with the aim of minimising the overall cost. The decision variables include identifying which of the demand sites are selected as HRSs, the estimated daily demand of these HRSs and then, for each HRS, whether hydrogen should be supplied from on-site and/or off-site production, as well as the quantities of hydrogen to be supplied by either option. Additionally, if on-site production is selected, the size of electrolyser (based on a provided selection) is provided and, if off-site production is selected, the number of deliveries required along with the specific off-site production facility from which the hydrogen will be supplied are provided. In minimising the number of HRSs, the model allows for the demand over more than one demand site to be aggregated if within a specific coverage distance from one another based on the set covering approach [15]. The primary modelling constraints include a maximum coverage distance governing the aggregation of demand between demand sites, a maximum capacity for an HRS (such that the aggregated demand does not exceed this capacity at an HRS), and maximum production capacities for both on-site and off-site production facilities. Furthermore, all of the demand needs to be satisfied by the set of HRSs and all of the allocated demand to HRSs need to be supplied by either on-site or off-site hydrogen production. An additional modelling constraint which may be relaxed is a maximum number of tube trailer deliveries per day.

For the application of the optimisation model to the NP11 region, data on the centralised production facilities are collected, along with data relating to the cost factors and the capacities of both on-site and off-site production. Five centralised production facilities are identified primarily within the Teesside, Humber, Leeds, Merseyside areas. For both the rollout and mature phases, green hydrogen production is assumed at these facilities with no limitation to the production capacity. In the case of on-site production, the options of 1MW, 5MW, 10MW, 30MW and 50MW electrolysers are considered.

In Experiment I, a parameters variation is performed in which the maximum coverage distance parameter for both the rollout and mature phases are varied. The output for Experiment I is summarised in Figure 6 where (a) refers to the rollout phase and (b) refers to the mature phase[4]. In the rollout phase the maximum coverage distance is varied from 5 to 50 km, while in the mature phase this distance is varied from 1 to 5km. In both cases, the number of HRSs decreases in a non-linear fashion as the maximum coverage distance increases. The maximum coverage distance parameter is calibrated and, after consultation, the base case in the rollout phase is set to 20km with the base case in the mature phase is set to 2km.

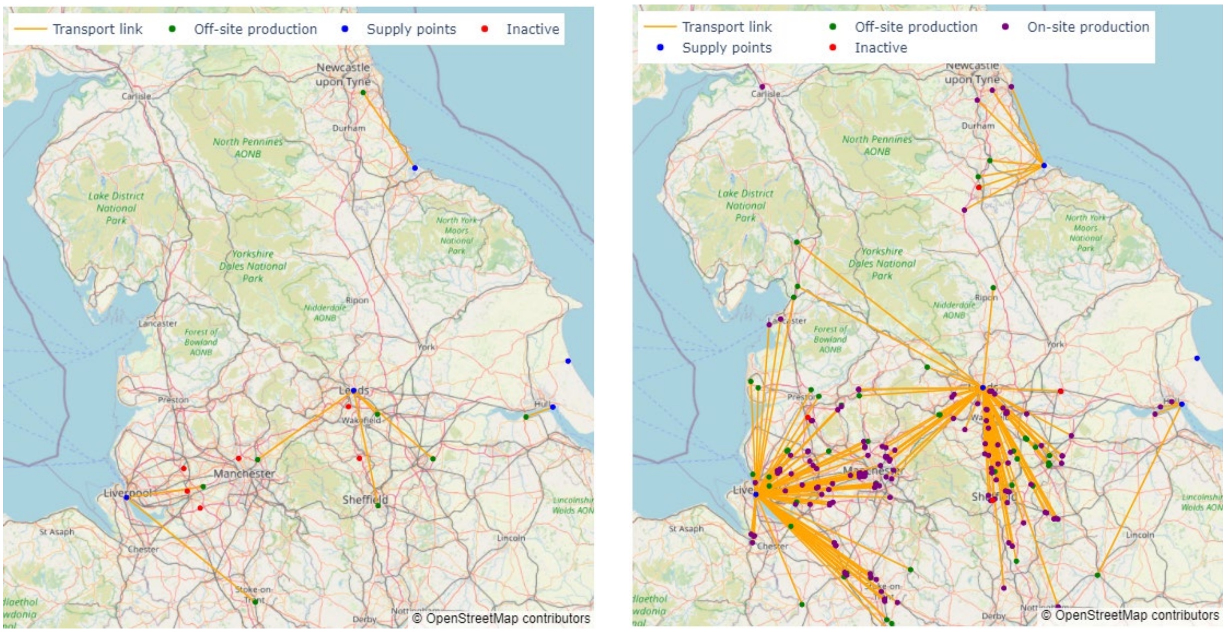
[4] The optimisation model output for Experiment I is included in Appendix C.



(a) Rollout phase *(b) Mature phase*

Figure 4: Parameter variation of the maximum coverage distance and the demand for the rollout and mature phases.

The optimisation model output for the base case of the rollout and mature phases are geographically illustrated in Figure 7. The red icons indicate inactive demand sites that are not activated as HRSs, while the green and purple icons indicate HRSs with off-site and on-site production supply, respectively. The blue icons represent the centralised production facilities, and the orange lines indicate the transportation link between HRSs and centralised production facilities. Note that the case where an HRS requires both on-site and off-site production supply is illustrated where a purple icon is linked by an orange line to a centralised production facility.



(a) Rollout phase *(b) Mature phase*

Figure 5: The optimisation model output with a map of the different demand sites indicating which are active as HRSs, the type of supply production and the transportation link for off-site supply from the centralised production facilities.

In the rollout phase, there are 8 HRSs which make use of off-site hydrogen production supply, while in the mature phase, there are 189 HRSs of which 1% uses on-site hydrogen production supply, 24% uses only off-site hydrogen production supply and the remaining 74% uses both on-site and off-site hydrogen production supply. This high percentage of combined supply is due to certain binding constraints in the optimisation model which is further investigated.

In Experiment II, the on-site and off-site production alternatives in the mature phase is further explored. In Experiment II (A), the model only allowed on-site production supply by not allowing any tube trailer deliveries to HRSs, while in the Experiment II (B) there is no limitation to the number of tube trailer deliveries to HRSs. In Experiment II (A), the overall costs increased from the base case by 18.11%, whereas in Experiment II (B) the overall cost decreased from the base case by 31.44%. In the latter, however, the average number of tube trailer deliveries per day per HRSs exceeded nine which is not necessarily viable[5]. This indicates that the system optimality is limited by the feasible number of daily deliveries, which motivates the implementation of alternative delivery methods, such as pipelines. In Experiment III, the effect of on incrementally increasing number of daily deliveries allowed per HRS is investigated with consideration to the portion of HRSs across the different supply options. The analysis is shown in Figure 8 with the average number of daily deliveries per sub-experiment indicating a non-linear increase[6]. This suggests that in the case with no limit on the maximum number of deliveries, the majority portion of HRSs will have off-site production supply, however, there will still be a portion with on-site production supply.

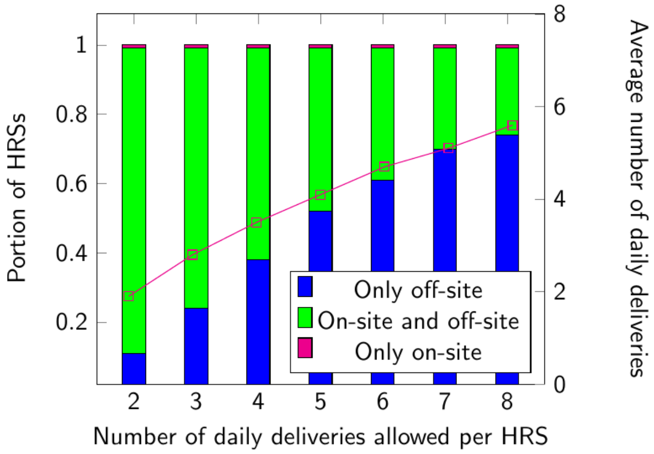


Figure 6: The effect of an increasing number of daily deliveries allowed per HRSs.

This concludes the second phase of the ATHENA framework in partial fulfilment of Work Packages 2, 3 and 4 addressing Objectives 2 and 3 in the project, where an optimisation model was designed, tested and implemented, followed by model experimentation and analysis with economic insight provided.

3.3 Phase 3: Agent-based model and analysis

The final phase of the ATHENA framework entails an agent-based model and analysis in which the output from the optimisation model is further analysed. This phase, similar to the second phase, aligns with Work Packages 2, 3 and 4, and addresses Objectives 2 and 3 in the project.

The agent-based model allows for the operational aspects to be modelled and, where the optimisation model considered a deterministic demand, the agent-based model has the ability of capturing the stochastic nature of refuelling demand which reflects reality more accurately. The simulation model incorporates HRSs, production facilities and tube trailers as agents and simulates the hydrogen production, storage and dispense with the output of the optimisation model as input. A reorder policy is developed in the case of off-site hydrogen production supply where an HRS requires tube trailers to replenish hydrogen from a centralised production facility. Furthermore, each HRS is modelled to serve a stochastic demand profile which simulates the real-world demand from end-users throughout the day.

The size of the storage at an HRS directly influences the cost and therefore it is necessary to determine the size of the storage required in relation to the demand at the HRS. An analysis is performed within the agent-based model to investigate the effect of the storage size on the cost and hydrogen demand. The optimisation model provides an upper bound defined as the baseline scenario where there is no unserved demand. The HRS capacity is varied as a percentage of the daily demand from 100% to 50% in increments of 10% with the key performance indicators the percentage savings in HRS costs and the percentage unserved demand, as shown in Figure 9. As the capacity of an HRS is decreased, there is an increase observed in both the HRS cost savings and the unserved demand which represents a trade-off between these two factors.

[5] The optimisation model output for Experiment II is included in Appendix C.
[6] The optimisation model output for Experiment III is included in Appendix C.

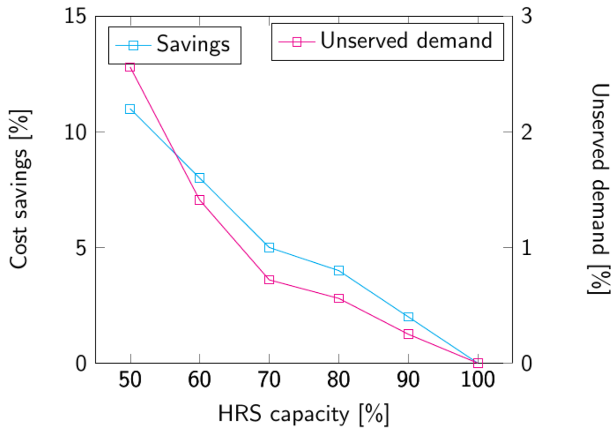


Figure 7: The effect of decreasing the capacity of an HRS on the cost and unserved demand.

This concludes the final phase of the ATHENA framework, in fulfilment of Work Packages 2, 3 and 4 addressing Objectives 2 and 3 in the project, where an agent-based model is developed with the ability to perform scenario analyses of the hydrogen refuelling infrastructure network design.

4. Key contributions and research impact

The ATHENA project made the following key research contributions:

- A novel framework encapsulating three key phases in delivering a robust hydrogen refuelling infrastructure network design.
- A methodology for identifying and geospatially mapping the hydrogen demand for a given area incorporating the logistics flow data for the case where granular data are inaccessible.
- A novel optimisation model which provides the minimum number of HRSs with their locations and capacities while further providing the supply configurations (*i.e.* on-site or off-site production) for each of the HRSs in minimising the overall costs.
- An agent-based simulation model which allows for the incorporation of stochasticity and modelling of operational decisions within the hydrogen refuelling infrastructure.
- A recommended hydrogen refuelling infrastructure network design for the rollout and mature phases with the cost implications for the case of the NP11 region with analyses performed.

The ATHENA framework may inform and support decisions of policy makers, practitioners, technology providers, energy suppliers and other role-players with respect to hydrogen strategies and infrastructure investments. The project has successfully led to further research projects which are addressing aspects not considered in this project, such as the additional of pipelines as delivery method and the incorporation of multiple modes of transport and multiple modes of energy. The findings from this project will further be disseminated in a paper to be published in a peer-reviewed journal, presented at conferences and workshops, as well as incorporated in teaching.

5. Conclusion

The research project proposed a framework with the aim of mapping the hydrogen freight demand in determining the hydrogen refuelling infrastructure required for effective deployment. The framework was implemented for the NP11 region in Great Britain delivering the hydrogen demand analysis, geographic location and capacities of HRSs and the hydrogen supply to these HRSs with specific consideration to on-site and off-site hydrogen production supply with the use of tube trailers. The research identified an area for future work relating to the implementation of different delivery and dispense alternatives to tube trailers, such as a pipeline network. The research may further benefit from investigating the incorporation of different modes of transport, as well as an overarching model integrating different energy models in combination with hydrogen, such as battery electric vehicles and the electric road system. Additional future work recommended is the use of reinforcement learning in the agent-based model developed in which a self-organising system is created to allow for a robust, optimised solution. Other future work may relate to the refining of input data, specifically the use of actual journey data which may be incorporated in both the demand analysis and the agent-based model.

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