Place-based decarbonisation for transport

Hydrogen for Sustainable Waterways

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Hydrogen for Sustainable Waterways

DecarboN8 Network Plus
Seedcorn Funding Project
Final Report

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Executive Summary

The Hydrogen for Sustainable Waterways (H4SN) project performs a techno-economic feasibility study on converting small passenger boats from a diesel power train to hydrogen fuel. The target location is the Lancaster and Cumbria region. Furthermore, it compares the hydrogen-based propulsion and storage against other zero-carbon alternatives, such as battery electric propulsion, from a technological, economic, environmental and safety perspective.

It also looks at what refuelling infrastructure would be required and where the hydrogen could be sourced from. It delivers a fully costed and subsequently submitted proposal for converting one or two watercrafts to hydrogen in the Lake District National Park, with a clear understanding of the new supply chain requirements for fuel and maintenance. During the process, it also raised awareness of stakeholders of the benefits of moving towards hydrogen based power trains for leisure craft.

For the technical analysis, conducted in partnership with Kingfisher and Hypermotive company collaborators, a techno-economic feasibility was conducted that assessed the conversion of an existing leisure canal boat (owned and operated under a regular cruise schedule by Kingfisher) to fully hydrogen-based fuel cell electric operation to serve the entire route autonomously, fossil-free. It was found that a conversion would be possible using a hydrogen storage tank on top of the vessel, compose of 17 standard small-sized Linde hydrogen storage cylinders, with 2 hydrogen refuelling points (not actual stations, just cylinder swap-points) at the ends of the cruise journey. This would equate to a usage of 27kg of hydrogen/month. Due to the high cost of stored hydrogen, this would lead to an increase in monthly operational costs from ~£400 to ~£5000. With mobile refuelling stations, this could be reduced to ~£2000 – not taking into account the capital cost or rental of the station. However, with hydrogen prices at existing large-scale commercial refuelling stations, such as the one at Shell/ITM Rotherham, the monthly running cost could be as low as £270. This underlines the necessity of thinking in terms of infrastructures when developing future sustainable waterway transportation.

Based on the output of the simulation phase, the team to put together a consortium with 7 company partners for an Innovate UK bid jointly led by Lancaster University and Connected Places Catapult, for the Clean Maritime Competition 2 with the proposal entitled *LAKeS Project - inLand maritime decArbonization networKed catalyst.* The total value of the proposal was £2,993,161. It received 2 *yes* and 3 *no* recommendations for funding, and a reviewer score of 57%, unfortunately, it did not get funded. It received a 5/5 for the project scope.

1. Aims

The Hydrogen for Sustainable Waterways (H4SW) project aims to investigate the techno economic case for converting diesel powered light watercraft to zero-carbon (fuel cell) or low-carbon (combustion) hydrogen powered units. This is conducted as a pre-feasibility study for underpinning a pilot case for submission for future funding to UKRI councils or Innovate UK.

In the seed phase, it focused on assessing the feasibility of hydrogen conversion for a passenger canal boat operating on the Lancaster canal. This served as a steppingstone towards a ~£3M InnovateUK proposal for implementing the pilot conversions and to extend the use cases for other waterways across the country. While that bid was not successful, the project has a strategic significance, as it created a core group of interested stakeholders of applied hydrogen transportation in inland water environments, especially the Lake District National Park. This group includes academic stakeholders such as Lancaster University, national research institutes, such as the Centre for Ecology and Hydrology, the Lake District National Park, and several interested industry partners, both small, medium and large enterprises from the hydrogen refuelling, powertrain and water transportation and navigation sectors.

The core aims of H4SW were perform a techno-economic feasibility study on converting small passenger boats from a diesel power train to a hydrogen fuelled power train in the Lancaster and Cumbria regions to compare the hydrogen-based zero-carbon (fuel cell) or low-carbon (combustion) conversion options against other alternatives, such as battery electric propulsion, from a technological, economic, environmental and safety perspectives. It also looked at what refuelling infrastructure would be required and where the hydrogen fuel could be sourced from – ideally, one would aim to source green hydrogen produced from renewable energy. It also to aimed to investigate any HSE related issues surrounding hydrogen as a fuel, real or imagined
to map the social acceptance of such infrastructure, from the boat-owners' and the users' perspectives and to engage with as many stakeholders as possible providing the project with as much information as possible and affording an opportunity to begin the journey for societally accepting of hydrogen as a fuel for inland waterways.

The project's specific objectives were to have a fully costed proposal for converting one or two watercrafts to hydrogen, to have a clear understanding of the new supply chain requirements for fuel and maintenance, and to raise the awareness of stakeholders and the general public of the benefits of moving towards hydrogen based power trains for leisure craft.

2. Background

There are approximately 82,000 motorboats and 38,000 canal boats registered in the UK, all powered by diesel, making this sector an ideal candidate for decarbonisation using hydrogen as a fuel. As well as decarbonisation, a fuel cell power train has zero 'tailpipe' emissions addressing both water and air quality issues in the sensitive and fragile environments these craft operate in. Hydrogen is seen by most industry professionals as an indisputably essential part to fully decarbonise complex societies. While there have been industrial scale applications in the automotive sector for a few years now, watercraft powertrains have been lacking innovation. However the UK Government has recently (1) awarded £30M worth of projects in the hydrogen sector, underlining its importance (the Co-Is of this proposal were lead partners on one of the proposals that made the final stage in this call, but did not win the award). The hydrogen watercraft industry, however, is in its early innovator stage, even globally. In 2018, the first (2) commercial license was granted in Florida, with San Francisco following (10) soon after. Japan aims (3) to convert its fishing boats to hydrogen by the mid 2020s, following the announcement of a hydrogen-powered circumnavigation (4) expedition. In the UK there have been two significant hydrogen watercraft projects to date: a small catamaran conversion by Cheetah Marine (5) on the Isle of Wight in 2016 – with this being a conversion to internal combustion of hydrogen; and an early stage hydrogen hybrid canal boat study (6) sat the University of Birmingham in 2007.

We believe, therefore, that the H4SW project was timely and can function as a strong incentive for looking at green hydrogen as a future sustainable fuel for British watercraft, by raising awareness about its benefits across operators and users alike.

Hydrogen Powered Boats around the World

a) Overview

The global market for hydrogen boats is still at an early stage of development. Whilst trial projects are underway in some countries, and there is growing awareness of the potential of these technologies longer-term, work in this area is still somewhat fragmented and aspirational at the current time. Work is also unevenly distributed, with President of GTW, Elia Greenbaum[1] suggesting that "*As you know, most of the action in this area is in Europe*".

[1] *Wherever mentioned by name, sources of the data are personal interviews. The interview structure went through the standard ethics approvals processes of Lancaster University.*

There are a number of different use-cases for Hydrogen-powered boats. Jos Boere, Director of **Netherlands-**based Hysolar, for example, points to the highly-developed inlands water transportation network in the Netherlands, where his firms are involved in the hydrogen conversion of inland boats. Dirk Graszt, Managing Director of Clean Logistics in **Germany**, meanwhile is currently in discussions with the Hamburg port authority regarding the conversion of port tugs and working vessels, whilst in **Scotland** the MV Shapinsay ferry will be converted to partly run on carbon free hydrogen produced from curtailed energy (7). As Michael O'Mahony of Hyitf in **Ireland** summarises "There is a huge range of boats which can be potentially converted to hydrogen ranging from pleasure craft, fishing vessels, cargo ships to large passenger ro-ro ferries".

b) Usage

The use of hydrogen in boats has a number of advantages:

- It is highly efficient and fuel cells operate without placing mechanical stress on components.
- It is a zero-emission process, and can replace both conventional ship engines and auxiliary units for supplying secondary consumers.

It is quiet and low-vibration, and can be used in ecologically sensitive sea areas where conventional engines might provide too much disruption. It also helps to improve air quality, especially in ports.
However, here it is important to mention that hydrogen can be generated through one three main routes (green/blue/brown) from an emissions perspective (21). Out of these options only hydrogen generated through electrolysis, using electricity generated with renewable energy would qualify as truly zero-emissions. Furthermore, the lifecycle emissions would need to be taken into consideration concerning all equipment. However, for the sake of simplicity and keeping the report concise, in this study we will refer to all hydrogen as it would have been produced using the green route.

Smaller ferries have a power requirement of 100–300kW which can be covered by Proton Exchange fuel cells in low temperature operation (NT PEM). For mega yachts (where there is already demand), container and cruise-ships, power requirements are in the megawatt range, and here high-temperature fuel cells (MCFC) are used to cover demands (8).

c) Projects

Despite the early stage of development there are nevertheless a number of notable projects underway:

- Following earlier successes with batteries, **Norway** is currently building the first fuel cell-powered ferries. Whilst battery-powered solutions are better for short distances up to 40 kilometres, shipping company Norled is ordered the world's first "larger" hydrogen ferry, designed by LMG Martin and under construction by Westcon shipyard. The ferry will carry 299 passengers and 80 cars, and could be in service as early as next year on the 3km Hjelmeland – Nesvik route. Whilst this route is relatively short, by around around 2030 Sigve Aasebø believes that distances up to 100 kilometers should be possible, suggesting that by this point Norway will need 10,000 tonnes of hydrogen a year for ferry traffic (9). In addition to Ferries, Norway is also getting involved in Cargo, as the Wilhelmsen shipping company has received NOK 80 million in EU support to build a hydrogen-powered cargo vessel. The project will sail under the name Topeka and draws together 14 European partners (10, 11).

- A similar project is underway in the **USA**, as First Hydrogen is constructing a Fuel Cell e-Ferry in SF Bay. The 84-passenger ferry is under construction using private funding from SWITCH and a $3m grant from California Air Resources Board. The project leverages technology from partners including Golden Gate Zero Emission Marine, BAE Systems, and Hydrogenics and is being over seen by Hornblower Group's Vessel Construction Management Team. In order to scale this technology further, SWITCH is partnering with Clean Marine Energy to develop charging and hydrogen fuelling infrastructure in multiple US ports.
- In **Germany**, e4ships is an important collaboration between "leading German shipyards, shipping companies, fuel-cell manufacturers, suppliers and classification societies". E4ships has come together to design and test fuel cell systems to meet the needs of industry on a pre-competitive basis. They also aim to participate in the development of rules by the International Maritime Organization and European authorities in order to help facilitate the unrestricted use of full cells including those with a low flash point, of which Hydrogen is one. The International Maritime Organization (IMO) as well as the authorities of the Federal Ministry of Transport responsible for inland navigation in Germany and the European bodies (ZKR / CESNI) are currently the conditions for the approval of fuel cells in ships including fuels with a low flash point (IGF Code for Low Flash Point Fuels) for all European ports and waterways have been created. However, further framework requirements still have to be adapted in order to allow unrestricted use of fuel cells (12).
- The **EU** project Seafuel has similarly strategic aims, working in the Atlantic region with the aim of using the renewable resources across the Atlantic Area to power the local transport fleet and support the shift towards a low-carbon economy. The project will use the expertise and infrastructure of the partners in renewable energy, namely solar, wind and marine, to demonstrate the viability of hydrogen as a fuel to be used by the local transport authorities (13).

Many projects are either smaller-scale or at a different stage of development:

- In **Italy**, for example the Hepic Project "Hydrogen Electric Passenger VenICe boat" in Venice has produced a small-scale Hydrogen vessel for use in the city. However this has not been followed up with the development of a larger fleet (14).
- Likewise, Yanmar (**Japan**) has developed a system for smaller boats using Toyota's Mirai powertrain, hoping to start field demonstrations by the end of 2020. The energy observer project also focusses on a smaller-scale, having produced the first hydrogen-powered zero-emission vessel to be self-sufficient in energy, it now advocates and serves as a laboratory for ecological transition, combining expeditions and innovations in order to explore solutions. The project boasts a number of innovations including a land-based power generator and maritime range extender (15).
- In **France** the Seabubbles projects aims to produce the water taxi of the future. ABB is scheduled to provide a power and propulsion solution for a fuel-cell based river boat which will operate along the river Rhône, and ABB have larger ambitions alongside this, having in 2020 signed a memorandum of understanding with Hydrogène de France to jointly manufacture megawatt-scale fuel systems capable of powering ocean-going vessels (16, 17).
- There is interest in a hydrogen-based system in **India**, where, following the example of some European navies, the Indian navy are investigating fuel cell-based propulsion systems as an option to offer their submarines greater submerged endurance, as well as for surface-based vessels and Kerala's Water Metro project is considering various green propulsion systems for the water transport sector (18).

It is not just the use of hydrogen for fuel which connects it to the maritime industry, however, and in April 2020 **Brunei** and **Japan** established the world's first international hydrogen supply chain, using LOHC (C7H8) to safely transport hydrogen at room temperature and ambient pressure insider containerised tanks from Brunei to Japan for hydrogen extraction (19).

In conclusion, while there is clearly a lot of advancement globally in the hydrogen vessel space, focus is on rather large conversion, and almost exclusively in a maritime context. Therefore, the H4SW project represents an opportunity to examine the more local, inland waterway context, especially in the proximity of a large national park.

Project partners

Hypermotive have a strong capability in the development and integration of fuel cell systems for motive and stationary power applications. They are developing power systems that can replace the diesel motor and auxiliary power generator in light marine vessels. In this project, they looked at the technical feasibility of converting the power units of one of the small passenger ferries in the Lake District National Park and a passenger canal boat operating on the Lancaster Canal from diesel to hydrogen. They provided their services as a consultancy.

Lake District National Park: They provided introductions to the ferry operators in the LDNP and patrol boats. They investigated the impact of converting the diesel-powered crafts within the national park and concluded that it has serious potential for carbon reduction (as the watercraft are the largest source of emissions after cars and the national park is one of the largest carbon sinks in the UK). Furthermore watercraft are also the major source for air and water pollution, which a hydrogen conversion would significantly improve.

Kingfisher Cruises: They own and operate passenger canal boats on the Lancaster canal. They were involved in the technical feasibility study providing the technical information about the vessels to Hypermotive so that a techno-economic feasibility study can be performed.

3. Methods

Upon commencement of the project we have arranged a project launch meeting virtually (planned to be held in-person in Lancaster, but moved online due to COVID-19) with the initial project partners (Hypermotive, Lake District National Park, Kingfisher Cruises). At this event we have identified which vessels will be best suited to the study. The final choice was a passenger canal boat operated by Kingfisher between Lancaster City Centre and Carnforth on the Lancaster Canal. Hypermotive, who have experience in hydrogen boat conversions, along with the vessel owner, looked at the practicalities of converting this vessel to fully hydrogen-based operation. In parallel to this, the project team looked at other issues such as the refuelling infrastructure, green hydrogen source, maintenance, HSE and legislation.

Our intention was to source a supply of green (zero or low emissions) hydrogen produced from renewable energy. The practicalities and economics of this was deemed infeasible, as currently in the UK there is a very limited supply of green hydrogen. This part of the study built on the recent work done by EDF and Lancaster University Hydrogen 2 Heysham project (20). This BEIS funded project investigated the feasibility of producing hydrogen by electrolysis at the Heysham nuclear power station. We have gotten in touch with one of the partners from the Hydrogen 2 Heysham project, NanoSUN. They provide mobile hydrogen refuelling solutions and we used their input for the cost estimates of the canal boat conversion. We identified that a local renewable energy fed electrolyser would be the best source of hydrogen, as there could also be a spin off benefit in capturing the ‘waste oxygen’ form the electrolyser and using it to improve water quality in some of the Lakes.

We summarised these findings in a detailed techno-economic report about the conversion of the Kingfiher canal cruise boat to a fully hydrogen-based operation, prepared by Hypermotive. This report was then be used as a core for a feed-in for a larger proposal, for making the conversions a reality. In the following sections we present the main methodology and findings of this report.

Kingfisher Hydrogen Fuel Cell Hybrid Powertrain Design

The case study of the H4SW project is based on a cruise canal boat, operated by Kingfisher (Figure 1). As the results of extensive discussions with the owner and a physical examination, the conversion parameters were identified and calculated. This vessel is a common type on the English canals, and would be considered mid-size.

a) Powertrain Specification

We start by examining the powertrain requirements on the existing Kingfisher vessel.
Specifications:

- Overall length: 70ft (21.3m)
- Beam: 10ft (3.0m)
- Draft: 21 inches (0.53m)
- Displacement: 28 tonnes
- Passenger capacity: 48
- Crew: 3
- Engine: Isuzu 70 3.0-litre 4-cylinder diesel, 75bhp @ 2,600rpm
- Gearbox: PRM 260, 2:1 ratio
- Generator: Beta Marine BetaGen7 1.1-litre 3-cylinder diesel, 6.7kVA rating
- Bow thruster

Figure 1. The Kingfisher cruise canal boat

Propulsion power demand is calculated using scaled from data for an electric 60ft narrowboat to account for Kingfisher's greater displacement and width. We also need to account for the fact that power demand increases in narrow canals due to the blockage effect of the large hull cross-section in a narrow and shallow channel (Figure 2). We use a broad canal / river profile used for the majority of the Lancaster Canal. However, we also consider two narrow sections: Lune Aqueduct and Town End Bridge near Hest Bank.

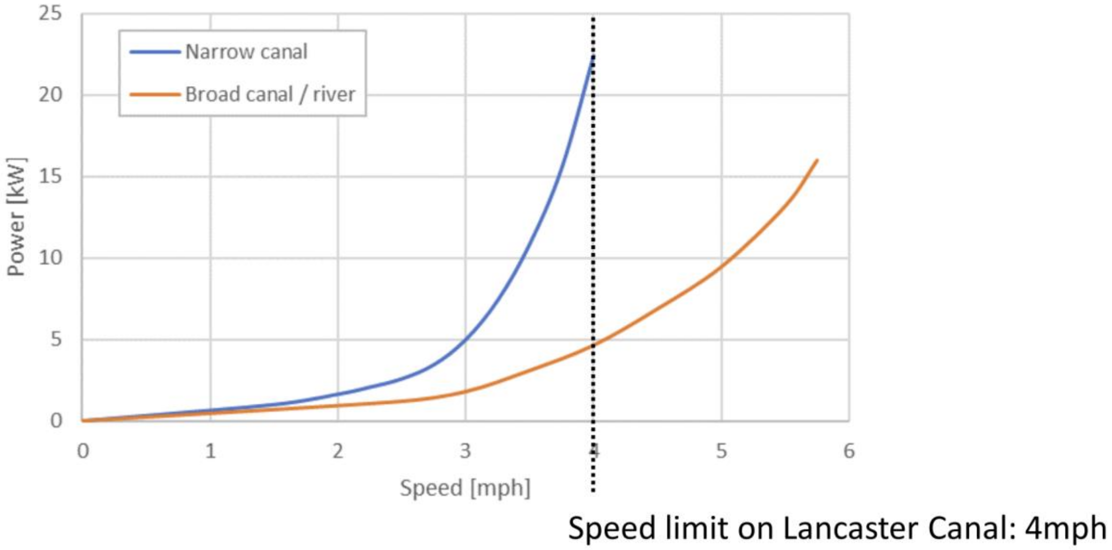

Figure 2. Power dependency as a function of speed for various canal river profiles

Electric propulsion

We also need to into account that power ratings for electric boats are typically less than for equivalent diesel engines due to their ability to provide maximum torque at low shaft speeds. Therefore the proposed electric motor is a Bell Marine DriveMaster Ultimate 20 (Figure 3A). This fulfils the power requirements with the following specifications:

- Continuous power: 20kW (equivalent to 27bhp)
- Maximum speed: 1,450rpm
- Maximum torque: 132Nm
- Supply voltage: 48V
- Existing gearbox and propeller retained
- Can be integrated with current keel cooling system
- Used on Elton Moss Kingsley 70ft x 12ft widebeam Dutch barge range (Figure 3B)

Using a 48V electrical system has advantages from an electrical safety and cost perspective. Even though cruising power requirement is typically less than 5kW, a 20kW motor provides sufficient reserves to accelerate the boat from a standstill.

A. 
B. 

Figure 3

A. Proposed electric motor

B. Elton Moss Kingsley 70ft x 12ft widebeam, a similar vessel in size and power requirements to Kingfisher

Hydrogen Fuel Cell

After the power consideration and use-case discussion with the vessel's current owner, a liquid-cooled hydrogen fuel cell system (FCS) is selected, specified to allow coolant to be used for cabin heating in cooler months. Two models from Hydrogenics HyPM range (Figure 4) were simulated with 8kW and 12kW power ratings. Powertrain control strategy ran each system at discrete points between 25% and 90% of rated power to maximise lifetime, as presented in Table 1. The results are presented in Figure 5.

Table 1. Fuel cell specifications for different power ratings

	Hydrogenics HyPM HD8	Hydrogenics HyPM HD12
Continuous power rating	8kW	12kW
Voltage range	20-40VDC	30-60VDC
Maximum current	350A	350A
Efficiency at rated power	48%	48%
Ambient operating temperature range	-5°C to +46°C	-5°C to +46°C
System mass	40kg	55kg

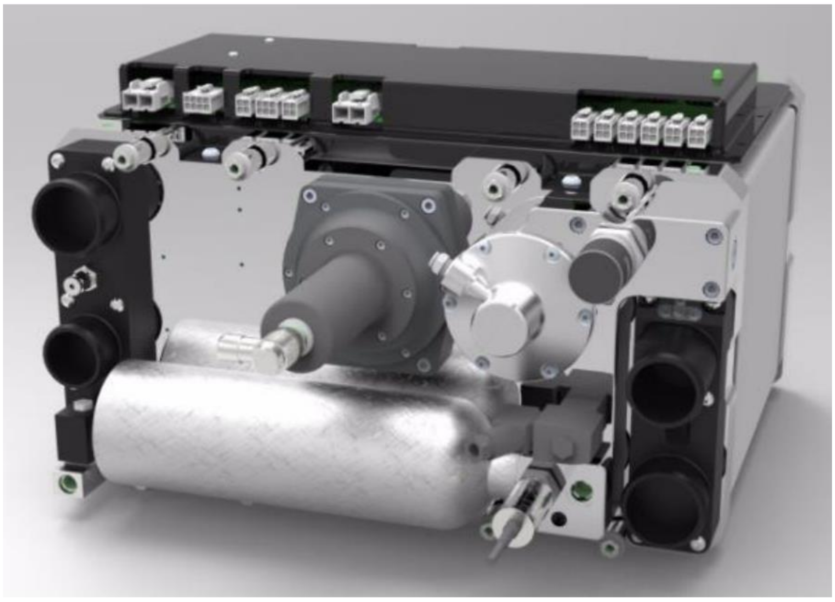

Figure 4. Hydrogenics HyPM fuel cell

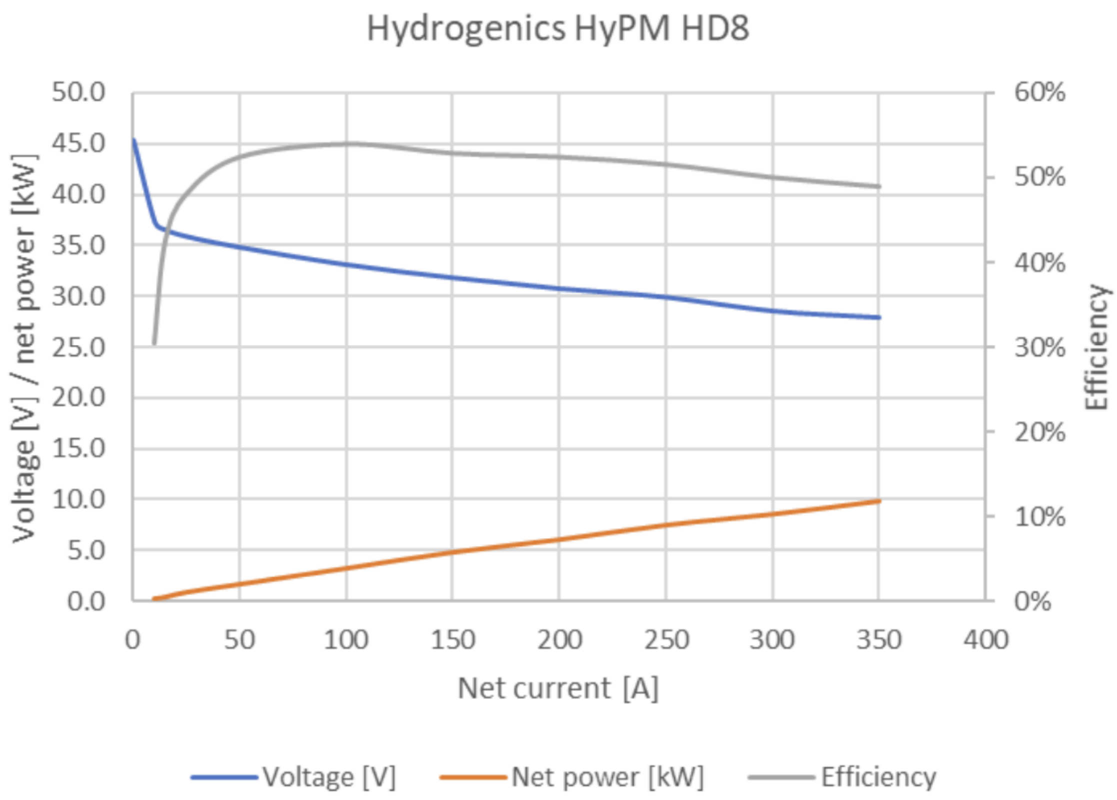

Figure 5. Simulation results of the Hydrogenics HyPM HD8 fuel cell. Note how power increases linearly with a larger terminal current, but efficiency peaks at 55% around 100A, after which it starts to slightly drop towards 50%

Electric Battery

Hyperdrive 48V battery modules used for the feasibility study simulations A nominal 48V battery voltage matches the propulsion system, and the modules use the same lithium NMC cells as found in the Nissan LEAF, and are being used in a range of off-highway and industrial applications, being easily accessible. The Hydrogen fuel cells are hybridised with a 9.9kWh battery pack (two Hyperdrive modules connected in parallel). The battery system specifications are presented in Table 2. The full electrical wiring diagram of the propsed system is presented in Figure 6.

Table 2. Battery system specifications

	Fuel cell hybrid battery pack
Battery modules	Hyperdrive Innovation HY Energy Plus Peak
Gross energy capacity	9.9kWh
Cell configuration	12S 4P
Pack voltage range	43.4 – 58.1V (51.8V nominal)
Maximum discharge current	600A
Pack mass	100kg (approx.)
Volume of modules	65 litres (approx.)

The 48V bow thruster thus will be powered by the battery and/or fuel cell system. This will be used for winding and manoeuvring at moorings. A 230V AC electrical system will be supplied by the 48V DC system via two inverters:

- Inverter model: Victron Energy Phoenix 48/3000
- Configuration: 2 inverters in parallel
- Input voltage range: 38-66VDC
- This can provide continuous AC power output: 4.8kW @ 25°C
- Maximum efficiency: 95% / Average efficiency: 93% (assumed)

The expected AC electrical system loads will be:

- Baseload (cabin lighting, fridge & ancillaries): constant 250W
- Kettle / tea urn: 2.7kW maximum
- Entertainment system for evening cruises: 1,000W music system
- Additional, event-based lighting 200W

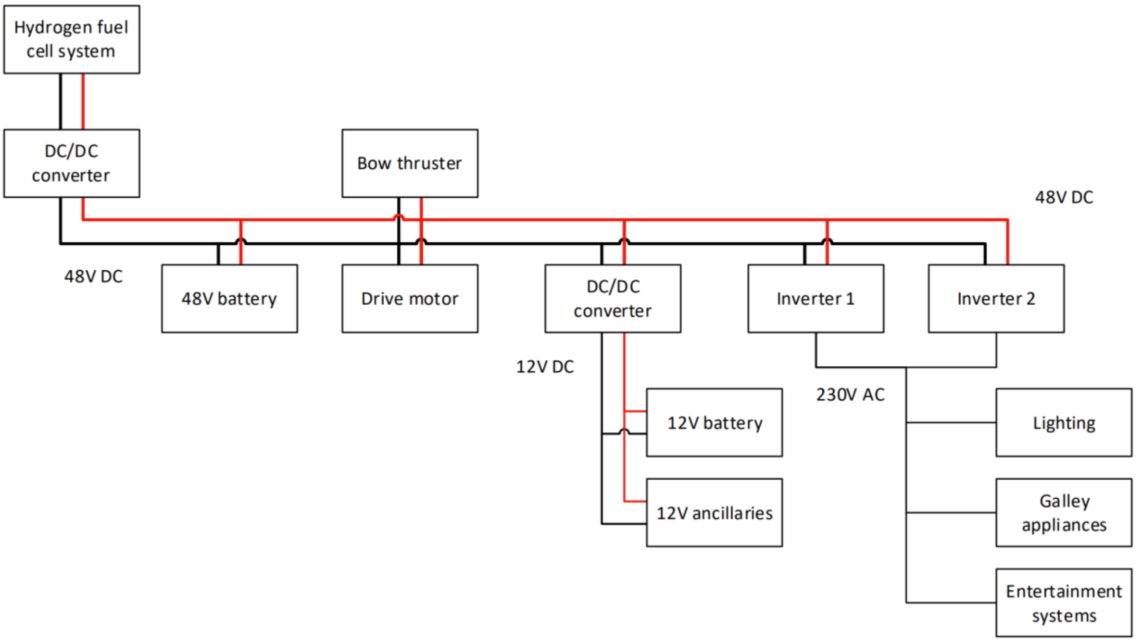

Figure 6. Electrical wiring diagram of the electric systems of the hydrogen vessel conversion

b) Cruise simulations

After designing the specified powertrain, the cruise timetable and schedule needs to be taken into account in order to get an accurate estimate of the energy storage requirements – and thus inform any decision on whether any installation of canal-side energy storage or charging infrastructure is needed. For these simulation, we considered the June cruise schedule for the short summer season from the year 2020 (Table 3).

Table 3. June 2020 Kingfisher cruise schedule

Date	Cruise
2nd June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
3rd June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
6th June	Fish & Chip Cruise (Barton Grange)
7th June	Afternoon Tea Cruise (Barton Grange)
9th June	Afternoon Tea Cruise (Barton Grange)
	Lune Aqueduct Cruise
10th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
11th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
12th June	Evening Live Entertainment Cruise

Date	Cruise
13th June	Waterbus: Lancaster to Carnforth
	Afternoon Tea Cruise (Carnforth – Tewitfield)
	Afternoon Tea Cruise (Tewitfield – Carnforth)
14th June	Waterbus: Carnforth to Lancaster
15th June	Lune Aqueduct Cruise
16th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
17th June	Lune Aqueduct Cruise
18th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
19th June	Murder Mystery Cruise (Barton Grange)
20th June	Fish & Chip Cruise
	Afternoon Tea Cruise
21st June	Afternoon Tea Cruise

Date	Cruise
21st June	Afternoon Tea Cruise (Barton Grange – Garstang)
22nd June	Lune Aqueduct Cruise
23rd June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
24th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
25th June	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
	Lune Aqueduct Cruise
27th June	Barton Grange Cruise
28th June	Afternoon Tea Cruise
	Afternoon Tea Cruise
	Afternoon Tea Cruise (Barton Grange – Garstang)

The June 2020 Kingfisher cruise schedule is comprised of 48 individual journeys across 14 different routes, including day cruises (return and one-way), a Waterbus cruise from Lancaster to Carnforth and back, evening entertainment cruises, and liaison sections (moving Kingfisher from one location to another without passengers). We break down each of these journeys based on distance and time (Table 4). The average distances and comparative cruise times might seem to take too long. However, this is due to the low speed limit imposed along the Canal – especially the around Lancaster-Carnforth area.

Table 4. Kingfisher June 2020 journeys

Route no.	Description	Type	Distance [km]	Duration	Number
1	Lancaster to Lune Aqueduct and back	Day cruise	7.6	1:27	25
2	Barton Grange to Bilsborrow and back	Day cruise	9.7	1:51	7
3	Barton Grange to White Horse WH and back	Day cruise	6.4	1:12	2
4	Lancaster to Carnforth	Waterbus	14.1	2:51	1
5	Carnforth to Lancaster	Waterbus	14.1	2:51	1
6	Carnforth to Tewitfield	Day cruise	6.3	1:12	1
7	Tewitfield to Carnforth	Day cruise	6.3	1:12	1
Route no.	Description	Type	Distance [km]	Duration	Number
8	Barton Grange to Hollowforth WH and back	Evening cruise	12.2	2:19	1
9	Barton Grange to Garstang	Day cruise	7.8	1:29	2
10	Barton Grange to Lancaster	Liaison	27.2	5:12	2
11	Lancaster to Barton Grange	Liaison	27.2	5:12	3
12	Garstang to Lancaster	Liaison	19.5	3:43	1
13	Lancaster to Garstang	Liaison	19.5	3:43	*
14	Lancaster to Galgate WH and back	Evening cruise	14.3	2:44	1

* Lancaster to Garstang route simulated as part of planning for refuelling points.

Map 1. Key Kingfisher cruise locations (also see Table 4)

4. Findings

With the power specifications, as well as the cruising schedule and parameters at hand, we simulated all routes as if they were undertaken on hydrogen propulsion. Of interest are the electrical energy and hydrogen consumption, in order to proceed to the final step of sizing the hydrogen storage requirements and thus estimating the canal-side infrastructure needs, as well as the conversion's feasibility as a whole.

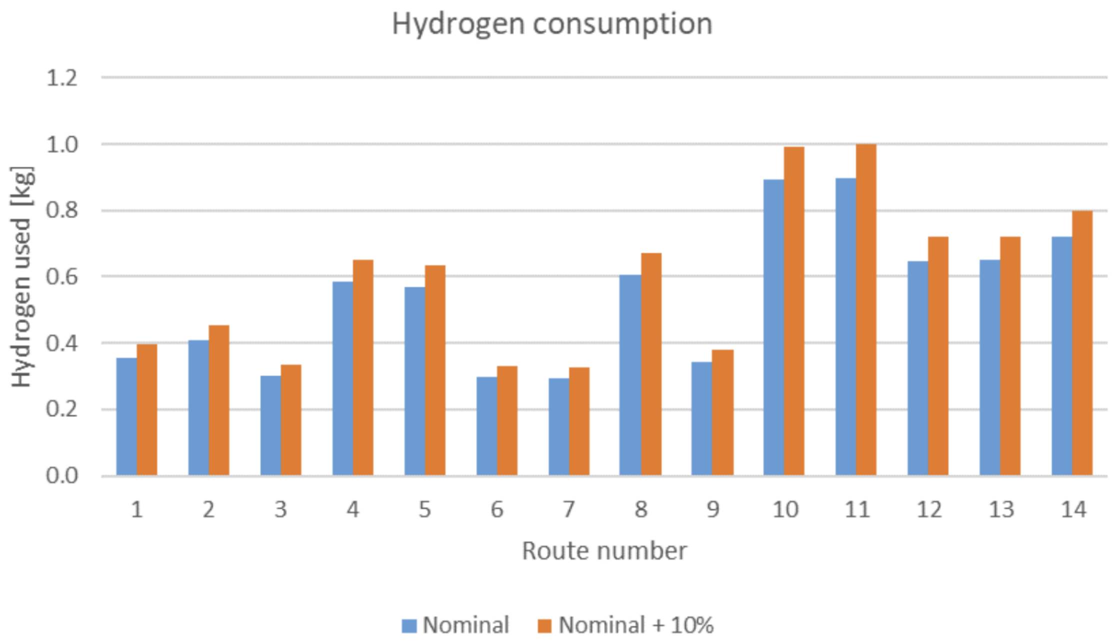

Figure 7. Simulated hydrogen consumption of each route segment

Hydrogen consumption (Figure 7) was adjusted to give the same battery state of charge at the start and end of each journey. The difference between hydrogen consumption of 8kW and 12kW FCS was less than 1% (due to the larger system not being utilised to its full capacity), so the results for the 8kW system were used for all subsequent analysis. Finally, a safety margin of 10% was added to hydrogen consumption to account for effects of extreme hot/cold temperatures and degradation.

Electrical energy consumption (Figure 8) shows how the energy produced by the fuel cell system is used on the boat for each journey. This allowed for approximate sizing of the battery for a battery-only powertrain system to be carried out.

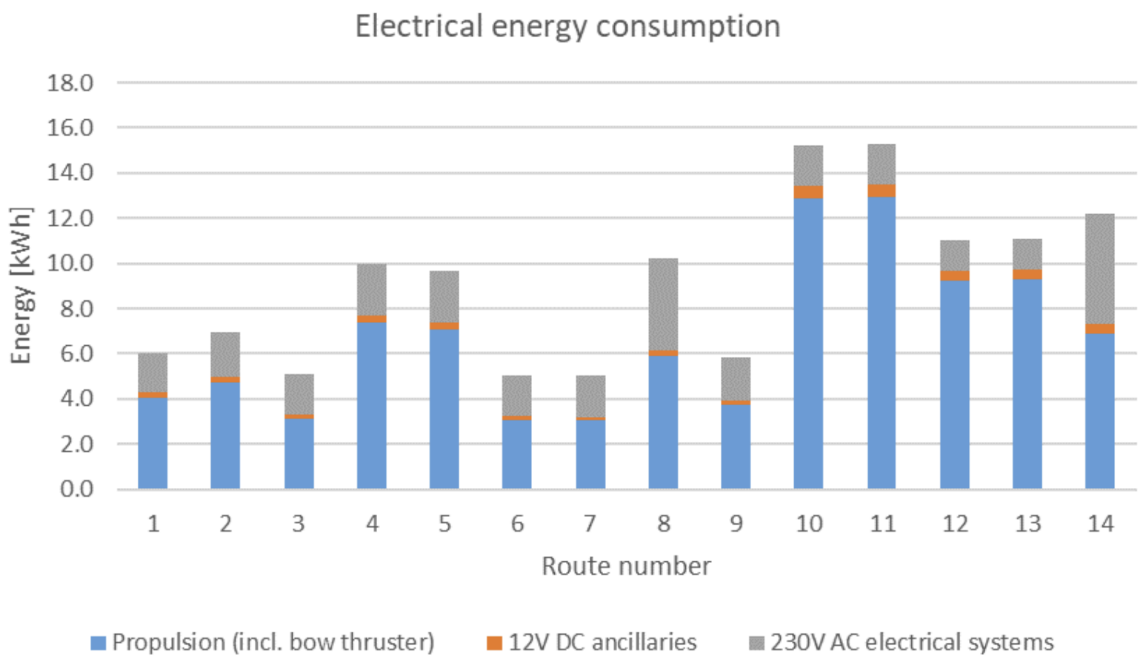

Figure 8. Simulated electrical energy consumption of each route segment

Based on the outcome of the hydrogen fuel estimates, we created an estimation for a fully autonomous hydrogen operation mode – i.e. carrying all hydrogen onboard. An initial proof-of-concept hydrogen hybrid powertrain would need to use bottled hydrogen before dedicated hydrogen refuelling infrastructure could be built. In this case BOC GENIE hydrogen cylinders (Figure 9 & Table 5) are a potential option, where cylinders are swapped at 'refuelling points' – if there was no cylinder refilling on-site, at least initially.

Figure 9. BOC GENIE hydrogen cylinder

	BOC GENIE G20 hydrogen cylinder
Hydrogen storage capacity	424g
Maximum pressure	300bar
Cylinder mass (gross)	22kg
Maximum diameter	325mm
Height	660mm

Table 5. BOC GENIE hydrogen cylinder specifications

Two refuelling scenarios were used to define the amount of hydrogen that would need to be stored onboard Kingfisher to meet the planned June 2020 itinerary:

- Scenario 1: Hydrogen cylinders swapped at Barton Grange Marina and Garstang Marina (same situation as for diesel refuelling)

- Scenario 2: Hydrogen cylinders can also be swapped at a location in Lancaster
- Calculations used nominal hydrogen consumption of the FCS + a 10% margin

Scenario 1 results

Operating from Lancaster for several days would be problematic, requiring an additional 10-hour return journey to the nearest refuelling point at Garstang Marina (total of 50 journeys for the month). There would be an additional trip required between last Lune Aqueduct cruise on 11th June and live entertainment cruise on the evening of 12th June. This results in the minimum onboard storage capacity of around 7kg of hydrogen, which equates to 17 GENIE hydrogen cylinders.

The 50 journeys for the month would be split into 7 sections between hydrogen cylinder swaps (Figures 10A and 10B). This is largely unfeasible due to the volume of the cylinders and the space required for a safe gas locker outside the passenger cabin.

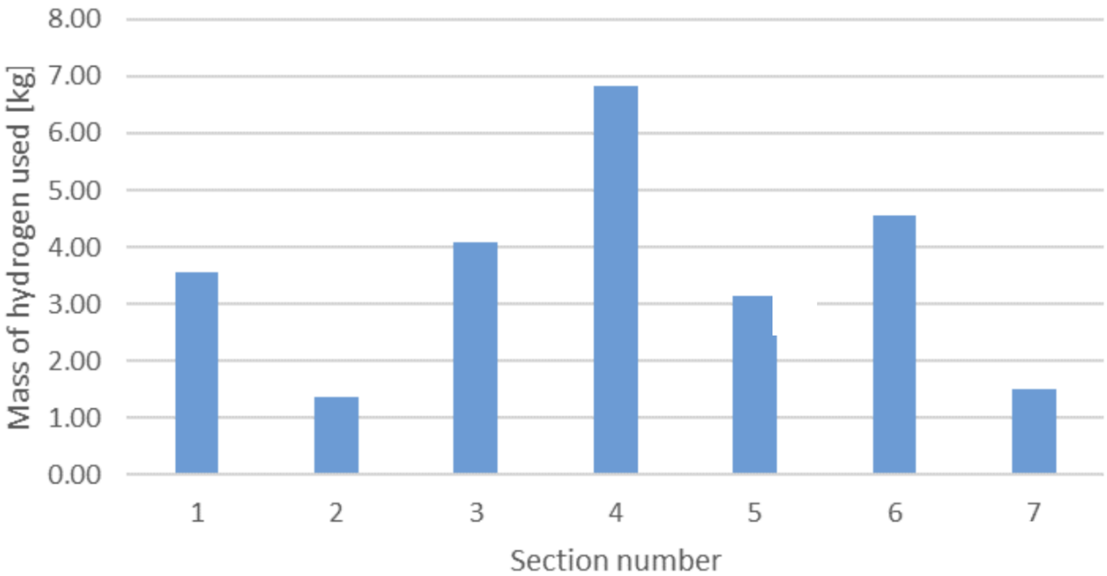

Figure 10A. Hydrogen consumed per section

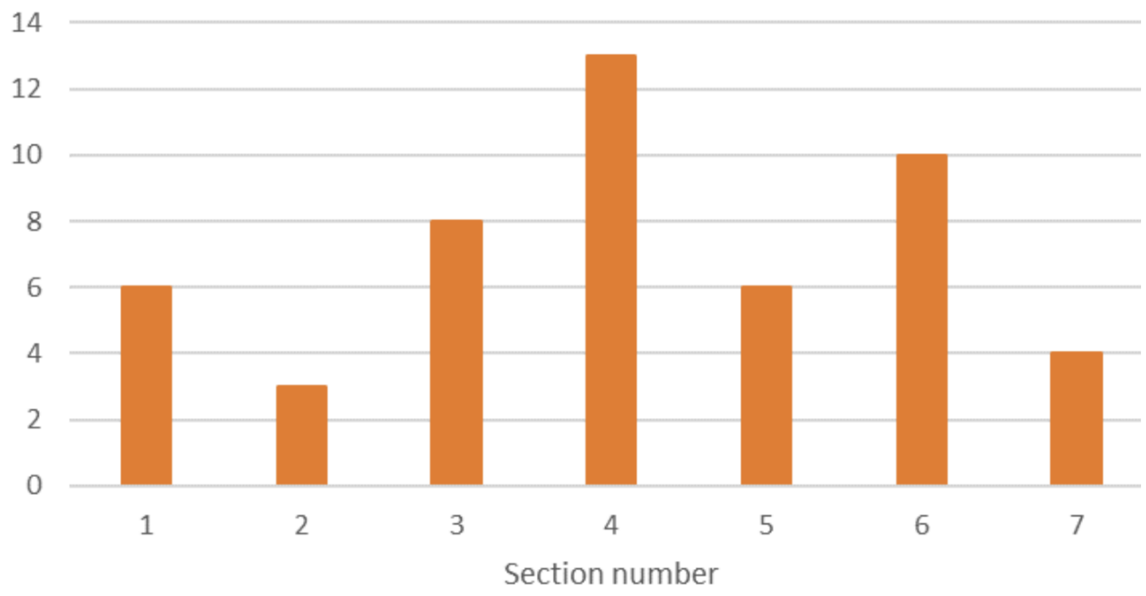

Figure 10B. Number of journeys per section

Scenario 2 results

Allowing hydrogen cylinders to be swapped in Lancaster as well reduced the maximum distance between swaps to 42.5km (26.4 miles). Under this scenario, cylinders are swapped 16 times in the month, with 64 cylinders required in total. The would be a need space for 5 GENIE G20 hydrogen cylinders onboard Kingfisher in this scenario, reduced from the 17 in Scenario 1.

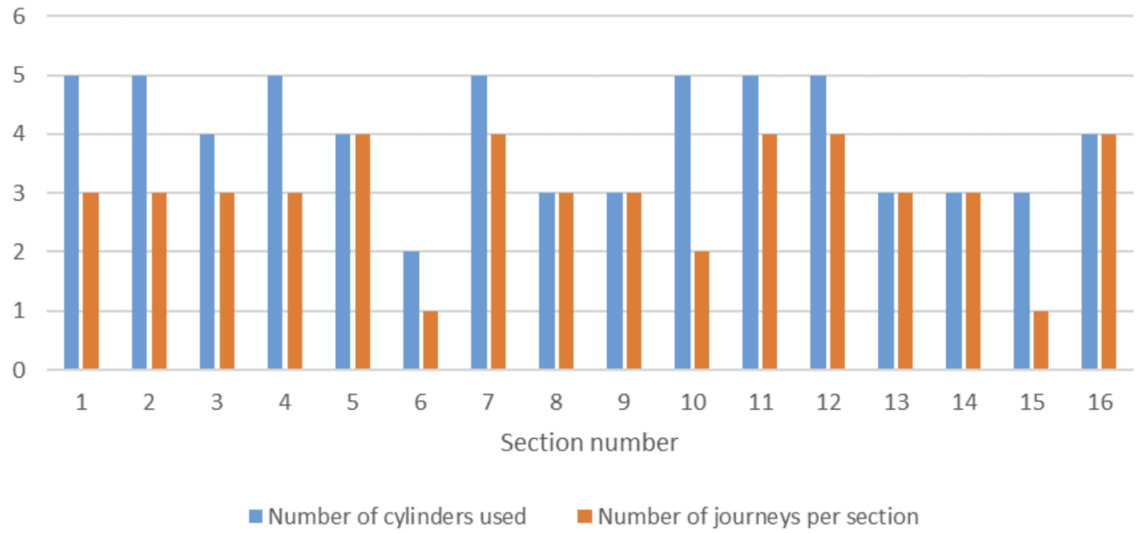

Figure 11. Hydrogen cylinders used and number of journeys per section

Figure 11 and Table 6 show the detailed consumption characteristics of hydrogen per journey section.

Table 6. Hydrogen consumption per section under Scenario 2

Section no.	Distance travelled	Cylinder swap location	Cylinder swap date	Hydrogen consumed
1	42.5km (26.4mi)	Lancaster	2nd June	1.78kg
2	42.5km (26.4mi)	Barton Grange	5th June	1.79kg
3	29.1km (18.1mi)	Barton Grange	7th June	1.36kg
4	42.5km (26.4mi)	Lancaster	9th June	1.78kg
5	30.5km (18.9mi)	Lancaster	11th June	1.58kg
6	14.3km (8.9mi)	Lancaster	12th June	0.80kg
7	40.7km (25.3mi)	Lancaster	14th June	1.94kg
8	22.9km (14.2mi)	Lancaster	16th June	1.18kg
9	22.9km (14.2mi)	Lancaster	18th June	1.18kg
10	39.4km (24.5mi)	Barton Grange	19th June	1.67kg
11	36.8km (22.9mi)	Garstang	21st June	1.74kg
12	22.9km (14.2mi)	Lancaster	23rd June	1.90kg
13	22.9km (14.2mi)	Lancaster	24th June	1.18kg
14	22.9km (14.2mi)	Lancaster	25th June	1.18kg
15	27.2km (16.9mi)	Barton Grange	26th June	1.00kg
16	30.1km (18.7mi)	Garstang	28th June	1.50kg

Comparison with battery electric powertrain

Since both scenarios represent a significant challenge from a hydrogen infrastructure perspective, as a comparison, the charging times for a battery electric Kingfisher were estimated (Figure 12), assuming a 16A/230V charging point was available in Lancaster and at the Barton Grange and Garstang marinas.

- Under this scenario, the battery would need to be charged overnight 17 times in the month, for between 3½ and 8½ hours per charge.
- Charge points in Lancaster (11 charges) and Barton Grange Marina (6 charges) would provide sufficient energy.
- The Required battery energy capacity at least 42.5kWh, assuming 70% of gross energy capacity was useable to give an acceptable service life.

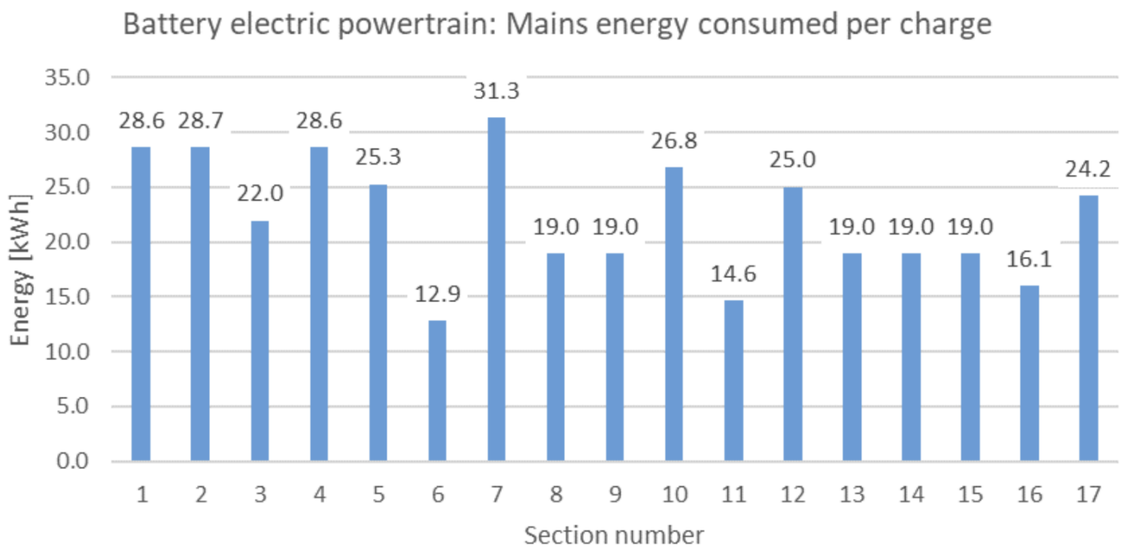

Figure 12A. Electric energy consumed per section

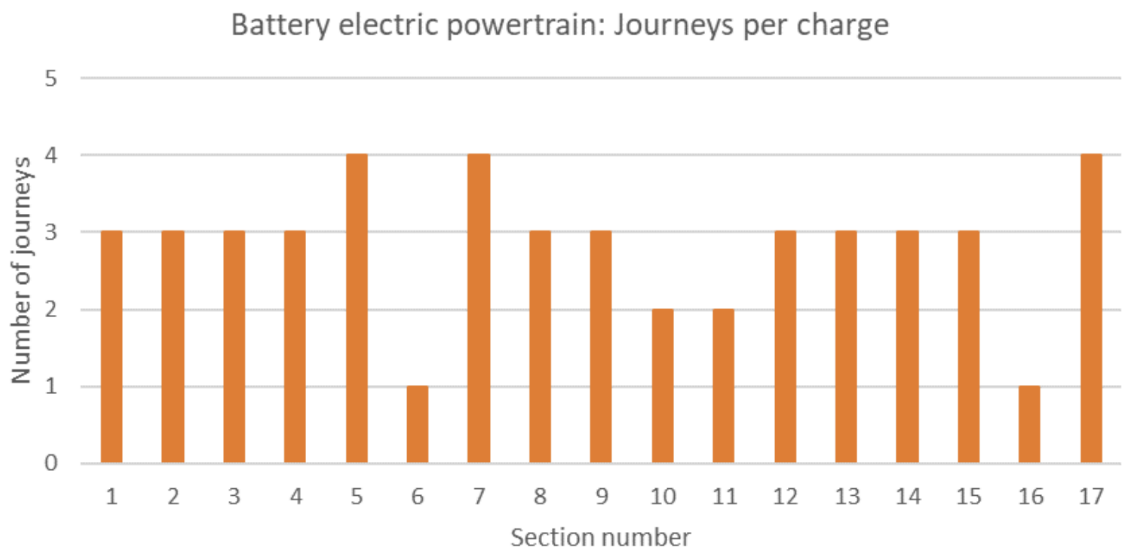

Figure 12B. Number of journeys per section

Overall, the analysis of the Kingfisher passenger boat has shown that a hydrogen fuel cell hybrid powertrain would be technically feasible without adversely impacting the operation of the canal cruises.

- An 8kW hydrogen fuel cell system + 10kWh 48V battery would be optimal.
- Bottled hydrogen gas could be used for initial vessels before hydrogen refuelling infrastructure is developed.

- A location to store and swap hydrogen cylinders in Lancaster would be required, otherwise the onboard energy storage requirements become too great.
- This initial analysis does not include considerations for providing cabin heating, which would be required for operations in colder months. This would have a greater impact on a battery electric vessel:
    - Coolant at 50-60°C from the hydrogen fuel cell system could be used to provide cabin heating
    - Electric heating energy requirements for a battery electric boat could equal those of propulsion from Hypermotive experience on similar projects.
    - Another alternative would be a diesel-fuelled water heater, but this would not be an emission-free solution.

As the results of the simulation clearly point to the necessity of hydrogen charging infrastructure to be co-developed together with the deployment of hydrogen-powered vessels, for the follow-up proposal a mobile charging solution was proposed, bringing in NanoSUN as a partner.

5. Conclusion

The overall aim of the H4SW project was to act as a catalyst for a larger research grant in the hydrogen vessel space and serve as a pre-feasibility study for underpinning a pilot hydrogen vessel conversion case for submission for future funding to UKRI councils or Innovate UK. It achieved this completely, with the proposal entitled *LAKeS Project - inLand maritime decArbonization networKed catalySt,*submitted to Innovate UK jointly by Lancaster University and Connected Places Catapult, for the Clean Maritime Competition 2 in July 2021.

The stated primary outcome the proposal was a techno-economic feasibility study looking at the practicalities and costs of converting vessels, providing refuelling infrastructure, addressing HSE concerns and looking at how such a project could help societal acceptance of hydrogen as a fuel for the future. In terms of deliverables, the project commited to (a) having have a fully costed proposal for converting one or two watercrafts to hydrogen, (b) to have a clear understanding of the new supply chain requirements for fuel and maintenance and summarise these in a public report and (c) to raise the awareness of stakeholders and the general public of the benefits of moving towards hydrogen based power trains for leisure craft. The project delivered of all of proposed objectives.

In partnership with Kingfisher and Hypermotive company collaborators, a techno-economic feasibility was conducted that assessed the conversion of a leisure canal boat owned by Kingfisher and operated under a regular cruise schedule to fully hydrogen-based fuel cell electric operation to serve the entire route autonomously, fossil-free. Using a computer simulation to take into account the engineering characteristics of the Kingfisher canal cruise boat as well as the operating schedules and feasible potential charging locations, it was found that a conversion would be possible using a hydrogen storage tank on top of the vessel, compose of 17 standard small-sized Linde hydrogen storage cylinders, with 2 hydrogen refuelling points (not actual stations, just cylinder swap-points) at the ends of the cruise journey. This would equate to a usage of 27kg of hydrogen/month. Due to the high cost of stored hydrogen, this would lead to an increase in monthly operational costs from ~£400 to ~£5000. With mobile refuelling stations, this could be reduced to ~£2000 – not taking into account the capital cost or rental of the station. However, with hydrogen prices at existing large-scale commercial refuelling stations, such as the one at Shell/ITM Rotherham, the monthly running cost could be as low as £270.

Decarbon8 connected the project awardees with Connected Places Catapult as part of the round-table discussion on the future of maritime transport. After involving the Lake District National Park as well as a partner, this lead to the seed-corn team to put together a consortium with 7 company partners for an Innovate UK bid jointly led by Lancaster University and Connected Places Catapult, for the Clean Maritime Competition 2 with the proposal entitled *LAKeS Project - inLand maritime decArbonization networKed catalySt.* The total value of the submitted proposal was £2,993,161 total cost / £1,982,833 requested. Receiving 2 *yes* and 3 *no* recommendations for funding, and a reviewer score of 57%, unfortunately, *LAKeS* did not get funded – however, it received a 5/5 for the project scope, further underpinning the validity of the project. Researchers at Lancaster University are hoping to use the core ideas and partnerships of the LAKeS bid to apply for further funding.

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Denes Csala (DC), Steve Wrigley (SW) and Alison Ireland (AI) from Lancaster University, Stuart Chubbok (SC) and Adam Huckstep (AH) from Hypermotive, Barry Cole (BC) from Kingfisher cruises and Emma Moody (EM) from the Lake District National Park all contributed to this study. DC and SW designed the study. SW managed the project and set up consultations. DC, SW, SC, AH and EM participated in the consultations. BC provided boat schedules and cruise parameters. SC designed and performed the simulations, and summarised the results. DC, SW, AH reviewed the results. AI analysed and wrote the section on recent hydrogen developments across the globe. DC wrote the report and presented the project at dissemination events. DC, SW, EM, AH held discussions on the follow-up bid. Finally, DC, SW and EM were named co-investigators in the follow-up bid submitted to InnovateUK.

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