HSSMI techno-economic assessment report for the HyDIME Project

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HYDIME

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MV Shapinsay leaving Kirkwall harbour. Source: EMEC

Executive Summary

During the HyDIME project, HSSMI conducted a techno-economic assessment of the HyDIME system being installed in Orkney and identified potential threats of the system as well as opportunities to scale and replicate it across the UK.

The purpose of this report is to present the findings, outcomes, and insights that were generated during this work.

The methodology for carrying out the work is described, followed by the results of the environmental and economic impact assessment of the system. Potential threats of the system are addressed, and the report concludes with recommendations of where this system could be replicated and/or scaled elsewhere in the UK.

This work concluded that the HyDIME system represents a feasible stepping stone solution in the journey to decarbonise the marine industry. The HyDIME system can offer significant emission reductions (up to 43,000 kg CO_2 per year) to existing vessels. This can be achieved with minimal vessel invasiveness and is significantly more economical than manufacturing as new.

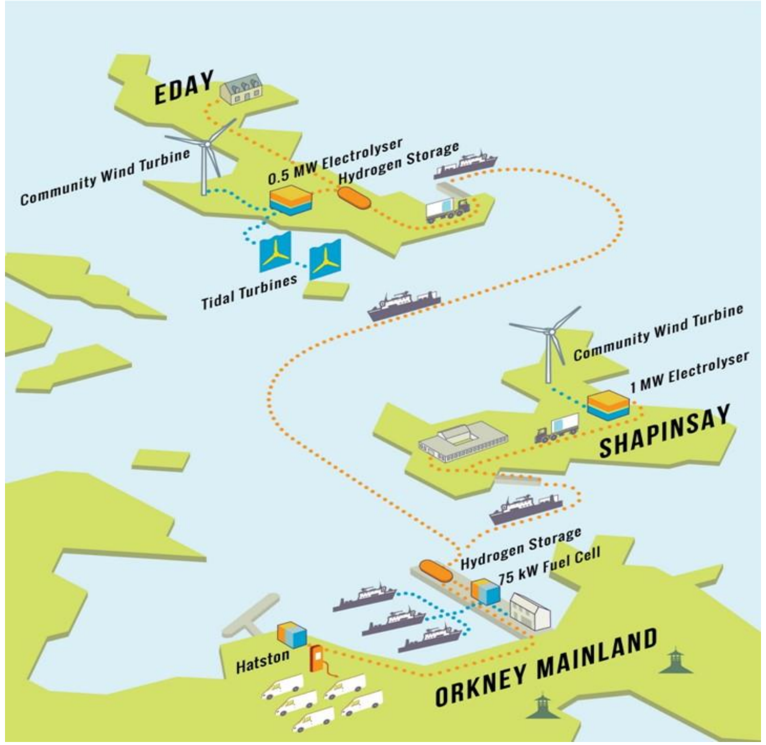
The HyDIME project was also crucial in overcoming the regulatory barriers that exist in the transition to integrate hydrogen into the marine market. This project will de-risk future marine, hydrogen projects.

This work identified that the transportation of hydrogen between the point of production and consumption presents the biggest challenge for the HyDIME system being installed in Orkney. The impact of a centralised production infrastructure in Orkney was analysed and was found to provide significant emissions savings as well as solve many of the logistical problems currently faced.

As expected, the biggest barrier with developing any hydrogen technology is the cost of the fuel. Until the cost of hydrogen becomes cost partitive with marine diesel, it is difficult to foresee this system providing cost savings.

Despite the economical challenges, the HyDIME system acts as a stepping-stone project and is a positive stride in the right direction towards incorporating hydrogen as a fuel into the marine market.

The HyDIME System (Hydrogen Diesel Injection in a Marine Environment)



Orkney hydrogen economy ambitions. Courtesy of BIG HIT project

Hydrogen injection is a technology proven to reduce emissions within the automotive industry. This is achieved by injecting hydrogen into the ICE (internal combustion engine) and displacing the amount of diesel required. The HyDIME project is concerned with proving this technology in the marine industry.

The HyDIME system will interact with the Surf 'n' Turf Project where carbon free hydrogen is produced using curtailed energy from wind and tidal turbines. This hydrogen is produced at EMEC's site in Eday and is transported to Kirkwall by ferry in a dedicated hydrogen tube storage trailer (250kg) to be utilised by a 75kW fuel cell powering shoreside activities.

It is proposed that the HyDIME system will utilise 25 kg of this hydrogen as onboard fuel for the hydrogen injection.

As part of the HyDIME project, a model was to be developed to represent how the HyDIME system could ideally operate and to try quantify the impact that it would have environmentally and economically.

Simulation Modelling

To assist with assessing the impact of the HyDIME system, a model was created using AnyLogic, a Discrete Event Simulation software package. The purpose of the model is to quantify the impact that the system would have, economically and environmentally, as well as identify potential bottle necks and threats that might exist when the system is rolled out.

Modelling techniques were used in order to incorporate the complex logistics of transporting the hydrogen from one island, where it is produced to another island, where it is consumed.

Multiple assumptions had to be made when creating the simulation model. The primary reasons these assumptions were required was due to a lack of accurate information, and restrictions and difficulties within the software when trying to model the real scenario. The table on the following pages lists the assumptions in the model, what is happening in reality, and why the assumptions were necessary

Simulation modelling. Source: © Creative Images – stock.adobe.com

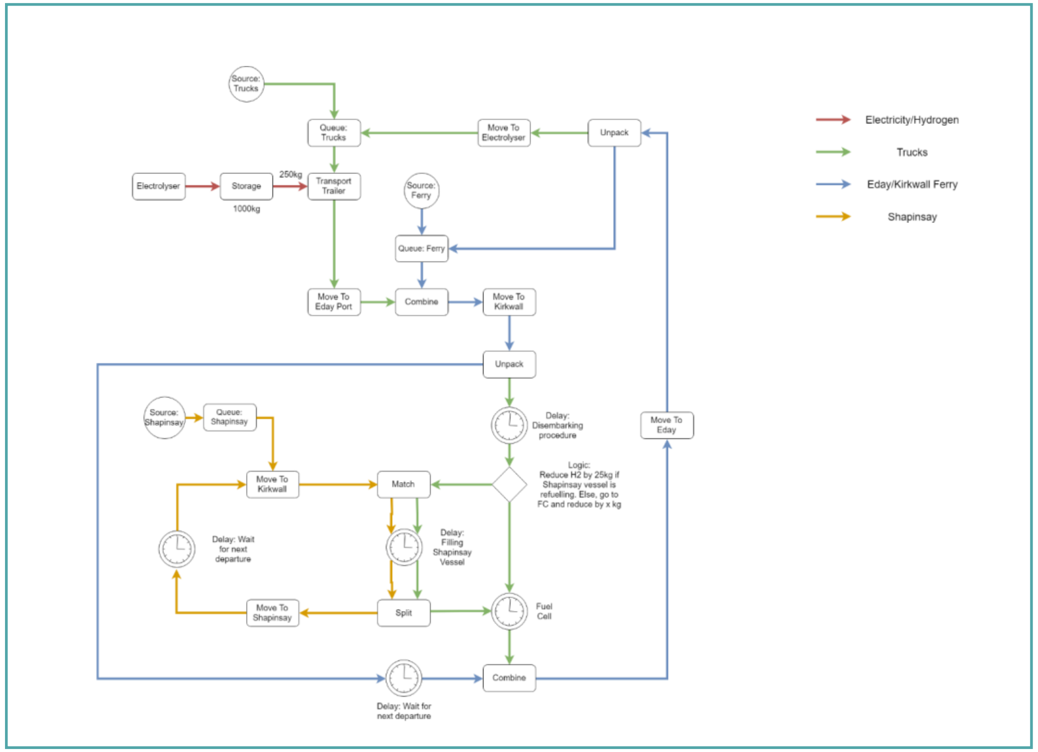
No.	Assumption	Reality	Why necessary
1	Hydrogen production at Eday electrolyser is based on 250 kg per 24 hours at max capacity and is constant	The hydrogen production rate will fluctuate according to the availability and profile of electricity that is feeding it. This profile is not constant.	Unavailable accurate data regarding the production rate of hydrogen at the Eday electrolyser
2	Inter-island ferry movement is represented by the winter timetable	There is a summer and winter timetable with slightly different timings within each timetable	Having both timetables would have insignificant effect on the model, and it was very complex to incorporate them both
3	Two of the three the hydrogen trailers act as stationary storage assets. Thus, the stationary storage at the Eday electrolyser is 1000 kg	There is 500kg of stationary storage along with three 250kg trailers.	Only one trailer can move at a time while the other two are based at the Eday electrolyser site. Therefore, it is reasonable to assume that there is 1000 kg of hydrogen storage. This reduces the complexity of the hydrogen transport logistics modelling without reducing the realism of how the model operates
4	The hydrogen trailers can be transported on all public ferries	The hydrogen trailers, when filled, can only be transported on ferries with less than 25 passengers on board	The model was deigned to simulate an ideal representation of the system. It is likely that the restrictions on transporting hydrogen will change and the assumption will soon become the reality. Model modifications were eventually made to assess the impact of the passenger restrictions (see later in report)
5	The trailer does not fully empty of hydrogen – a value of 25 kg was chosen to be left unused	An amount of hydrogen is unable to be fed to the fuel cell as the pressure is too low.	It is unknown how much hydrogen is left in the trailer once the pressure drops too low to be utilised in the fuel cell
6	The MV Shapinsay vessel can only be refilled once per trailer trip	It is unknown how the refuelling logistics of the MV Shapinsay and the fuel cell will interact. It is possible that if the MV Shapinsay empties of hydrogen before the fuel cell utilises all of the available hydrogen in the trailer, the MV Shapinsay could refill again	It makes more logistical sense for the MV Shapinsay to refuel once and for the remainder of the hydrogen be used in the fuel cell. The logistics of repeatedly moving the trailer to and from each consumption asset is unrealistic
7	Hydrogen consumption rate at fuel cell is based on that it takes 3 days to empty trailer at optimum usage. The rate of consumption is constant.	It is unlikely that the fuel cell operates at max capacity at all times at a constant rate	Unavailable accurate data regarding the hydrogen consumption rate of the fuel cell
8	Once the hydrogen trailer is emptied by the fuel cell and the MV Shapinsay vessel, if there is a full hydrogen trailer available at the electrolyser, it will be sent to replace the empty one as soon as possible	It is possible that the trailers cannot always be delivered as soon as they are required due to reasons such as unavailability of truck/trailer drivers	The availability of the hydrogen trailers to be moved from Eday to Kirkwall is unknown.

Assumptions used in simulation modelling

Base Model Operation

A high-level description of how the base model works is as follows:

1. Hydrogen is produced at the electrolyser in Eday at a specified rate and stored up to a max capacity of 1000 kg.
2. If the hydrogen trailer feeding the fuel cell is empty, a truck carrying a 250 kg H_2 trailer is sent to the Eday port where it waits for a ferry to arrive.
3. If the ferry is going to Kirkwall, the truck will board the ferry and move to Kirkwall.
4. On arrival, if the MV Shapinsay vessel needs to be refueled with hydrogen (condition for this is if capacity is <= 5 kg), it will first deposit 25 kg to the MV Shapinsay ferry. Otherwise, this step is skipped. The hydrogen on the ferry is consumed at a specified rate when the ferry is moving between islands.
5. The tractor carrying the trailer will then leave the trailer with the fuel cell and return to the Eday electrolyser on the first available ferry.
6. The trailer will feed hydrogen to the fuel cell at a specified ratel until the capacity in the trailer depletes to a specified amount.
7. Steps 2 – 4 are carried out again.
8. The truck will leave the full 250 kg trailer with the fuel cell and return the empty trailer to the Eday electrolyser where it can be refilled with hydrogen.



Conceptual model of system to be modelled. Source: HSSMI

Environmental Impact | Scenario 1: 20% Hydrogen-Diesel Displacement

The key factors for measuring the environmental impact are diesel and CO_2 reductions. Diesel displacement was calculated using correlations between the hydrogen injection percentage and the diesel consumption rate of the auxiliary unit. The CO_2 reductions could then be calculated using a simple approximation: for every litre of diesel displaced, 2.7 kg of CO_2 is displaced[1]. Depending on the type of diesel used, this value can vary slightly. It has been assumed that the fuel used for the MV Shapinsay is standard diesel.

Calculating the hydrogen used by the MV Shapinsay vessel is also an important parameter, as this represents energy that if not utilised, would otherwise be lost due to curtailment. Every kg of hydrogen requires 55 kWh of carbon free electricity. For every kwh of carbon free electricity produced, there is a saving of 0.283 kg of CO_2.[1]

The model parameters were defined, and the model was run for a full year with the MV Shapinsay vessel operating at a hydrogen-diesel displacement level of 20%.

Parameter	Value
Auxiliary Unit Diesel Consumption Rate (L/min)	0.13
Hydrogen injection percentage (%)	20
New Auxiliary Unit Diesel Consumption Rate (L/min)	0.104
Diesel Displaced (L/min)	0.026
Hydrogen Consumption Rate = Diesel Displaced/3.21 (kg/min)	0.0081

Model parameters describing hydrogen injection system properties for 20% diesel displacement

Parameter	Value
Total Diesel Displaced (L)	2,958
CO_2 Displaced from Diesel Displacement (kg)	7,926
H_2 Consumed by MV Shapinsay (kg)	824
Electricity Required to Produce H_2 Used by MV Shapinsay (kwh)	50,833
CO_2 Displaced from Carbon Free H_2 Production (kg)	14,389

Environmental results of model operating at 20% diesel displacement level

[1] *Greenhouse gas reporting conversion factors" – Department for Business, Energy and Industrial Strategy*

Environmental Impact | Scenario 1: 20% Hydrogen-Diesel Displacement

The CO_2 produced when transporting the hydrogen via public ferry is one of the key contributors to negative environmental impact. However, this transportation happens regardless of whether the HyDIME system is in place or not. It can be argued that the negative carbon footprint associated with transportation is out of the scope of this report.

On the other hand, the carbon emissions associated with transporting hydrogen for use in the HyDIME system can be calculated using the percentage of the total transported hydrogen which is used by the HyDIME system. The model was able to estimate the CO_2 emitted by the ferries transporting the hydrogen by using an estimate of the fuel consumption of the Orkney ferries. The CO_2 emissions were calculated using a ratio between the number of hydrogen refills required for the MV Shapinsay and for the fuel cell, as well as a ratio between the amount of hydrogen used by the MV Shapinsay and the total amount stored per trailer. It was calculated that approximately 3,33% of the total carbon emissions associated with the transportation of hydrogen can be attributed to the HyDIME system.

Parameter	Value
Number of Fuel Cell Refills	157
Number of MV Shapinsay Refills	48
CO_2 Emissions from Transporting Hydrogen (kg)	350,000
CO_2 Emissions Associated with Transporting Hydrogen for HyDIME Use (kg)	11,500

Number of hydrogen asset refills and associated CO_2 emissions of transporting the hydrogen (20% diesel displacement)

Parameter	Value
Total CO_2 Displaced (kg)	22,315
Total CO_2 Produced (kg)	11,500
Net CO_2 Displaced (kg)	10,815

Net CO_2 displaced for 20% diesel displacement level

Environmental Impact | Scenario 2: 60% Hydrogen-Diesel Displacement

The hydrogen injection system on the vessel has the capability of operating at up to 60% diesel displacement levels.

This new displacement level was implemented within the model and the impact it had on the outputs was captured. The MV Shapinsay consumes the 25 kg of hydrogen stored on the vessel three times faster than the previous scenario and thus is available to be refilled more often. The amount of diesel displaced annually by the vessel is increased and therefore the amount of CO_2 reduced is larger. Furthermore, due the increase of hydrogen usage, there are further CO_2 reductions from carbon free electricity consumption.

The altered model parameters and outputs of the model a are shown in the following tables.

Parameter	Value
Auxiliary Unit Diesel Consumption Rate (L/min)	0.13
Hydrogen injection percentage (%)	60
New Auxiliary Unit Diesel Consumption Rate (L/min)	0.052
Diesel Displaced (L/min)	0.078
Hydrogen Consumption Rate = Diesel Displaced/3.21 (kg/min)	0.024

Model parameters describing hydrogen injection system properties for 60% diesel displacement

Parameter	Value
Diesel Displaced (L)	8,337
CO_2 Displaced from Diesel Displacement (kg)	22,343
H_2 Consumed by MV Shapinsay (kg)	2,605
Electricity Required to Produce H_2 Used by MV Shapinsay (kwh)	143,289
CO_2 Displaced from Carbon Free H_2 Production (kg)	40,561

Environmental results of model operating at 60% diesel displacement level

Environmental Impact | Scenario 2: 60% Hydrogen-Diesel Displacement

An impact of the increasing the hydrogen diesel displacement percentage from 20% to 60% is that the MV Shapinsay needs to be refilled with hydrogen more often. This in turn increases the CO_2 emissions associated with transporting the hydrogen from Eday to Kirkwall for the HyDIME system. The proportion of the total CO_2 emissions generated when transporting hydrogen that can be attributed to the HyDIME system is now 7.14%.

Accounting for the increased negative emissions of the system operating at 60% displacement, the net CO_2 displaced is over three times larger than for 20% displacement.

Parameter	Value
Number of Fuel Cell Refills	157
Number of MV Shapinsay Refills	114
CO_2 Emissions from Transporting Hydrogen (kg)	350,000
CO_2 Emissions Associated with Transporting Hydrogen for HyDIME Use (kg)	25,500

Number of hydrogen asset refills and associated CO_2 emissions of transporting the hydrogen (60% diesel displacement)

Parameter	Value
Total CO_2 Displaced (kg)	62,904
Total CO_2 Produced (kg)	25,500
Net CO_2 Displaced (kg)	37,404

Net CO_2 displaced for 60% diesel displacement level

Environmental Impact: 20% vs 60% Diesel Displacement

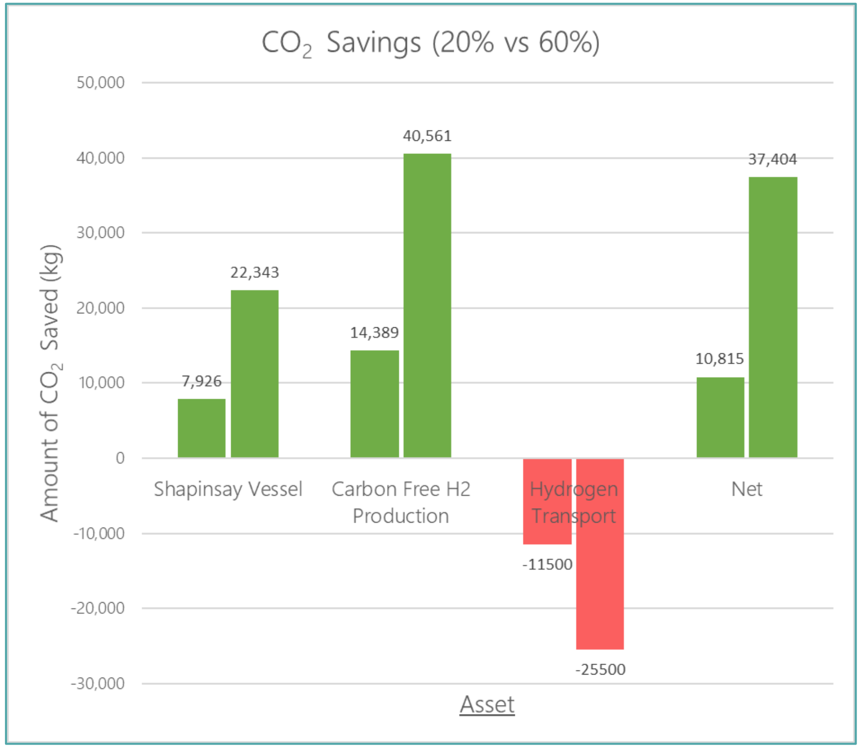
For 20% and 60% hydrogen-diesel displacement, the net yearly emissions are shown in the following tables and graph

Parameter	Value
Total CO_2 Displaced (kg)	22,315
Total CO_2 Produced (kg)	11,500
Net CO_2 Displaced (kg)	10,815

Net CO_2 displaced for 20% diesel displacement level

Parameter	Value
Total CO_2 Displaced (kg)	62,904
Total CO_2 Produced (kg)	25,500
Net CO_2 Displaced (kg)	37,404

Net CO_2 displaced for 60% diesel displacement level



CO_2 savings achieved from hydrogen injection system for 20% and 60% displacement levels

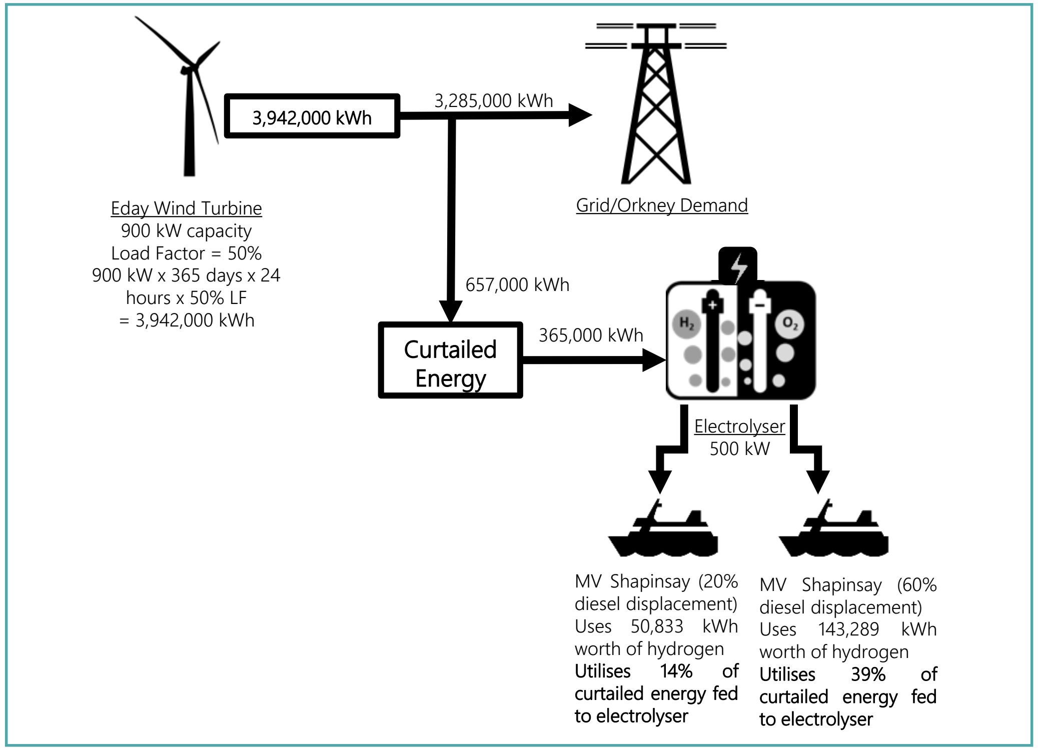
Environmental Impact | Curtailment of the Eday wind turbine

The HyDIME system is making use of curtailed energy which would otherwise be lost. An effort was made to try quantify this.

For 20% and 60% displacement, the MV Shapinsay vessel uses 50,833 kWh and 143,289 kWh worth of hydrogen, respectively. This diagram gives an approximated indication as to how the HyDIME provides a solution to the curtailment issue experienced by the Eday wind turbine.

Assumptions:

- The wind turbine has a capacity factor of 50%
- Orkney produces 120% of their demand from renewables
    - This correlates to the community wind turbine on Eday feeding 10/12ths of its electricity to the grid and the remaining 2/12ths to the electrolyser
- The electrolyser only consumes 55.5% of the electricity from the wind turbine as the electrolyser is rated at 500 kW and the wind turbine 900 kW



Overview of how the HyDIME system utilizes curtailed energy from the Eday wind turbine

Environmental Impact | Scenario 3: Altering the Hydrogen Refuelling Logistics

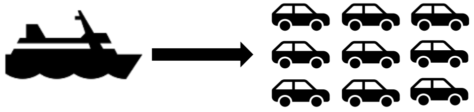
The MV Shapinsay vessel can only be refilled with hydrogen at times when the hydrogen trailer feeding the fuel cell also needs to be refilled. This means that there are times when the hydrogen trailer begins feeding the fuel cell and soon after this, the MV Shapinsay vessel requires a refill of hydrogen but cannot receive one until the fuel cell consumes all of the hydrogen from the trailer and a fresh trailer is delivered. The model was altered slightly so that a truck and trailer would only be sent to Kirkwall when both the fuel cell and the MV Shapinsay needed hydrogen refueling.

With these changes, there are only slight improvements to the performance of the full system:

- There are minimal increases in the annual quantities of diesel and CO_2 displaced, and hydrogen consumed,
- The number of times that the fuel cell is provided a new trailer of hydrogen has been significantly reduced. The hydrogen trailer cannot move to Kirkwall to feed the fuel cell unless the MV Shapinsay, which consumes hydrogen much slower than the fuel cell, also requires hydrogen.
- There are larger net CO_2 savings as there are less CO_2 emissions associated with the transport of the hydrogen as there are now less fuel cell and MV Shapinsay refills.

The new refuelling logistics ensure that the MV Shapinsay vessel is optimally refuelled and the emissions savings are greater. However, this means that the fuel cell is no longer being utilised as often and the total amount of hydrogen being used in the full system is reduced.

To put the environmental impact of the HyDIME system into perspective, for both refuelling scenarios, the net impact of the MV Shapinsay vessel's auxiliary engine operating at 60% diesel displacement reduces CO_2 emissions by the equivalent of removing approximately 9 passenger cars from the road each year.[2]



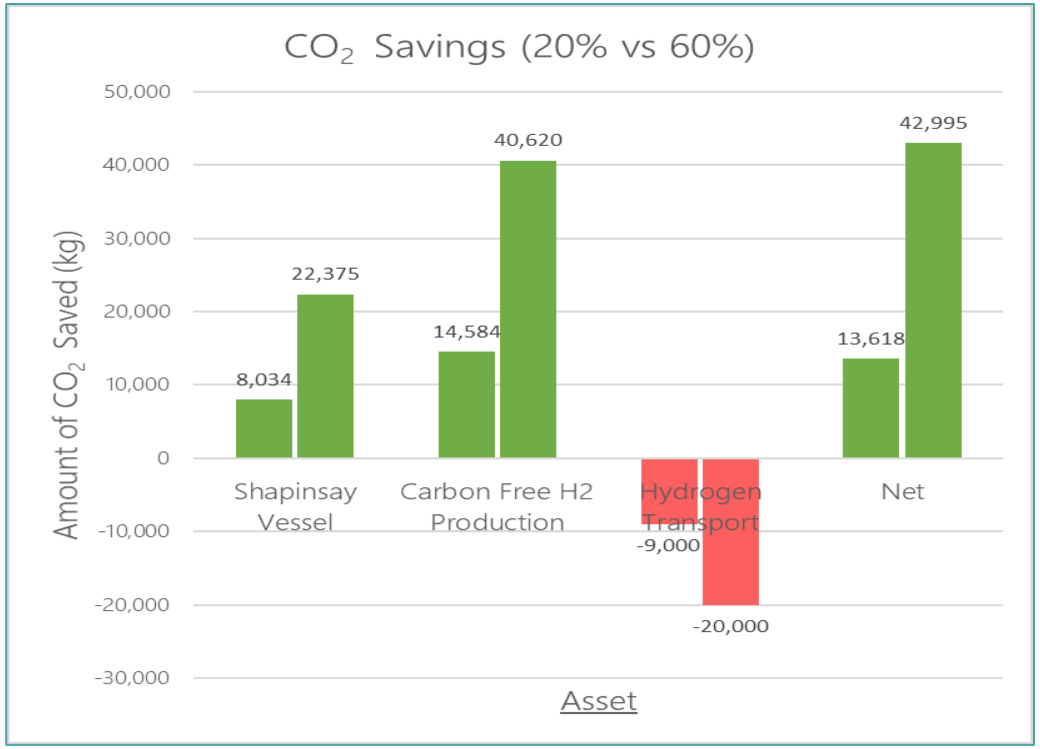
Infographic representing the CO_2 savings achieved from 60% diesel displacement

[2] https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

Environmental Impact | Scenario 3: Altering Refuelling Logistics

Parameter	Value and difference between previous model results	
Displacement Percentage	20%	60%
Total Diesel Displaced (L)	2,998 (+40)	8,349 (+12)
Total CO_2 Displaced from Diesel Displacement (kg)	8,034 (+108)	22,375 (+32)
Total H_2 Consumed by MV Shapinsay (kg)	937 (+113)	2,609 (+4)
Electricity Required to Produce H_2 Used by MV Shapinsay (kwh)	51,522 (+689)	143,499 (+210)
Total CO_2 Displaced from Carbon Free H_2 Production (kg)	14,584 (+195)	40,620 (+59)
Total CO_2 Displaced (kg)	22,618 (+303)	62,995 (+91)
Number of Fuel Cell Refills	44 (-113)	105 (-52)
Number of MV Shapinsay Refills	44 (-4)	105 (-9)
CO_2 Emissions from Transporting Hydrogen (kg)	90,000 (-260,000)	200,000 (-150,000)
CO_2 Emissions Associated with Transporting Hydrogen for HyDIME Use (kg)	9,000 (-2,500)	20,000 (-5,500)
Net CO_2 Displaced (kg)	13,618 (+2,803)	42,995 (+5,591)

Results produced after altering the refuelling logistics of the model (20% and 60% displacement levels)



CO_2 savings achieved after changing refuelling logistics For 20% and 60% displacement levels

Environmental Impact | Scenario 4: Chartered Vessels for Hydrogen Transport

Due to safety regulations, the hydrogen trailer can only board a ferry that is carrying 25 passengers or less. An attempt was made to represent this behaviour within the model by adding a function that generates a number between 0 and 150 (the min and max capacity of the ferry leaving Eday) based off a triangular distribution with a mode of 75.

The model was run at 20% and 60% diesel displacement and it was found that the hydrogen trailer and truck were only able to make 19 and 28 trips to Kirkwall for refilling, respectively, compared to the previous 42 and 105 trips achievable using any public ferry. Therefore, to ensure optimum refilling, an additional 23 and 77 trips would be required.

It is possible that in cases where the ferry has more than 25 passengers and cannot transport the hydrogen trailer, a dedicated vessel can be chartered in order to move the hydrogen to where it can be consumed. However, this would be a very costly expense and render the HyDIME system economically and environmentally redundant.

MV Shapinsay vessel sailing in Orkney. Source: EMEC

Economic Impact | Capex

One of the most attractive aspects of a hydrogen injection system as an emission reducing solution is the fact that it is retrofittable - the engine does not need to be removed from the vessel.

The cost of building a new fuel cell/hybrid vessel will dwarf that of a retrofittable solution. The Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2 JU) estimated that the CAPEX of a new build fuel cell vessel to be ~€11-15 million[3].

The hydrogen tanks are a key component of the HyDIME system and are also one of the more costly items. Hydrogen tanks can vary in price depending on size, storage pressure, and type I/II/III for example.

However, the hydrogen economy is still developing and there are limited applications for the types of tanks being utilised in the HyDIME system. Subsequently, there are no UK manufacturers of appropriate hydrogen storage tanks for use on marine vessels. To bring the costs of the HyDIME system down, and facilitate a more secure procurement strategy, the hydrogen equipment supply chain needs to be developed in the near future.

A full detailed breakdown of the HyDIME capex cannot be provided due to confidentiality reasons.

[3] https://www.fch.europa.eu/sites/default/files/FCH%20Docs/171121_FCH2JU_Application-Package_WG3_Ferries%20%28ID%202910573%29%20%28ID%202911659%29.pdf

Economic Impact | Opex

For confidentiality reasons, a full breakdown of the operational costs cannot be provided.

The HyDIME system is being coupled with the Surf 'n' Turf project and so some operating costs can be discounted.

The cost of hydrogen is key in determining the full opex cost. In order to estimate it, the cost of electricity required to produce the hydrogen and the operating cost of the electrolyser needs to be considered:

- 4-5 pence per kWh for the electricity used to produce hydrogen for the vessel (approximately, 50,000 – 140,00 kWh per year, at 20% vs 60% displacement, respectively);
- Information regarding the operating cost of the electrolyser is scarce. However, estimates generalise the operating cost of hydrogen production via electrolysis to be approximately £4 per MWh[4].
- Considering the above and with the estimation that 55kWh of electricity are required to produce 1 kg of hydrogen, the cost of hydrogen can be estimated at £2.97 per kg for the HyDIME system.

The labour costs associated with retrofitting the MV Shapinsay vessel with the necessary equipment has been approximated as 4 full working weeks' worth of labour for 4 technicians / engineers.

Vessel operators must be trained to run the upgraded MV Shapinsay. The HyDIME system requires 9 operators undergo basic IGF stream marine training plus tanker fire training.

Maintenance costs associated with the HyDIME system are difficult to estimate as this will be the first application of a hydrogen injection system in a marine application. It has been approximated as <£1,000 per year.

[4] https://www.carboncommentary.com/blog/2017/7/5/hydrogen-made-by-the-electrolysis-of-water-is-now-cost-competitive-and-gives-us-another-building-block-for-the-low-carbon-economy

Economic Impact | Cost Savings and Cost Balance

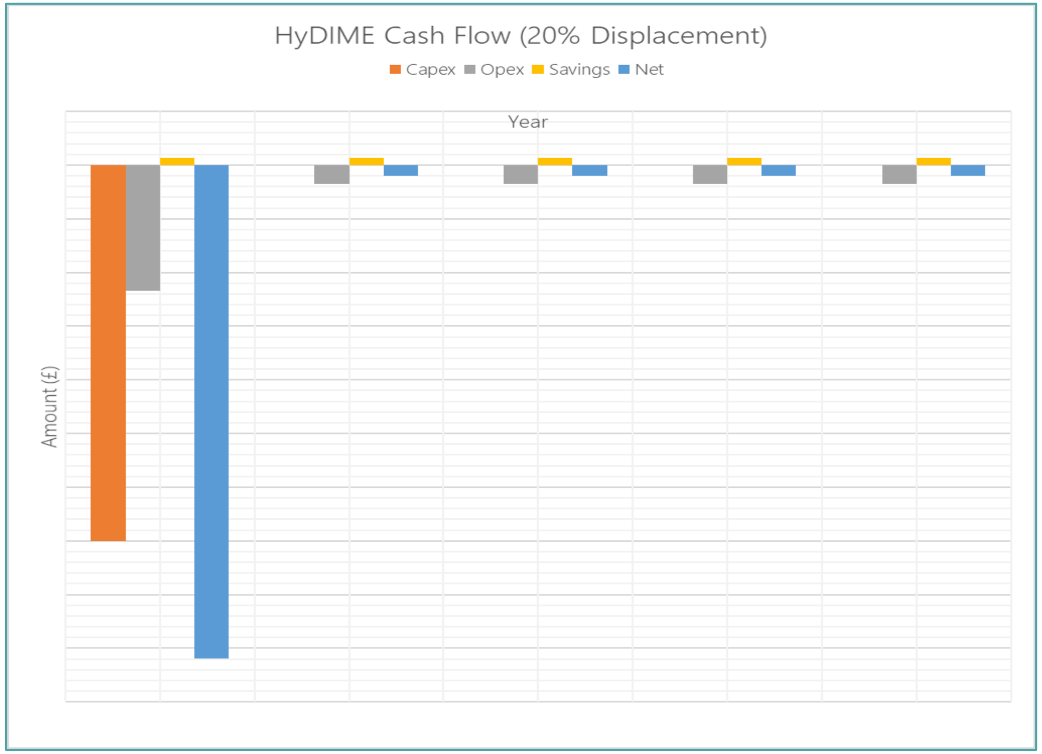
The HyDIME system displaces marine diesel and thus, there are fuel cost savings to be considered. It was estimated that between 3,000 and 8,500 L of diesel can be saved per year if operating at 20% and 60% displacement levels, respectively. Assuming, the cost of marine diesel is £0.48 per L, yearly fuel savings will be between approximately £1,400 and £4,000 depending on displacement level

The graphs on the next page represent the total net cost of running the HyDIME system at 20% and 60% over 5 years.

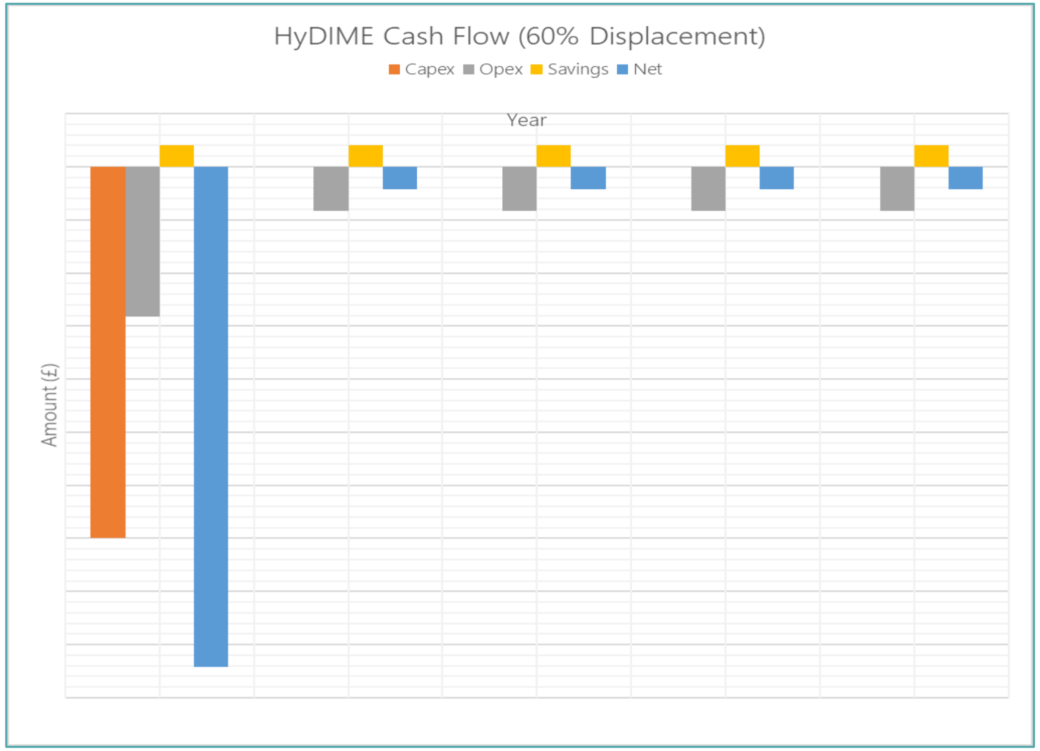
It can be seen that for both levels of displacement, there is a net loss every year as the cost savings from diesel displacement are not significant enough to outweigh the operational costs of the system. At a larger displacement level, larger volumes of diesel are being displaced and thus there are greater savings. However, since hydrogen costs approximately 6 times that of marine diesel (£2.97 per kg vs £0.50 per L), the balance of cost and the net loss is larger.

Economic modelling - © Jirapong – stock.adobe.com

Economic Impact | Cost Balance



Cost balance graph of the system operating at 20% diesel displacement



Cost balance graph of the system operating at 60% diesel displacement

Economic Impact | Potential Changes in the Future of Hydrogen

It is worth noting that these results have been estimated under the assumption that the cost of producing hydrogen and the cost of marine diesel does not change. In reality, it is likely that the cost of hydrogen will decrease as technology and efficiencies improve, and with the potential of support from government subsidies. Furthermore, the cost of marine diesel will increase due to tightening legislation around emissions.

It is likely that a carbon tax or other similar incentives will be implemented in the near future which will significantly increase the cost of diesel and provide a further incentive to move away from marine diesel and towards utilise green fuels. Once hydrogen becomes more competitively priced, a positive net cash balance can be expected.

Furthermore, the hydrogen injection system in question is a proof of concept and so is installed on the auxiliary engine of the vessel. This is a relatively small unit compared to the propulsion engine and therefore, it was expected that the fuel savings would be small. The HyDIME system also provides a further benefit to the community in that it is providing a use of the curtailed renewable energy.

One of the main messages of the HyDIME project was to demonstrate the significant emission savings that could be achieved with the technology as well as the further benefits the project brings to the community. It was expected that until there is a scaled-up version of the system in operation, and hydrogen is more competitively priced, it would not result in significant economic savings.

Societal Impact

View from the MV Shapinsay deck. Source: HyDIME Consortium

The most significant societal impact of the HyDIME project is that of the skills and capabilities being developed. Nine vessel operators will be undergoing specialised training in order to operate the retrofitted vessel and in doing so, will become some of the very first marine vessel operators within the world who can safely operate a ferry storing and utilising hydrogen as a fuel. This not only adds skill and expertise to the MV Shapinsay vessel crew in Orkney, but also to Scotland and the UK, increasing their competitiveness and furthering the ambition of being world leaders in low carbon transport.

HyDIME has been strongly disseminated throughout the duration of the project and as a result, has been featured in multiple articles, magazines and conferences. The HyDIME project and the attention it has received, will continue to support and advance Orkney's journey in becoming one of the UK's most attractive tourist destinations and the money this brings in is hugely important to Orkney's economy.

Threats and Opportunities | Curtailed Hydrogen

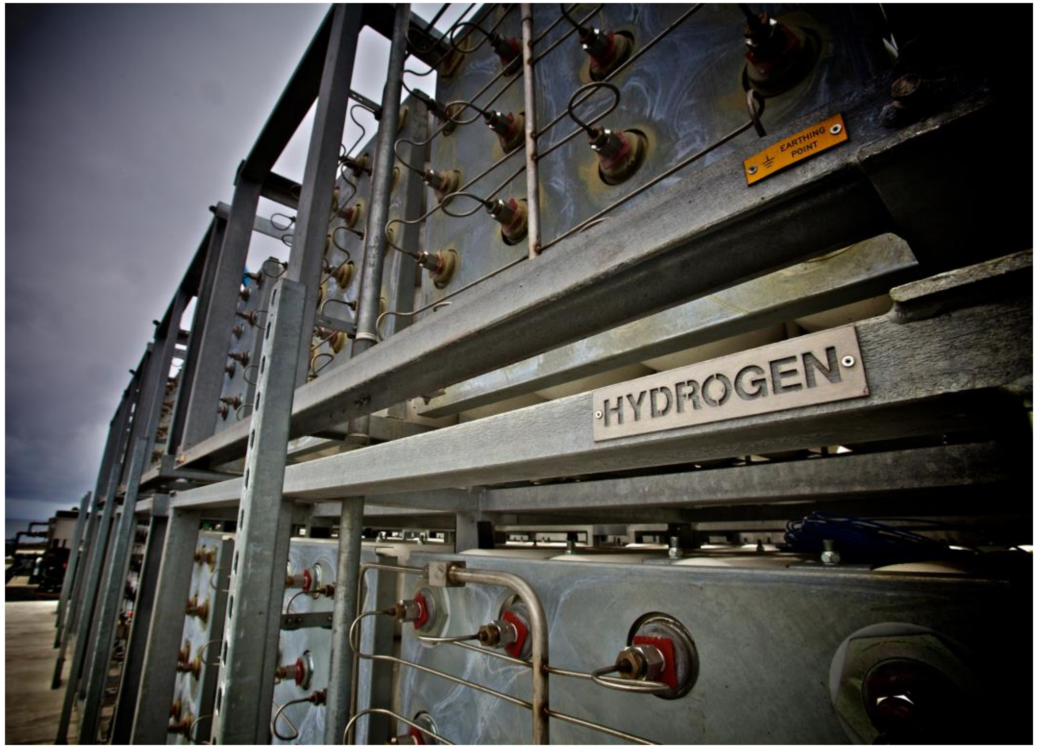
When running the model at 20% and 60% displacement, it was found that the hydrogen storage at Eday spends 315 days and 252 days of the year (86% and 69%) at max capacity. Altering the hydrogen production rate parameter to half of the max rate (0.075 kg/min) still resulted in a significant curtailment time: 266 and 139 days of the year (73% and 38%).

The primary reason for this behaviour is the fact that the production site is decentralised relative to the consumption site. Both of the systems that are consuming hydrogen are situated at Kirkwall, but the point of production is on a separate island (Eday).

The issue of curtailed hydrogen presents a strong argument to consider centralising the Orkney Isles' hydrogen production at Kirkwall. This would eliminate the lengthy timescales of transporting hydrogen between islands and allow almost immediate hydrogen refills.

Field of wind turbines. Source: © Rafa Irusta - stock.adobe.com

Threats and Opportunities | Hydrogen Transport



Electrolyser in Orkney: Source: EMEC

As discussed earlier in the report, hydrogen cannot currently be transported on public ferries which have more than 25 passengers on board. Due to the random nature of passenger numbers, it is difficult to optimise the movement of hydrogen between the production and consumption sites.

Another point to consider is that of the seasonal ferry timetables. In Summer, Orkney Ferries operate a higher number of crossings to facilitate the increased number of people visiting Orkney. This means that with the hydrogen system installed, the hydrogen onboard will likely run out quicker and will need to be refueled more often. However, due to the high number of people onboard the ferry crossings, the likelihood of a ferry having less than 25 people on board is less probable. In conclusion, there will be less hydrogen available to be transported on public ferries in times when it is needed the most.

The above points present another motive for centralising the production site or developing a dedicated hydrogen transport infrastructure.

Future Developments | Centralising H_2 Production

To assess the potential benefits of developing a centralised, large-scale hydrogen production system in Orkney, the model was altered:

- The hydrogen production site is now located at the Kirkwall port;
- The amount of static storage and production rate of hydrogen remains unchanged;
- The fuel cell and MV Shapinsay vessel can be refilled independently;
- Hydrogen refueling can take place immediately due to close proximity of production site to consumption assets.

Running this version of the model with 20% and 60% diesel displacement has very little effect on the total amount of hydrogen used by the vessel. To fully exploit the centralised production site, a larger amount of hydrogen would need be consumed.

A scaled-up version of the MV Shapinsay hydrogen injection system was also created by altering the model parameters to represent the injection system operating at 60% diesel displacement on the **propulsion** engine. To facilitate for increased hydrogen consumption, the onboard storage was increased to 100kg

Parameter	Value
Propulsion Engine Diesel Consumption Rate (L/min)	0.915
Hydrogen injection percentage (%)	60
New Propulsion Engine Diesel Consumption Rate (L/min)	0.366
Diesel Displaced (L/min)	0.549
Hydrogen Consumption Rate = Diesel Displaced/3.21 (kg/min)	0.171
Onboard Hydrogen Storage (kg)	100

Model parameters describing hydrogen injection system properties for 60% diesel displacement on propulsion engine.

Future Developments | Centralising H_2 Production – Environmental Impact

Operating the system with the propulsion unit has a significantly greater environmental impact with a net saving of almost 500 tonnes of CO_2 being displaced.

Not only is there a greater amount of diesel being displaced, but the CO_2 emissions associated with transporting the hydrogen have been eliminated. It can be argued that there is no negative emissions associated with the HyDIME system in this configuration.

Another benefit of this scaled up system is that the amount of time where the hydrogen is curtailed (reaches max storage capacity) has been significantly reduced. Comparing 60% diesel displacement on the auxiliary unit and production at Eday, with 60% diesel displacement on the propulsion engine with production at Kirkwall, results in a 50% reduction in hydrogen curtailment time (252 days vs 125 days).

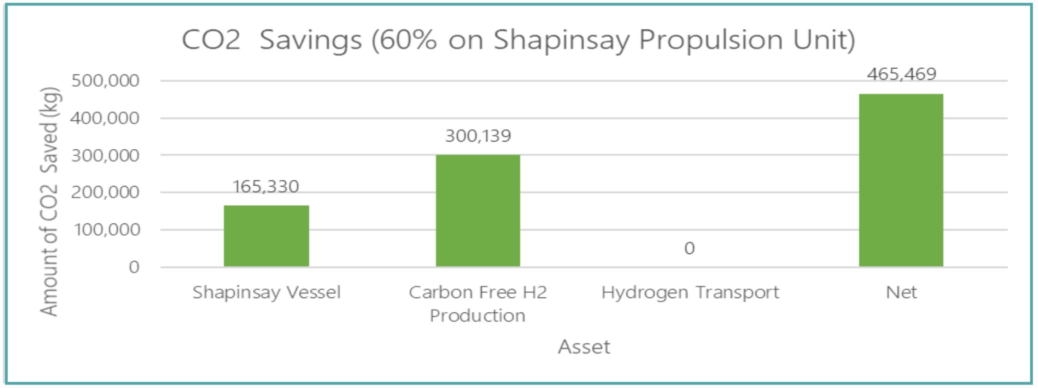
The net CO_2 savings of the system at 60% displacement on the propulsion unit are equivalent to removing 100 passenger vehicles from the road per year.

Due to the increased hydrogen consumption rate, the number of refuel operations has increased significantly. In order to operate a system such as this, there would need to be a robust strategy in place to ensure that the vessel could be refuelled when needed, whilst not interrupting normal ferry timetables and operation.

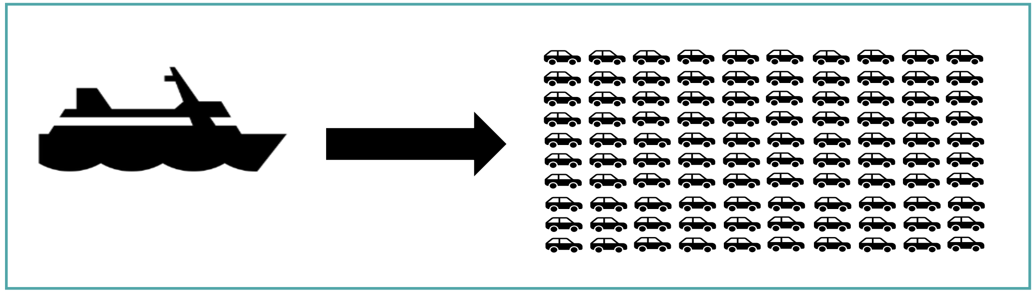
Future Developments | Centralising H_2 Production – Environmental Impact

Parameter	Value
Displacement Percentage	60%
Total Diesel Displaced (L)	63,192
Total CO_2 Displaced from Diesel Displacement (kg)	169,361
Total H_2 Consumed by MV Shapinsay (kg)	19,748
Electricity Required to Produce H_2 Used by MV Shapinsay (kwh)	1,086,155
Total CO_2 Displaced from Carbon Free H_2 Production (kg)	307,458
Total CO_2 Displaced (kg)	476,819
Number of Fuel Cell Refills	256
Number of MV Shapinsay Refills	209
CO_2 Emissions from Transporting Hydrogen (kg)	0
CO_2 Emissions Associated with Transporting Hydrogen for HyDIME Use (kg)	0
Time spent with curtailed hydrogen (days)	125 days
Net CO_2 Displaced (kg)	**476,819**
Cost Reductions Through Fuel Savings (£)	30,333

Results produced for 60% diesel displacement on vessel propulsion engine (one year of operation)



CO_2 savings achieved from 60% diesel displacement on propulsion engine



Infographic representing the CO_2 savings achieved from 60% diesel displacement on vessel propulsion engine

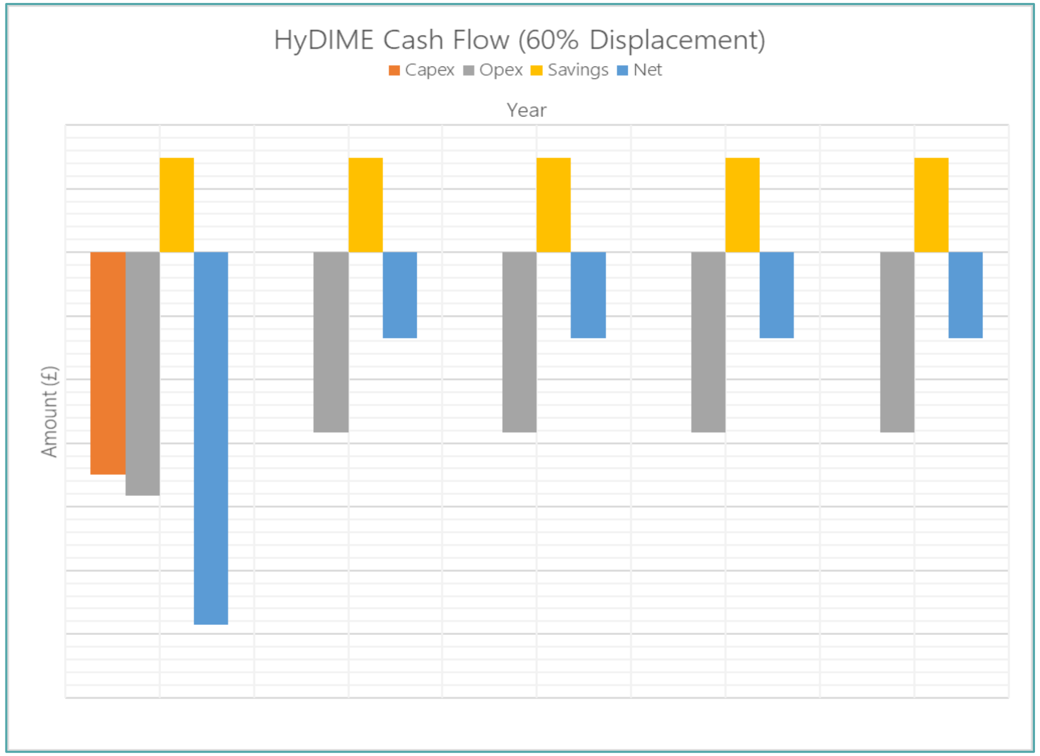
Future Developments | Centralising H_2 Production – Economic Impact

The full economic impact of this system is difficult to assess as there is no understanding of the costs associated with setting up a production infrastructure in Kirkwall. However, applying the same logic as before, a high-level overview of the operating costs can be estimated.

There is a yearly saving of 61,690 L of marine diesel fuel. At a cost of £0.48 per litre, this results in a yearly saving of £29,611.

The capex costs have been unchanged from the previous graphs. However, the cost of setting up a new production infrastructure in Kirkwall has not been included and this is likely to be a significant sum.

As before, the cost of producing hydrogen is much larger than the cost savings from diesel displacement. Until the cost of hydrogen decreases and/or the cost of diesel increases, there will always be a net loss regardless of how much diesel is displaced.



System cash flow for 60% diesel displacement on vessel propulsion unit

Future Developments | Centralising H_2 Production - Summary

From modelling a centralised production system specifically for Orkney, it was possible to conclude that this production model could facilitate a more efficient hydrogen consumption strategy. Eliminating the complex hydrogen transport logistics dictated by the number of passengers on board, and the expensive alternative of chartering a vessel specifically for transporting the hydrogen trailer, allows the consumption assets to refill independently and when necessary. This in turn, if the refuelling logistics were in place, enables the system to operate on the propulsion unit, resulting in significant emission savings.

However, the large cost of producing hydrogen coupled with the likely significant cost of setting up the hydrogen production infrastructure, means that until the cost of hydrogen decreases and/or marine diesel increases, this will be an expensive infrastructure to operate and there will be no ROI.

Kirkwall port. Source Orkney Islands Council

Replication Opportunities | Isle of Wight

Red Funnel ferry operating in the Isle of Wight. Source: visitisleofwight.com

One of the advantages of the hydrogen injection system is that it can be feasibly integrated with any vessel engine, as long as there is sufficient space for onboard storage and there is an available supply of hydrogen. As the hydrogen economy develops within the UK, more opportunities will arise for the HyDIME system to be replicated and scaled within other locations around the UK.

The Isle of Wight has ambitions to become a self-sustaining island utilizing green hydrogen as a fuel., making it the perfect platform for replicating the HyDIME system.

Red Funnel ferries have expressed interest in utilizing hydrogen as a fuel to reduce marine diesel emissions. Similarly to the Orkney Islands, the Isle of Wight also experiences periods of energy curtailment, which could be used to produce hydrogen.

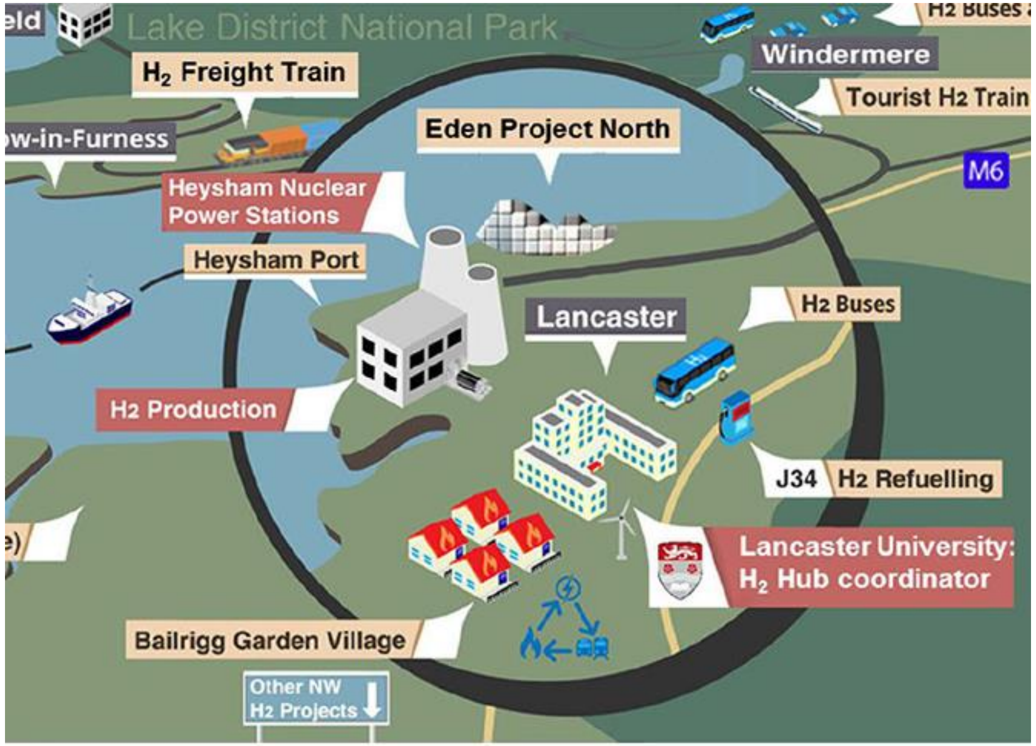
Integrating the HyDIME system within the Isle of Wight ferry services would allow the island to fully exploit their renewable energy assets to produce carbon free fuel.

Replication Opportunities | Lancaster Hydrogen Hub

Lancaster University is currently coordinating the Lancaster Hydrogen Hub, which aims to build and grow local hydrogen production, storage, and transport facilities. As part of the initiative, several key hydrogen hubs will be developed: Green H_2, H_2 Rail, H_2 Sea, H_2 Road, H_2 Transport, H_2 Energy Systems at Scale, and H_2 Research, Development, Demonstration and Innovation. Integrating the HyDIME system would allow many of the H_2 hubs to interact.

For example, coupling the Green H_2 hub, which will produce hydrogen using nuclear power plants, and the H_2 Sea hub at the Heysham Port would facilitate a hydrogen injection system onboard ships leaving the port.

To compliment the full system, the H_2 Research, Development, Demonstration & Innovation hub will be addressing fueling and transport logistics which are two of the key complexities being experienced within Orkney.



Lancaster Hydrogen Hub plans. Source: Energy Lancaster

Replication Opportunities | Western Isles

A harbor in the Western Isles. Source: © Nikokvfrmoto – stock.adobe.com

Residents of the Western Isles rely heavily on interisland ferry services and thus, with the many crossings between various locations, there are significant emissions being generated. A recent feasibility report assessed the potential for replacing the current vessels with hydrogen powered alternatives. The carbon savings are significant but replacing a full fleet of vessels with hydrogen equivalents is currently a very costly solution and will take a substantial amount of time.

Until suitable funding is secured and/or the technology is developed to a point where it is less costly to build a new hydrogen vessel, hydrogen injection would act as an effective interim solution.

The feasibility study set strong foundations for transitioning to a carbon free, hydrogen fueled fleet of vessels. Until purchasing solely hydrogen powered vehicles becomes a feasible option, hydrogen injection systems can help reduce emissions significantly without requiring invasive alterations to the vessel.

Replication Opportunities | Summary

Western Isles

- Excellent renewable potential
- Rely on interisland ferry crossings
- Potential savings of 13,000 tonnes of CO_2 with 60% diesel displacement on Stornoway – Ullapool ferry

Isle of Wight

- Operating solar plant generating 4.68 GWh of green electricity
- Experience energy curtailment - opportunity to produce hydrogen
- Rely on passenger ferries to transport residents to and from mainland (over 200 daily ferry crossings)
- Have ambitions to be self-sustaining island
- Ferry companies have expressed interest in hydrogen as a fuel

UK map showing recommended locations that could benefit from a system similar to that of the HyDIME project

Lancaster Hydrogen Hub

- Looking to develop hydrogen hubs across various industries including the regions port activities
- Using low carbon hydrogen from nuclear power plants
- Passenger ferries and large shipping vessels leave and enter the nearby port
- Aiming to have a dedicated research hub to assess hydrogen fueling and transport logistics

Conclusion

The objective of this report was to assess the potential impact of the hydrogen injection system that has been installed on the auxiliary unit of the MV Shapinsay vessel.

From an environmental point of view, the HyDIME system has the potential to offer significant emission savings through reducing diesel consumption of the ICE engine, as well as using curtailed, carbon-free electricity to produce hydrogen fuel.

From an economic perspective, the HyDIME system is unable to provide a reasonable ROI, as the cost of hydrogen, on a wide scale, is still unable to compete with marine diesel which is particularly inexpensive. However, in the future, the price of hydrogen is only going to decrease, while diesel prices will increase.

This work highlighted the most significant bottleneck within Orkney's hydrogen economy – the transportation of hydrogen between islands. A more efficient method of transporting hydrogen must be developed. This is currently being addressed as more electrolysers are planned to be deployed in Orkney to facilitate the refueling of the HySEAS III vessel – a hydrogen fuel cell powered vessel.

Until fully hydrogen powered vessels become more economical to manufacture, small scale hydrogen systems such as HyDIME can act as a stepping stone towards safely incorporating hydrogen as a fuel into the marine market.

Furthermore, it is clear that there are many opportunities throughout the UK where hydrogen dual fuel systems can be replicated and scaled.

The MV Shapinsay Vessel docked. Source: EMEC

HYDIME