6.17.10906.GLA.R.002

B5

Point and Sandwick Trust

Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH$_2$)

Feasibility Report

12 May 2019

Executive Summary

Point and Sandwick Trust, in collaboration with a range of partners, has undertaken a feasibility study as part of the proposed Scottish Western Isles Ferry Transport using Hydrogen project (SWIFTH_2).

The SWIFTH_2 feasibility study seeks to determine the viability of developing new island wind power in the Scottish Western Isles for the purposes of producing electrolytic or 'green' hydrogen. This hydrogen would then be utilised as a zero-emission fuel for a new class of hydrogen-powered ferry operating on one of the established passenger routes between the selected island and the Scottish mainland, or inter-island.

Greening the marine transport sector will be essential for meeting the Scottish Government's emissions reduction commitments. This project can assist the Scottish Government's ambition to increase low emission vessels in the publicly owned ferry fleet by 30%. It will contribute to the 37% (4.7 MtCO_2e) fall in transport sector emissions targeted for 2032 under the Scottish Government's Climate Change Plan 2018-2032[1].

Pioneering new advances in decarbonising marine transport will be valuable to Scottish industry which would gain significant expertise and first-mover advantage. Any future development will also act as a catalyst for further hydrogen deployment in the region. More widely, Scotland has a number of complementary hydrogen projects, both in existence and planned, in what can be considered a nascent hydrogen economy with a promising future given the right economic and political support.

The project can also bring important benefits at the local level. Due to the grid constrained nature of the region, new wind farm development for the purpose of power production is currently constrained by the capacity of the National Grid. The production of hydrogen would allow some of the Western Isles' renewables resource potential to be realised. This can be done in a manner which brings significant and long-lasting benefits to the local economy, businesses and communities.

To undertake the study Wood was appointed by Point and Sandwick Trust to provide feasibility study services for the consortium. This feasibility study is being partially supported by grant funding from the Scottish Government's Low Carbon Infrastructure Transition Programme (LCITP).

The participants in this project are: Point and Sandwick Trust (PST), Caledonian Maritime Assets Ltd. (CMAL), Ferguson Marine Engineering Ltd. (FMEL), Wood, Siemens Gamesa (SGRE), ITM Power, ENGIE and Johnston Carmichael Chartered Accountants (JCCA).

[1] http://www.gov.scot/Resource/0053/00532096.pdf

Scope and Methodology

CMAL provided data relating to 11 vessels operating on nine different ferry routes for evaluation. These ranged from the relatively short crossing between Gigha and Tayinloan, to the longer crossing and largest vessel between Stornoway and Ullapool. This allowed for a representative sample of ferries in the West Coast of Scotland to be analysed.

The hydrogen fuel requirement has been assessed. This has allowed for the projection of current fuel demand to a hydrogen equivalent, allowing for the higher efficiency of utilisation. A key consideration is the 'bunkering rate', i.e. how often refuelling should be carried out. It is found that daily to three times per week refuelling periods provide the best balance between the on-board storage volume required, and the range endurance required which needs to consider the longer-distance transit to dry dock for periodic vessel maintenance.

The on-board storage of hydrogen is also important as this dictates the volume of space and weight required within the vessel. Pressurisation options are considered between 350 bar and 700 bar, the alternative of liquid hydrogen storage is also discussed.

The report also considers the wind farm options potentially available, bearing in mind a range of technical, environmental and commercial factors. Some islands are considered to have limited developable wind resource available, and as such are discounted. Others have very large wind resource potential, well beyond the capacity of wind power required for the vessels under review. As an example, the largest hydrogen requirement would be for the Stornoway to Ullapool ferry: this would require 12 x 4.3 MW wind turbines for a total of ~50 MW of wind. Even this is well below the capacity of projects already being progressed by wind developers on the island.

This then leaves the question of the land-side hydrogen and grid infrastructure required, including sufficient storage to deal with variations in renewables resource and therefore hydrogen production. The study has considered various options at a conceptual level.

Conclusions

The assessment concludes that of the routes analysed, the two most viable ferry routes for conversion to hydrogen are:

- Barra to Eriskay
- Stornoway to Ullapool

Both are then evaluated in more detail. No selection is made between these in order to present two very different options (particularly in terms of scale) to the Scottish Government for further consideration. The potential emissions savings from replacement of the Barra – Eriskay and Stornoway – Ullapool routes with hydrogen vessels are ~676 and ~21,815 tonnes of carbon dioxide equivalent per annum respectively.

Financial Model

Financial modelling has been undertaken to forecast future cashflows to determine the indicative price that hydrogen could be sold to the ferry operator. The vessels on the two routes are currently fuelled by Marine Gas Oil (MGO). The indicative hydrogen price has been compared against the price paid for MGO per kWh and some suggestions are made at Section 6.1 as to how the ‘price gap’ identified could be narrowed.

The modelled assumptions are high level given the early stage of the feasibility study. The next stage would involve a more detailed feasibility study (development stage) which would seek to advance the Project design and produce more refined assumptions.

For both routes two scenarios have been modelled:

1. Base Case: Modelling the assumptions provided by the Key Partners; and
2. RTFO Case: Modelling the assumptions provided by the Key Partners and assuming the Project is eligible for Renewable Transport Fuel Obligation (RTFO).

Recommendations

Should the relevant stakeholders agree to proceed to the detailed feasibility phase, this can be undertaken on one or both of the two shortlisted ferry routes. Detailed feasibility should involve aspects pertaining to both specific site selection of a wind farm and port infrastructure, and detailed vessel design. Vessel architecture and land-side infrastructure design would be determined. Specific recommendations on the scope of such a study are presented within this report.

Alternatively it may be desirable to complete a more detailed selection process between the two options shortlisted above, to arrive at a single candidate route. This may be beneficial if time and/or resources will be too constrained to undertake detailed feasibility on both shortlisted routes and stakeholders remain uncertain as to which to take forward to the detailed feasibility phase.

Report Details

Client:	Point and Sandwick Trust
Client Contact:	Calum MacDonald
Report Distribution:	
Point and Sandwick Trust:	Calum MacDonald
Wood:	Adam Frew, Alan Mortimer
Report Classification:	Public

Approval Record

	Name	Job Title	Signature
Prepared by:	Adam Frew	Renewable Energy Consultant	
	Craig Morton	Senior Environmental Consultant	
	Rob Clayton	Renewable Energy Consultant	
	Conor O'Brien	Graduate Engineer	
	Paul McGeever	Senior Draughtsman	
	Andreas Chaimalas	Renewable Energy Intern	
Reviewed by:	Leanne Bloor	Renewable Energy Consultant	
Authorised by:	Alan Mortimer	Director of Innovation	
Date of issue:	12 May 2019		

Financial modelling content provided by Mark Conetta has been quality assured under Johnston Carmichael internal processes.

NOTICE

This document entitled *Feasibility Report,* document number 6.17.10906.GLA.R.002 B5 has been prepared solely for Point and Sandwick Trust in connection with Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH2). This document in whole or in part may not be used by any person for any purpose other than that specified, without the express written permission of Wood Group UK Limited.

Any liability arising out of use by a third party of this document for purposes not wholly connected with the above shall be the responsibility of that party who shall indemnify Wood Group UK Limited. against all claims costs damages and losses arising out of such use.

DISCLAIMER

This document is the work of its authors. The opinions and views contained reflect their knowledge, understanding and analysis of this development and the opportunities it holds for Scotland. The views of other parties named directly or implied may, but do not necessarily, accord with those of the authors. The authors have endeavoured to ensure that facts and figures quoted are as accurate as possible at the time of print however absolute accuracy is impossible to guarantee at the time of print.

The views and opinions expressed in this report are those of the contributing authors and do not necessarily reflect the views of Scottish Government and/or the Low Carbon Infrastructure Transition Programme (LCITP). No endorsement is provided by the Scottish Government and/or the LCITP.

Contents

Figures

Tables

Glossary

Abbreviation or Term	Definition
AEP	Annual energy production
CAS	Chemical Abstracts Service
CfD	Contract for difference
CGH2	Compressed gaseous hydrogen
CH_4	Methane
CMAL	Caledonian Maritime Assets Limited
COMAH	Control of major accident hazards
ConWx	Knowledge company supplying advanced weather and energy forecasting services
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
c-Si	Crystalline silicon
DSCR	Gearing, Debt Service Cover Ratio
FC	Fuel cell
FMEL	Ferguson Marine Engineering Limited
GIS	Geographic information system
HH	Hub height
HHV	Higher heating value
HICE	Hydrogen internal combustion engine
HSE	Health, safety and the environment
IMO	International Maritime Organisation
JCCA	Johnston Carmichael Chartered Accountants

Abbreviation or Term	Definition
LCITP	Low Carbon Infrastructure Transition Programme
LHV	Lower heating value
LH2	Liquid hydrogen
LLCR	Loan Life Cover Ratio
LNG	Liquid natural gas
LPA	Local planning authority
MERRA2	Modern-Era Retrospective analysis for Research and Applications, Version 2
MGO	Marine gas oil
MoD	Ministry of Defence
NATS	National Air Traffic Services
N_2O	Nitrous oxide
Ofgem	Office of Gas and Electricity Markets
OMU	Operations mobile unit
O&M	Operations and maintenance
PED	Pressure Equipment Directive (2014/68/EU): pressure equipment with a maximum pressure greater than 0.5 bar.
PST	Point and Sandwick Trust
PV	Photo-voltaic
Ramsar Sites	The Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat
REPD	Renewable Energy Planning Database
RFNBO	Renewable Fuel of Non-Biological Origin
RIW	Remote island wind

Abbreviation or Term	Definition
RTFO	Renewable Transport Fuel Obligation
SAA	Scottish Assessors Association
SAC	Special Area of Conservation
SGRE	Siemens Gamesa Renewable Energy
SPA	Special Protection Area
SSEN	Scottish and Southern Electricity Networks
TNUoS	Transmission Network Use of System
TPED	Transportable Pressure Equipment Directive
WTG	Wind turbine generator

Model Terms

Equation Variables	Definition
AEP	Annual energy production (wind turbine generator)
D	Daily operating distance
D_d	Dry dock distance
D_p	Period distance
E_b	Daily basic energy demand
E_d	Daily energy demand
E_f	Hydrocarbon period energy demand
E_h	Hydrogen period energy demand
E_p	Period energy demand
E_r	Daily energy reserve
E_s	Supply energy required

Equation Variables	Definition
HHV	Higher heating value
LHV	Lower heating value
M_f	Mass of hydrocarbon fuel required
M_h	Mass of hydrogen fuel required
P_h	Fraction of energy demand via hydrogen
P_{hd}	Hotel day power demand
P_{hn}	Hotel night power demand
P_p	Propulsion power demand
R	Fuel reserve factor
T	Period (bunkering frequency)
t_{hd}	Hotel day load duration
t_{hn}	Hotel night load duration
t_p	Propulsion load duration
u_f	Hydrocarbon energy density
u_h	Hydrogen energy density
V_f	Volume of hydrocarbon fuel required
V_h	Volume of hydrogen fuel required
Δ	Difference between period and dry dock distances
η_e	Electrolyser efficiency factor
η_h	Hydrogen power plant efficiency factor
η_f	Hydrocarbon power plant efficiency factor

1 Introduction

The Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH$_2$) project is a feasibility study investigating the viability of a new class of ferry which is powered by 'green' hydrogen generated by onshore island wind in the Scottish Western Isles. The proposal is to create hydrogen at an island location using wind powered electrolysis in a 'power-to-gas' process. The hydrogen would then be stored and utilised as a marine fuel by a hydrogen powered ferry that would operate from the island.

The study has been initiated by Point and Sandwick Trust with the aim of maximising the local economic benefit to the Western Isles from its renewable energy resources. To that end, the assumption underpinning this report is that both the wind farm and the electrolysis process will be community owned.

The purpose of this study is to carry out a high-level screening of ferry routes and potential onshore wind farm sites in the Western Isles to identify which are best suited, on the grounds of cost effectiveness and operational practicality, for further detailed investigation in a development study phase. The following criteria have been assessed to determine suitability:

- A high-level comparison of the energy and hydrogen requirements for each ferry based on power requirements, refuelling (bunkering) frequency, security of supply, and the implications for vessel equipment weight and volume.
- A high-level analysis of the potential for onshore wind farm development, hydrogen production, storage, and dispensing at or close to relevant harbours.
- Financial modelling of the most likely cost-effective ferry routes based on the estimated cost of fuel and other operational costs.

To undertake this study Wood was appointed by Point and Sandwick Trust (the Client) to provide feasibility study services for the SWIFTH$_2$ project. This study is being partially supported by grant funding from the Scottish Government's Low Carbon Infrastructure Transition Programme (LCITP).

In all, eight organisations participate in this study which together comprise the SWIFTH$_2$ consortium (the Consortium), with Wood acting as project coordinator. The complete list of participants includes:

- **Point and Sandwick Trust (PST)**: the UK's largest community-owned renewable energy company which owns the award-winning Beinn Ghrideag wind farm on the Isle of Lewis. Point and Sandwick Trust is the lead partner of the SWIFTH$_2$ project.
- **Caledonian Maritime Assets Ltd. (CMAL):** Wholly owned public corporation of the Scottish Government. CMAL own the ferries, ports, harbours and infrastructure for services in the West Coast of Scotland and the Firth of Clyde. They have provided the Consortium with high level technical data for a representative fleet of vessels to be modelled and have supported the study with technical advice.

- **Ferguson Marine Engineering (FMEL):** Port Glasgow based shipyard which is constructing the first UK passenger ferries to run on liquid natural gas and has constructed three battery hybrid ferries since 2011. FMEL have contributed technical advice to the study.
- **Wood**: A global leader in the delivery of projects, engineering and technical services to energy and industrial markets, supporting customers across the complete lifecycle of energy assets. Wood are acting as coordinator for the Consortium, have undertaken the feasibility assessments herein, and compiled the feasibility study report.
- **Siemens Gamesa Renewable Energy (SGRE)**: A leading supplier of wind turbines to the UK and overseas. SGRE have supported the project with detailed wind turbine technical information and advice.
- **ITM Power**: One of the world's leading specialists in hydrogen manufacture through electrolysis. ITM Power have provided technical data and advice relating to the hydrogen production process and electrolyser units.
- **ENGIE**: A global energy and services group, focused on three core activities: low-carbon power generation, mainly based on natural gas and renewable energy, global networks and customer solutions. ENGIE is an active founding member of the Hydrogen Council and is developing renewable hydrogen projects around the world. ENGIE have undertaken detailed technical modelling of hydrogen storage and dispensing scenarios.
- **Johnston Carmichael Chartered Accountants (JCCA)**: Scotland's largest independent firm of chartered accountants and business advisers, and specialists in renewable energy finance. JCCA have developed the financial model for this study.

It should be noted that FMEL, owing to restricted availability, have limited their contribution to technical advice. As such, no detailed naval architect input has been included in this report. Aspects relating to overall ship design are intended to be considered in the next phase of the SWIFTH$_2$ development.

This study first determines which ferry routes can be most viably operated by a hydrogen powered vessel. To undertake this task various assessment criteria have been established to appraise the localities under investigation. Additionally, hydrogen vessel design criteria have been modelled for consideration by the Consortium.

The purpose of this report is to detail the findings of the vessel modelling exercise and the route selection assessments which have been undertaken by Wood with input from the project Consortium. This document also provides content on system design and recommendations for further investigation.

1.1 Project Rationale

1.1.1 Hydrogen Option

In the Western Isles and many Scottish islands it is currently not possible to connect any new generation capacity of significant scale. For example, the Western Isles are connected by a 33 kV subsea cable which has been designated as a transmission asset so that the transmission system is continuous (33 kV would normally be a distribution connection asset). This makes the Western Isles transmission network the weakest in the country. Limited capacity has necessitated the use of diesel generators to meet peak power demand on the island because the transmission capacity is insufficient.

The SWIFTH$_2$ feasibility study seeks to determine the viability of exploiting this 'stranded' wind resource. The option proposed is to locally produce and store electrolytic hydrogen from island wind power thus avoiding the need for significant grid infrastructure. The hydrogen produced could then be utilised as a fuel by a new class of hydrogen powered ferry servicing the island hosting the wind farm and hydrogen production plant. The proposal therefore is to bring together key stakeholders to realise a commonly beneficial development.

The beneficiaries of this project will include wind farm suppliers and contractors, and the local community who would gain from a new wind farm which otherwise could not be developed. By constructing a hydrogen powered ferry to replace an existing fossil-fuelled vessel, asset owner CMAL will gain from the decarbonisation of the chosen ferry route owing to the strong environmental credentials of renewably generated hydrogen. Residents at either end of the ferry route would also enjoy improved air quality and decreased noise pollution as a result of a vessel using a hydrogen fuel cell power plant.

From a national perspective, the proposed development would aid the Scottish Government's ambition to increase low emission ferries in the publicly owned ferry fleet by 30%. This would contribute to the 37% (4.7 MtCO_2e) fall in transport sector emissions targeted for 2032 under the Scottish Government's Climate Change Plan 2018-2032[2].

The Scottish Government is committed to meeting the EU and UN targets for reducing greenhouse gases. Scotland is a coastal nation with a large publicly owned ferry fleet servicing its offshore islands. Greening the marine transport sector will be essential to meeting the Scottish Government's commitments. This is especially true given the decision by the International Maritime Organisation (IMO) in April 2018, to set a new target to reduce greenhouse gas emission from maritime transport by 50% by 2050[3].

---

[2] http://www.gov.scot/Resource/0053/00532096.pdf

[3] https://www.maritime-executive.com/article/imo-agrees-to-co2-emissions-target#gs.W4SpIkg

Hydrogen is recognised as a fuel with the potential to deliver 100% zero-carbon operation in marine transport. There are a number of initiatives around the world attempting to operationalise hydrogen for marine transport, including the HySeas project in Orkney which is supported by the Scottish Government and the European Commission.

Pioneering new advances in decarbonising marine transport will be valuable to Scottish industry which will gain significant expertise and first-mover advantage. Any future development could act as a catalyst for further hydrogen deployment in the region. Including, for example, road based transport or heat networks. More widely, Scotland has a number of complementary hydrogen projects, both in existence and at planned stage, in what can be considered a nascent hydrogen economy with a promising future given the right economic and political support.

1.1.2 Recent Developments in Marine Hydrogen

Hydrogen powered craft have been in operation at various times since the early 2000s. These have typically been smaller vessels; boats, riverboats, yachts, recreational and research vessels.

In recent years there has been increased interest in marine hydrogen applications, with an assortment of important developments in the area. The following summary lists vessels or planned vessels where hydrogen will provide partial or complete power delivery. These projects (in no particular order) are varied in scale and each represent an important development:

- **HySeas III project:** A consortium to build the world's first sea-going car and passenger ferry fuelled by hydrogen fuel cell propulsion secured EU funding in 2018. The vessel is planned to operate in and around Orkney by 2021, which is already producing hydrogen from constrained renewable energy. The project is being led by Ferguson Marine Engineering Ltd (which is also involved in SWIFTH$_2$) and St. Andrews University.
- **FellowSHIP (Fuel Cells for Low Emissions Ships) project:** FellowSHIP is a joint industry project managed by Det Norske Veritas (DNV). The project was among the first commercial fuel cell projects in the marine industry in 2009. The hybrid ship project involves a 330 kW fuel cell which has been successfully installed onboard the offshore supply vessel *OSV Viking Lady* for power around shores and ecologically sensitive areas. It has been reported to have operated for more than 18,500 hours, powered by both LNG fuel and the onboard fuel cell.
- **RCL cruise liner 'hotel' load:** Royal Caribbean (RCL) is set to install hydrogen fuel cells in their new *Icon* class ships to take up the vessels' hotel loads when docked at port, with a longer term goal of evaluating their suitability for main propulsion applications. The *Icon* class ships are due to be delivered in the second quarter of 2022 and 2024. Meanwhile, RCL are reported to have tested fuel cell technology on an existing *Oasis* class ship in 2017, and will run progressively larger fuel cell projects on new *Quantum* class vessels in the next several years.

- **Liquid hydrogen cruise liner:** Viking Cruises announced in 2017 their intention to build the world's first liquid hydrogen cruise liner capable of powering both propulsion and electrical loads from a hydrogen supply. The ship will be approximately 230 metres long and will accommodate more than 900 passengers and a crew of 500. Viking Cruises is in dialogue with Equinor (formerly Statoil) to develop a sufficiently large source of liquid hydrogen based on a Norwegian refinery.
- ***Nemo H2* passenger ship:** Developed by Fuel Cell Boat for 88 people, the 22 metre long canal boat generates power for its electric motor from a 60 kW hydrogen fuel cell. The *Nemo H2* was launched in Amsterdam in December 2009.
- ***FCS Alsterwasser* ZemShip (Zero Emission Ship):** The 100 person hydrogen power passenger ship is power-assisted by an electric motor and generates its electricity from a hydrogen fuel cell. In August 2008, the *Alsterwasser* was reported to be the first inland passenger ship in the world to set sail under fuel cell propulsion. The 25 metre long boat is run by ATG, and makes regular trips on the Alster, the inland lake at the heart of Hamburg.
- **Cheetah Marine hydrogen catamaran:** In 2016, Cheetah Marine launched a 9.95 long metre catamaran from the Isle of Wight, powered by a hydrogen internal combustion engine. The catamaran was developed as part of the Isle of Wight's now-defunct Ecoisland project, which aimed to make the island energy self-sufficient by 2020. ITM Power (which is also involved in SWIFTH_2) has built a marine refuelling station at Cheetah Marine's base in Ventnor, which produces the required hydrogen. The station was part of a £4m UK government-funded project.
- **PILOT E project:** Norway's Fiskerstrand Holding is working on a hydrogen powered ferry as part of the wider HYBRIDShips programme. The project was formally launched in January 2017 and Fiskerstrand has set an ambitious goal of having the ferry ready by 2020.
- ***Hydrogenesis* passenger boat:** Believed to be the first commercial fuel cell boat in the UK, the 12-seater *Hydrogenesis* was ordered by Bristol City Council in 2010 and initially ran for only six months in 2013. The boat was relaunched in 2016 after a refit and is now operated by Bristol Packet as a private hire passenger vessel.

1.1.3 Proposed Development

Figure 1-1 below is a high level general arrangement diagram outlining the proposed development. In summary, the principal components are the wind farm, the hydrogen production plant and dispensing equipment, and the vessel. There are various options for the system depending on the final design sought. For example; whether hydrogen is produced at the same location as the dispensing equipment (rather than at the wind farm or at an intermediate site between the wind farm and the port). In the example shown in Figure 1-1, energy is being exported from the wind farm as electricity to the port, where both hydrogen production and dispensing is done. This aspect is discussed further in Sections 7.1 and 7.2.

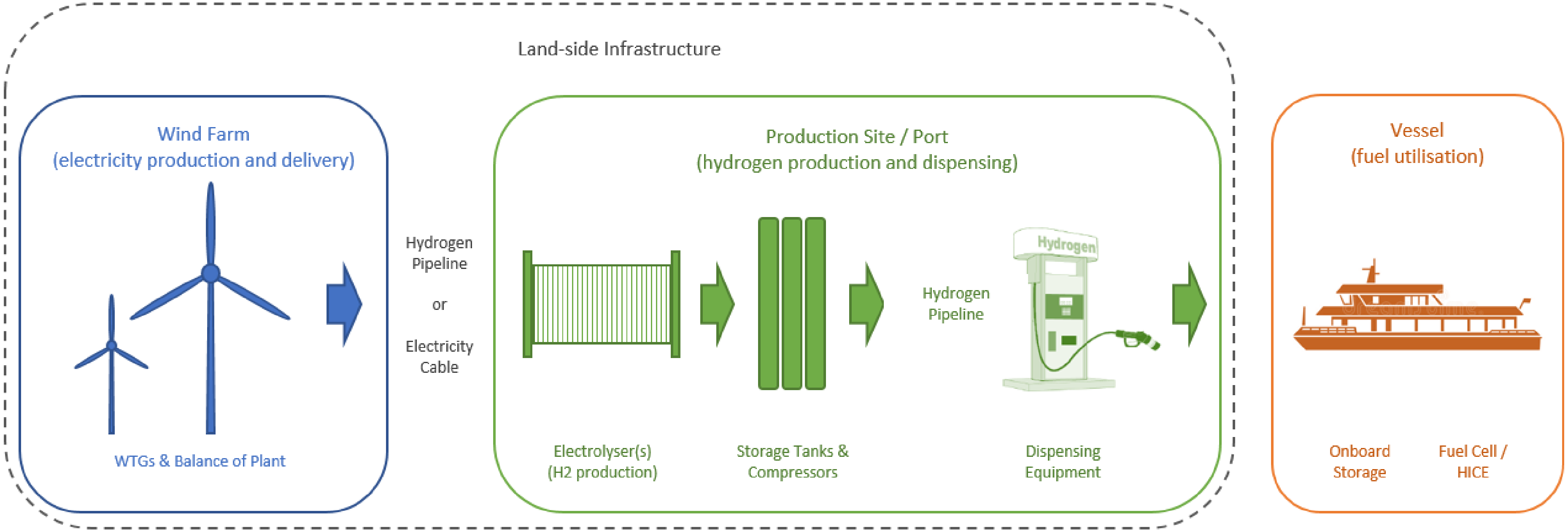


Figure 1-1 General Arrangement Diagram

1.2 Ferry Routes Analysed

Nine ferry routes were provided by CMAL for analysis as part of the SWIFTH$_2$ feasibility study including both mainland and inter-island connections. These routes were chosen as a representative sample of the 39 ferry services in operation in the region[4]. The nine ferry routes under investigation are currently serviced by 10 vessels, one on each route with the exception of the Oban - Craignure connection which has two vessels assigned to it.

A further vessel, the yet to be named '802' which will be assigned to the Uig - Tarbert - Lochmaddy route when commissioned, has also been included in the analysis. The '802' belongs to a new class of hybrid (duel-fuel) ship which runs on both traditional marine gas oil (MGO) and liquid natural gas (LNG).

The vessel currently assigned to the Ardrossan - Brodick route, the MV Caledonian Isles, will in the future be replaced by the yet to be commissioned MV Glen Sannox, also a MGO / LNG hybrid. The MV Glen Sannox is, however, not considered in this study.

It should be noted that this feasibility study makes no reference to, or has any interface with CMAL's current ferry replacement programme. The existing fleet of CMAL vessels used in this study are for indicative purposes only as comparators.

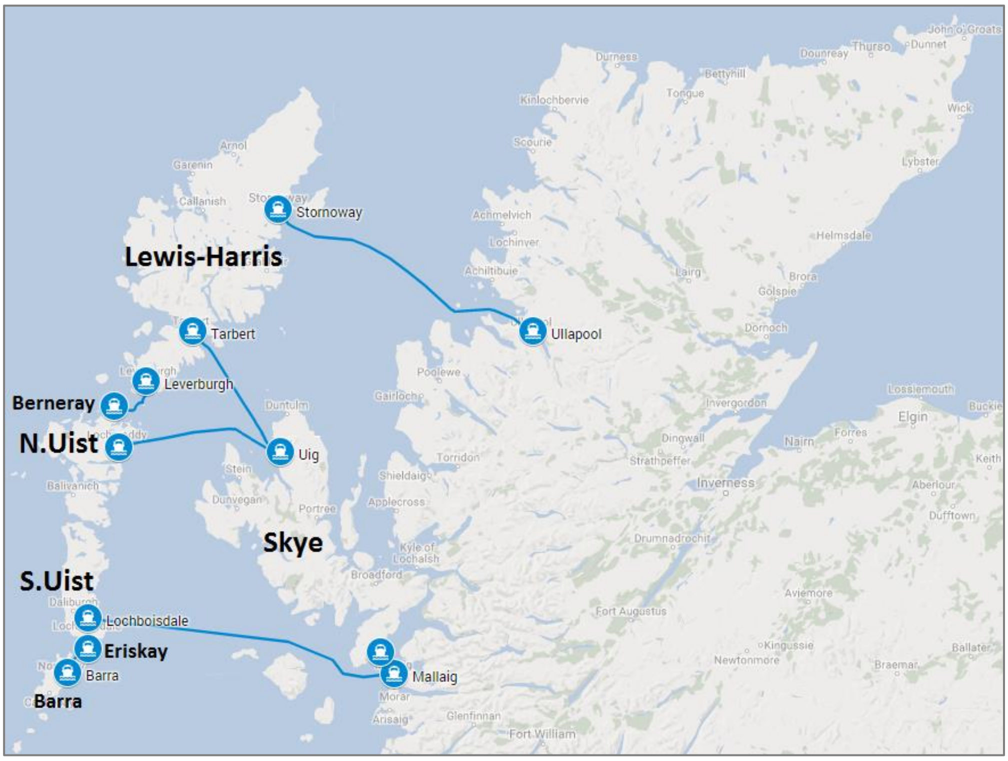


Figure 1-2 Route Summary (North)

---

[4] https://www.calmac.co.uk/calmac-summer-timetables

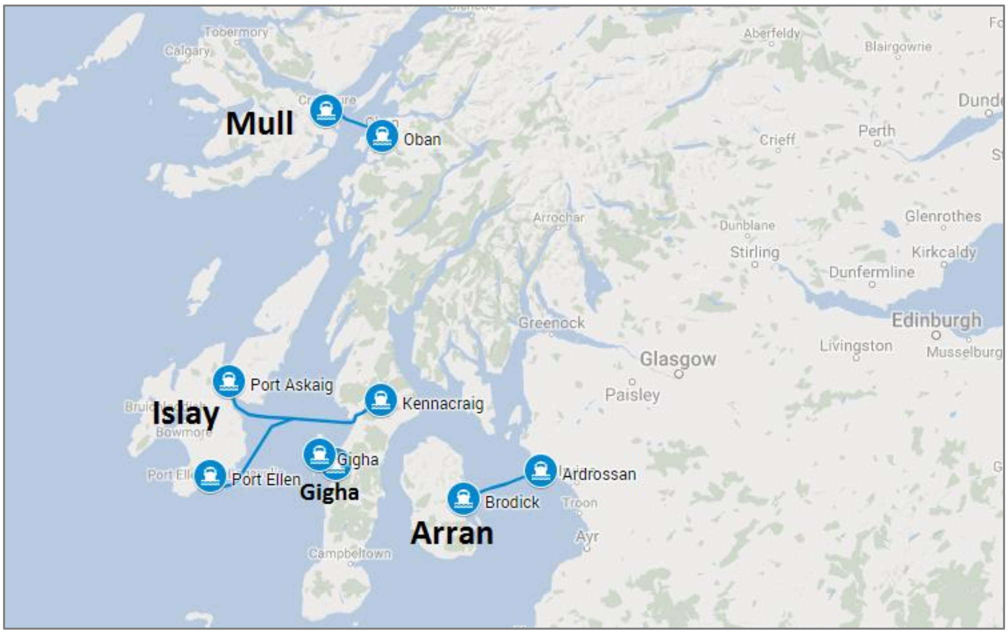


Figure 1-3 Route Summary (South)

Details for the following ferry routes were provided by CMAL for this study. Further details and route maps can be found in Appendix A.

Table 1-1 Ferry Routes Analysed

Ferry Route	Assigned Vessel(s)	Daily Distance Travelled [km]
Gigha - Tayinloan	MV Loch Ranza	81
Barra - Eriskay	MV Loch Alainn	97
Leverburgh - Berneray	MV Loch Portain	142
Craignure - Oban	MV Coruisk MV Isle of Mull	161
Ardrossan - Brodick	MV Caledonian Isles	209
Mallaig - Lochboisdale - Armadale	MV Lord of the Isles	237
Kennacraig - Port Askaig / Port Ellen	MV Finlaggan	237
Uig - Tarbert - Lochmaddy	MV Hebrides 802 (unnamed)	349
Stornoway - Ullapool	MV Loch Seaforth	541

2 Vessel Feasibility

To provide an understanding as to whether a hydrogen powered vessel could operate on one of the ferry routes under investigation, it is initially required to assess what such a vessel would look like in terms of the equipment required to be installed onboard. To do this, this study will use technical data and ship specifications of the existing CMAL fleet in order to:

1. Gain an understanding of the energy profile of the existing marine gas oil (MGO) fuelled vessels to model equivalent hydrogen systems. CMAL have provided energy consumption profiles for each vessel.
2. Express hydrogen equivalent systems in terms of the dimensions of the existing ships so as to provide convenient benchmarks. Note, it is expected that any hydrogen vessel proposed will be realised within a new build and not be a retrofit of an existing vessel, per comments from CMAL on this subject.

Firstly, the volume of onboard space required for hydrogen fuel is calculated for each vessel in order for it to service both its assigned operational route and the required range to dry dock facilities. Section 2.2 tests some key design considerations including fuel compressions, dry dock ranges, and indicative wind farm sizing.

The first two design considerations heavily influence the size of onboard fuel storage required and are tested against a range of set bunkering (refuelling) frequencies: daily, thrice weekly, twice weekly, weekly, and every 10 days in order to limit the scope of the analysis. The final scenario (wind farm sizing) is unaffected by bunkering frequency as this parameter does not change the overall annual hydrogen consumption.

It is important to note that the feasibility study has been conducted at a high level utilising the basic principal of comparison between the use of marine gas oil within the CMAL fleet and the potential future use of hydrogen as an alternative fuel source.

The benchmark of this comparison being measured in relation to the volumetric and weight consideration of each of the aforementioned fuel types only, in order to provide the medium for propulsion of a future hydrogen vessel design.

A high level propulsion system utilising conventional diesel driven components has been modelled against a comparable hydrogen fuel cell comparator. However, no assessment of the following points has been considered at this stage.

- Effect on basic particulars of a future vessel (length, breadth, depth, lightship, deadweight, speed).
- Hydrogen fuel cell integrated propulsion system design.
- Machinery arrangement configurations.
- Safety considerations, systems and legislation.
- Effects on timetables and services.
- Maintenance scheduling.

- Crew and training.
- Through-life costs.

It is important to note that in order to assess the aforementioned points a detailed ship design study would be required to be undertaken.

2.1 Model Methodology

This section sets out the methodology employed to model the design considerations mentioned above. Outcomes have been circulated across the Consortium for discussion and feedback, with certain design options established for further analysis. Section 2.3 therefore provides a more detailed opinion on what a hydrogen propulsion system (the onboard equipment) would look like in terms of masses and internal volume requirements. The vessels are subsequently appraised and scored according to their performance against key benchmarks as outlined in Section 2.3.5.

2.1.1 Hydrogen Fuel Requirement

The following steps were undertaken to derive fuel volumes and masses for daily energy demand. Please refer to the glossary of model terms at the start of this report for a full set of definitions. Appendix C contains the values chosen for the model variables.

Step 1 - Calculating Daily Energy Demand

CMAL has provided data on each vessel's daily power consumption and load durations. Power consumption is provided for both the propulsion load and the hotel load (climate control, communications, entertainment, lighting, refrigeration, water desalination and treatment, etc).

This data has been incorporated into the feasibility model as a daily basic energy demand (E_b). This daily energy consumption comprises the total number of return trips the assigned vessel makes for each route which was also provided for in terms of distance:

$$E_b = \left(P_p t_p\right) + \left(P_{hd} t_{hd}\right) + \left(P_{hn} t_{hn}\right)$$

Step 2 – Incorporating Reserve

In order to provide a degree of built-in redundancy and security, a fuel reserve (R) has been factored into the daily energy demand required to provide the value for daily energy reserve, (E_r):

$$E_r = R \cdot E_b$$

The daily energy demand (E_d), internal fuel requirement, and volume inclusive of the reserve factor is therefore defined as:

$$E_d = E_b + E_r$$

Step 3 – Applying Bunkering Frequency Variable

To extrapolate energy demand beyond the daily operational profile of each vessel a bunkering frequency factor (T) is applied to determine the period. The model limits this factor to a number of set variables: daily (1), thrice weekly (2.3), twice weekly (3.5), weekly (7), and every 10 days (10). This results in the energy requirement (including reserve) for the period (E_p):

$$E_p = T \cdot E_d$$

Step 4 – Energy Delivery Fractions and Power Plant Efficiencies

To arrive at the total hydrogen energy to be delivered over the period (E_h), the fraction of energy to be delivered by hydrogen must be applied as a factor (P_h). A pure hydrogen vessel being powered by 100% hydrogen being (P_h = 1) or a hybrid system employing both hydrogen and a hydrocarbon fuel, such as marine gas oil (MGO) or liquid natural gas (LNG), being ($0 < P_h < 1$). A hydrogen power plant (fuel cell or gas engine) efficiency factor (η_h) is also applied:

$$\boldsymbol{E_h = \frac{E_p}{\eta_h} \cdot P_h}$$

Equation 2-1

The model therefore calculates the resulting non-hydrogen fraction of energy required (E_f) using a hydrocarbon power plant efficiency factor (η_f) to meet demand as:

$$E_f = \frac{E_p}{\eta_f} \cdot (1 - P_h)$$

Equation 2-2

Step 5 – Conversion of Energy Demand to Fuel Volumes

To size the onboard space to hold the fuel required for each vessel for any given design variables, the energy to be delivered over the modelled period (E_h) and where applicable (E_f) must be converted from megajoules to litres. These volumetric figures are for fuel fluid only and can be considered the internal tank volumes, (V_h) and (V_F):

$$V_h = \frac{E_h}{u_h}, V_f = \frac{E_f}{u_f}$$

Where, (u_h) is the hydrogen energy density for a given compression and (u_f) is the energy density for the chosen hydrocarbon fuel selected where applicable as measured in MJ/L.

Step 6 - Conversion of Energy Demand to Fuel Masses

The equivalent masses of hydrogen and hydrocarbon fuels (M_h and M_f respectively) are also calculated using the lower heating values (LHV) for hydrogen and where applicable MGO or LNG.

$$M_h = \frac{E_h}{LHV_h}, M_f = \frac{E_f}{LHV_f}$$

Further analysis on tank wall thicknesses, dispensing apparatus, power plant, etc will need to be undertaken from a naval architecture perspective in order to establish the total internal vessel space required for any solution.

2.1.2 Dry Dock Ranges

The following steps are undertaken to determine if the fuel volumes calculated in Step 5 of the previous section are sufficient for each vessel to reach an annual journey to dry dock facilities as detailed further in Section 2.2.2.

As energy consumption data for the annual dry dock journeys by each vessel was unavailable at the time of writing this report version, the feasibility model has been designed to assess this minimum fuelling requirement based on distance alone.

Step 1 – Apply Bunkering Frequency Factor to Operational Route Distances

The bunkering frequency of the vessel will play a large part in the sizing of on board fuel requirement. The distance covered by the daily operating route (*D*) is multiplied by the bunkering frequency factor (*T*) to attain the period distance covered. The fuel reserve factor (*R*) is also applied to provide a degree of fuel security.

$$D_p = T \cdot D \cdot (1 + R)$$

Step 2 – Find Difference Between Period Distance and Dry Dock Distances

The difference between the period distance (D_p) and the distance to dry dock (D_d), (Δ), determines if the distance to be covered by the bunkering frequency also allows travel to one or more suitable dry dock locations. The fuel reserve factor (*R*) is further applied to the dry dock distance.

$$\Delta = D_d \cdot (1 + R) - D_p$$

If (Δ) results in a negative number then distance travelled on the operational route between bunkering is greater than the distance to reach a chosen dry dock location. Hence, the fuel sizing to meet the operational route energy demand can be considered sufficient to reach dry dock. Conversely, a positive number implies that the dry dock facility cannot be reached and therefore does not meet the minimum sizing required.

2.1.3 Wind Farm Sizing

Once a required quantity of hydrogen is designed for, the model calculates the commensurate number of wind turbine generators (WTGs) required to meet this demand. The following steps are undertaken to convert hydrogen demand to wind farm size.

Step 1 – Calculating Annual Hydrogen Supply

This step is performed on the hydrogen component of energy demand only, (E_h) which is converted to an annualised hydrogen supply (E_s) by taking into account the bunkering period (T). An electrolyser efficiency factor is (η_e) is also factored in to compensate for losses.

$$E_s = \frac{365.25 \cdot E_h}{T \cdot \eta_e}$$

Step 2 – Converting to WTG Equivalent

The number of WTGs required is obtained by dividing the annual energy supply by the annual energy production (AEP) figure for a given WTG and location.

$$No.WTG = \frac{E_s}{AEP}$$

2.2 Design Considerations

2.2.1 Fuel Compression

A variety of hydrogen compressions have been analysed. The model as currently set up assesses hydrogen storage at compressions of 350 bar, 700 bar and liquid hydrogen. This section calculates the volume of hydrogen required at each compression/state for all vessels under analysis assuming 100% energy delivery via hydrogen fuel.

2.2.1.1 Methodology

Assuming a pure hydrogen energy delivery system ($P_h = 1$), the scenario is executed by setting (u_h) as 8.50, 4.76 and 2.84 MJ/L for LH2, 700 bar and 350 bar respectively. This is repeated for all bunkering frequencies under investigation varying (T) as daily (1), thrice weekly (2.3), twice weekly (3.5), weekly (7), and every 10 days (10).

It has been agreed by the Consortium that a key aim of the study should be to investigate the viability of a purely hydrogen fuelled vessel as the starting point and not consider a hybridised (duel-fuelled) system unless said preferred starting position proves unviable.

A ferry fuelled purely by hydrogen, employing a fuel cell and battery power delivery system (as opposed to a hydrogen internal combustion engine), would be able to claim zero nitrogen oxide and carbon dioxide emissions, and noise pollution abatement.

Therefore, feasibility modelling has been undertaken on the basis of a 100% hydrogen energy delivery system. Appendix D provides results of hydrogen compression scenarios which initially informed the Consortium in the early stages of the study and is included therein for reference.

Table 2-1 Key Design Inputs & Assumptions

Parameter	Value / Setting
Hydrogen energy delivery (P_h)	1
Power plant*	Hydrogen fuel cell
Power plant efficiency[5] (η_h)	0.4
Fuel reserve[6] (R)	0.2
Bunkering frequency	Vessel period energy demand assumes uniform demand every day of the year.

*A fuel cell power plant has also been assumed as there will be no requirement for fuel blending within an internal combustion engine.

2.2.1.2 Results

The results from the vessel feasibility model (using the key input variables described in Section 2.2.1.1) are shown in the charts below. The volumes of hydrogen fuel required for each vessel and the mass equivalents (using the lower heating value) are shown in ascending order for the three fuel compressions/states considered. This has been undertaken for daily and thrice weekly bunkering frequencies. The data displayed in Figure 2-1 and Figure 2-2 is partially reproduced in Table 2-2, Table 2-3 and Table 2-4 below.

As can be seen, liquid hydrogen (LH2) offers the most advantageous fuel storage method, requiring substantially less fuel volume than hydrogen stored as a compressed gas (CGH2) at 350 bar. It is worth considering that although LH2 offers significant volume savings, the 'real' equipment volumes consisting of storage tanks, fuel cells, and ancillary systems remain to be calculated. This aspect is discussed further in Section 2.3.

[5] Value recommended by ITM Power

[6] Value recommended by CMAL.

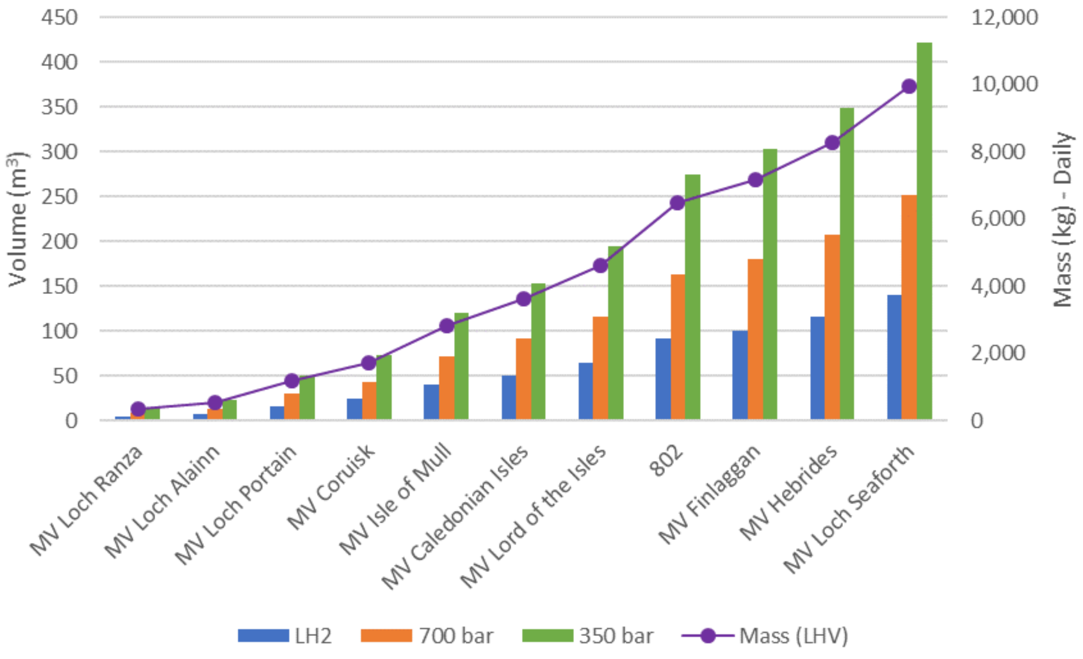


Figure 2-1 Daily Bunkering Frequency

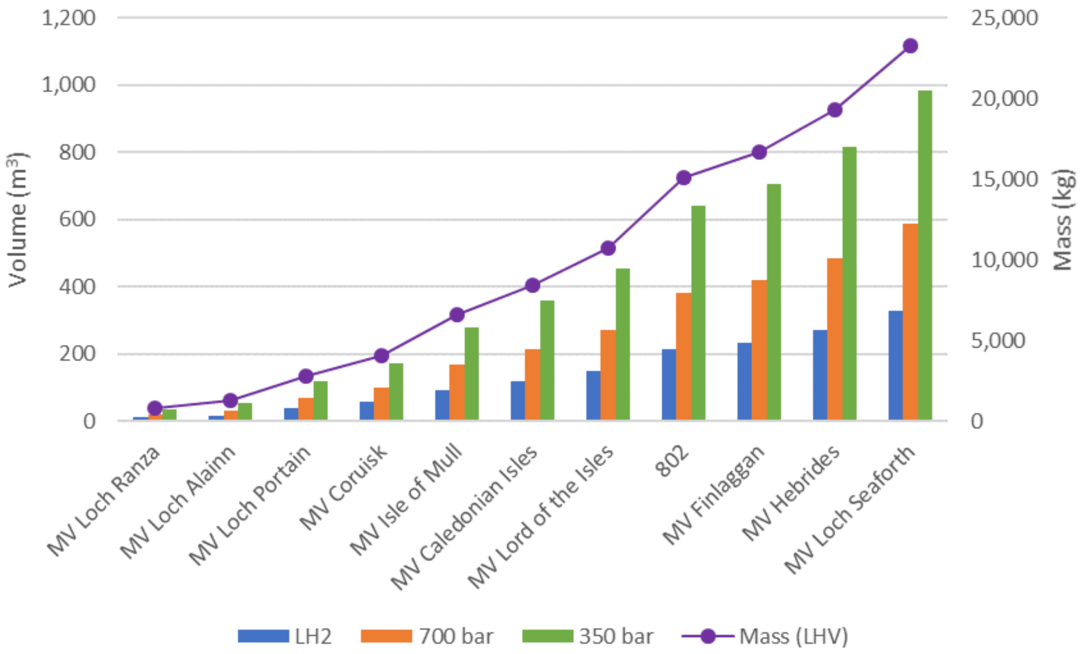


Figure 2-2 Thrice Weekly Bunkering Frequency

Table 2-2 Fleet MGO Storage Capacities Vs LH2

Vessel	MGO Storage Capabilities [m^3]	Volume Req'd for Daily H_2 Bunkering [m^3]	Variance	Volume Req'd for Thrice Weekly H_2 Bunkering [m^3]	Variance
MV Loch Ranza	11.70	4.95	6.75	11.56	0.14
MV Loch Alainn	24.20	7.86	16.34	18.34	5.86
MV Loch Portain	24.60	16.89	7.71	39.40	-14.80
MV Coruisk	63.70	24.51	39.19	57.19	6.51
MV Isle of Mull	126.40	40.23	86.17	93.86	32.54
MV Caledonian Isles	97.20	51.17	46.03	119.40	-22.20
MV Lord of the Isles	107.90	64.95	42.95	151.55	-43.65
802	144.20	91.41	52.79	213.28	-69.08
MV Finlaggan	137.10	100.93	36.17	235.51	-98.41
MV Hebrides	92.70	116.60	-23.90	272.06	-179.36
MV Loch Seaforth	308.90	140.60	168.30	328.08	-19.18

Table 2-3 Fleet MGO Storage Capacities Vs 700 Bar Hydrogen

Vessel	MGO Storage Capabilities [m^3]	Volume Req'd for Daily H_2 Bunkering [m^3]	Variance	Volume Req'd for Thrice Weekly H_2 Bunkering [m^3]	Variance
MV Loch Ranza	11.70	8.85	2.85	20.65	-8.95
MV Loch Alainn	24.20	14.04	10.16	32.75	-8.55
MV Loch Portain	24.60	30.16	-5.56	70.38	-45.78
MV Coruisk	63.70	43.79	19.91	102.17	-38.47
MV Isle of Mull	126.40	71.86	54.54	167.67	-41.27
MV Caledonian Isles	97.20	91.41	5.79	213.29	-116.09
MV Lord of the Isles	107.90	116.02	-8.12	270.72	-162.82
802	144.20	163.28	-19.08	380.99	-236.79
MV Finlaggan	137.10	180.30	-43.20	420.71	-283.61
MV Hebrides	92.70	208.28	-115.58	486.00	-393.30
MV Loch Seaforth	308.90	251.17	57.73	586.06	-277.16

Table 2-4 Fleet MGO Storage Capacities Vs 350 Bar Hydrogen

Vessel	MGO Storage Capabilities [m^3]	Volume Req'd for Daily H_2 Bunkering [m^3]	Variance	Volume Req'd for Thrice Weekly H_2 Bunkering [m^3]	Variance
MV Loch Ranza	11.70	14.85	-3.15	34.66	-22.96
MV Loch Alainn	24.20	23.56	0.64	54.97	-30.77
MV Loch Portain	24.60	50.62	-26.02	118.12	-93.52
MV Coruisk	63.70	73.48	-9.78	171.46	-107.76
MV Isle of Mull	126.40	120.59	5.81	281.39	-154.99
MV Caledonian Isles	97.20	153.41	-56.21	357.95	-260.75
MV Lord of the Isles	107.90	194.71	-86.81	454.33	-346.43
802	144.20	274.03	-129.83	639.39	-495.19
MV Finlaggan	137.10	302.59	-165.49	706.04	-568.94
MV Hebrides	92.70	349.55	-256.85	815.61	-722.91
MV Loch Seaforth	308.90	421.51	-112.61	983.53	-674.63

2.2.1.3 Key Findings

Hydrogen fuel volumes for a 100% hydrogen vessel (using the assumptions detailed in Section 2.2) have been calculated in the previous section alongside information provided by CMAL on current vessel MGO storage capabilities for various bunkering frequencies.

Table 2-2, Table 2-3 and Table 2-4 demonstrate the difference in internal volumes (variance) required for hydrogen fuel at the compressions/states analysed in cubic metres compared to the total internal volumes given over to MGO fuel in existing vessels. These have been considered for two bunkering frequencies: daily and thrice weekly.

A positive variance demonstrates hydrogen volumes equal to or less than the existing MGO storage capability, a negative variance demonstrates hydrogen volumes in excess of existing MGO storage capability for a given vessel.

The results show that for a daily refuelling profile, the internal volume of space required for a 100% hydrogen vessel can be considered comparable to that of existing volumes dedicated to MGO. However, it is important to caveat this result by stating that current MGO vessels carry enough onboard storage for many days' worth of fuel. The findings demonstrate that this is true for all but one of the vessels if liquid hydrogen storage is considered, six vessels if hydrogen at 700 bar compression is used, and two vessels if hydrogen at 350 bar compression is used.

For a thrice weekly refuelling profile, for all routes, hydrogen volumes in excess of existing MGO storage capacities are required, with the exception of four vessels if employing liquid hydrogen storage (LH2). It will be for a naval architect to determine the maximum internal volume that each vessel can dedicate to hydrogen fuel storage. Therefore the figures below should not automatically be viewed as prohibiting for the project.

For the purposes of this study, a fuel compression of 520 bar will be used to investigate the other aspects of the proposed project, particularly in Section 2.3 which relates to onboard fuel and equipment. The modelling of refuelling will be subsequently limited to higher frequency bunkering rates to reflect the findings of this section.

2.2.2 Dry Dock Range

In addition to the normal operational profile of the vessels and associated routes, it is required that any fuel sizing solution is capable, as a minimum, of providing enough fuel storage for the vessel to make an annual journey from its designated home port to a suitable dry dock facility for routine maintenance and repair.

CMAL have provided the locations of dry dock facilities around the UK utilised by their fleet. Each ferry route has a designated home port from which the serving vessel berths overnight, the distance from this location to dry dock facilities capable of servicing them has been projected.

2.2.2.1 Methodology

Each vessel under investigation has been assigned two or more suitable dry dock locations available for it to use. It has been recommended by CMAL that the farthest dry dock location for each vessel can be considered the minimum fuel sizing requirement. Each vessel has been analysed against all applicable dry docks for each pre-defined bunkering frequency with the following assumptions:

- Only enough hydrogen for a single one-way journey is required as per CMAL recommendation, with no alteration to vessel speeds.
- Fuel reserve (*R*) of 0.2 as per recommendation from CMAL (expressed in km).

To determine whether the fuel capacity using the design criteria above meets the requirements to reach at least one suitable dry dock facility the distance covered by the operational route is subtracted from the distance required to reach a dry dock. See Section 2.1.2 for further methodology detail.

2.2.2.2 Results

The results of the analysis are shown below in Table 2-5 and illustrated in Figure 2-3 to Figure 2-7 below. Most of the vessels have at least two dry dock options available to it, with the MV Loch Seaforth having a third option. The dry docks considered include Dales Marine in Aberdeen (A), Garvel Clyde in Greenock (G), Cammell Laird in Liverpool (L), Babcock Maine in Rosyth (R), and Dales Marine in Troon (T). The distances each vessel must travel from its home port to each of the dock options have been projected as follows:

Table 2-5 Distances to Dry Docks

Vessel	Home Port	Estimated Distance to Dry Dock [km]		
		Option 1 (Farthest)	Option 2	Option 3 (Nearest)
MV Loch Ranza	Gigha	205 (G)	154 (T)	-
MV Loch Alainn	Barra	448 (G)	396 (T)	-
MV Loch Portain	Berneray	508 (G)	456 (T)	-
MV Coruisk	Craignure	751 (A)	328 (G)	-
MV Isle of Mull	Oban	769 (A)	324 (G)	-
MV Caledonian Isles	Ardrossan	998 (A)	64 (G)	-
MV Lord of the Isles	Lochboisdale	642 (A)	449 (G)	-
802	Uig	564 (A)	511 (G)	-
MV Finlaggan	Kennacraig	877 (A)	229 (G)	-
MV Hebrides	Uig	564 (A)	511 (G)	-
MV Loch Seaforth	Stornoway	772 (L)	698 (R)	502 (A)

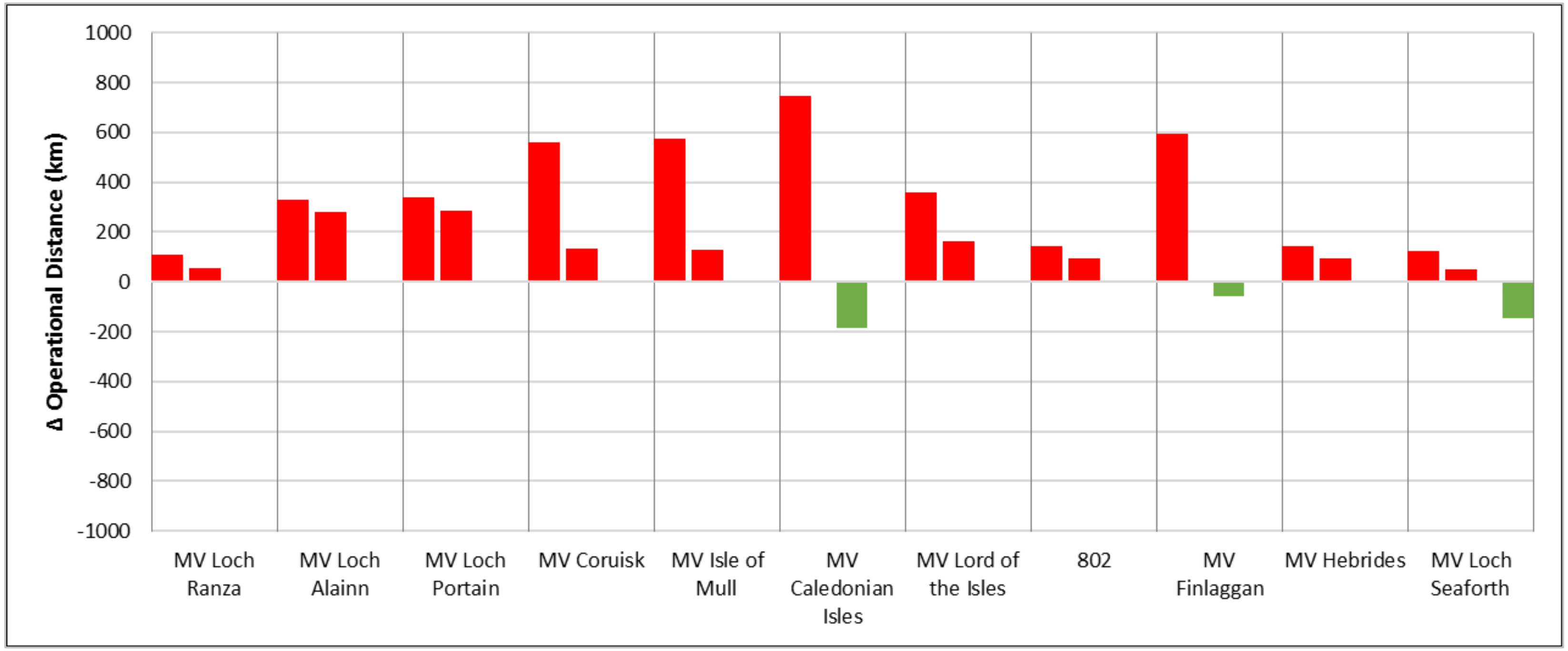


Figure 2-3 Dry Dock Versus Daily Operational Distances

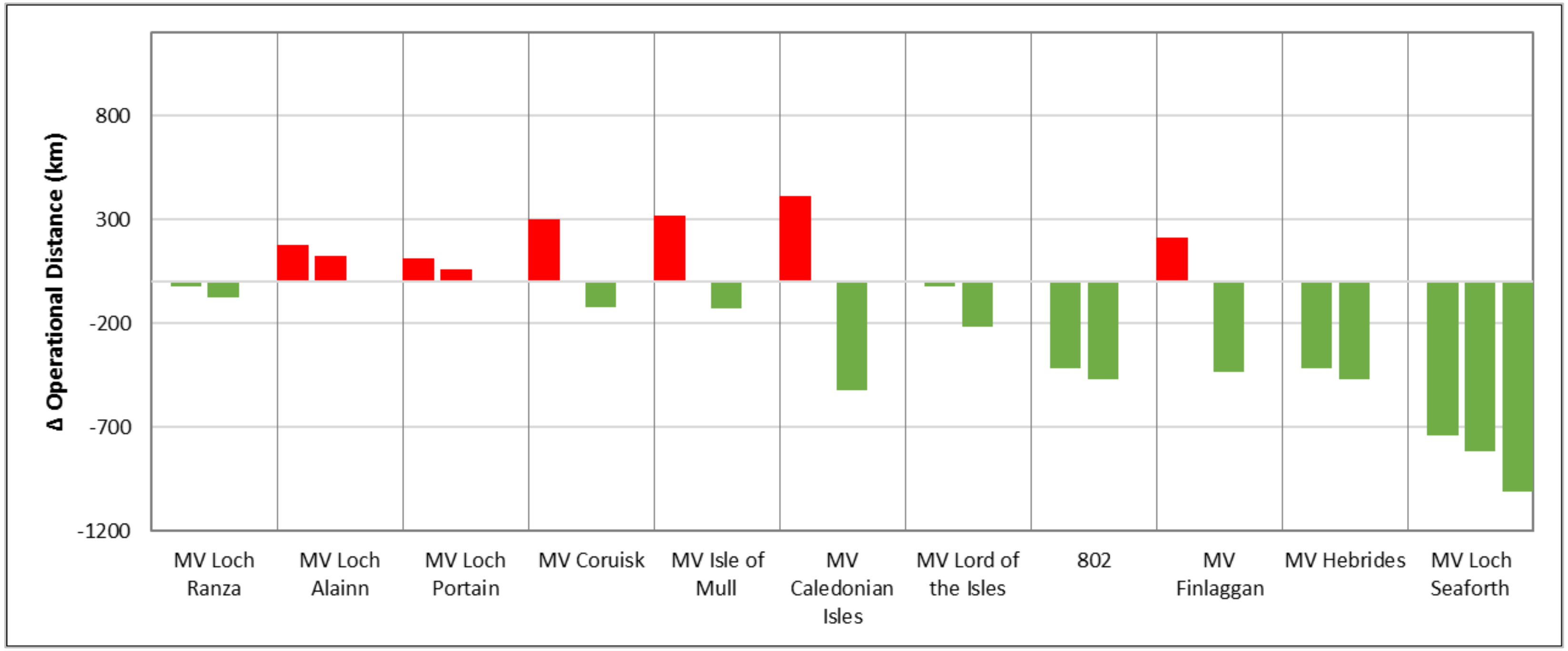


Figure 2-4 Dry Dock Versus Thrice Weekly Operational Distances

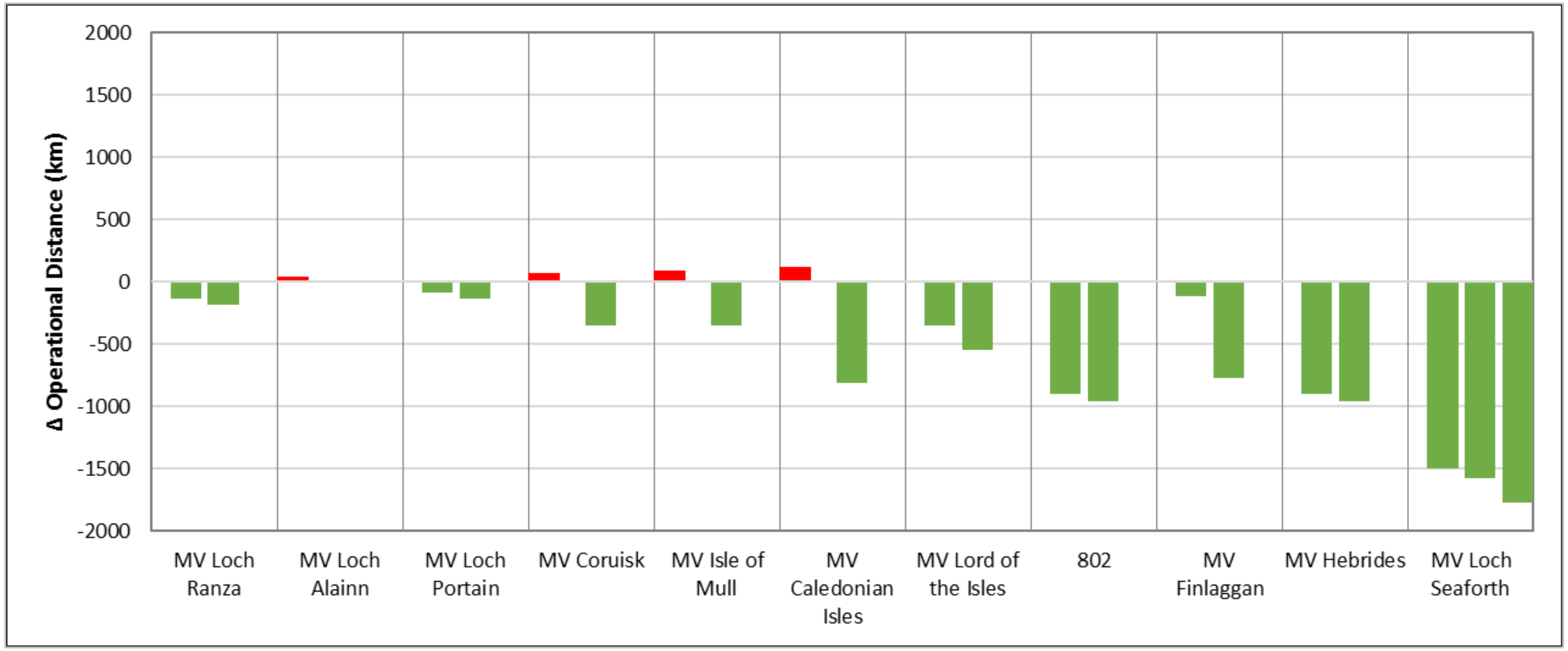


Figure 2-5 Dry Dock Versus Twice Weekly Operational Distances

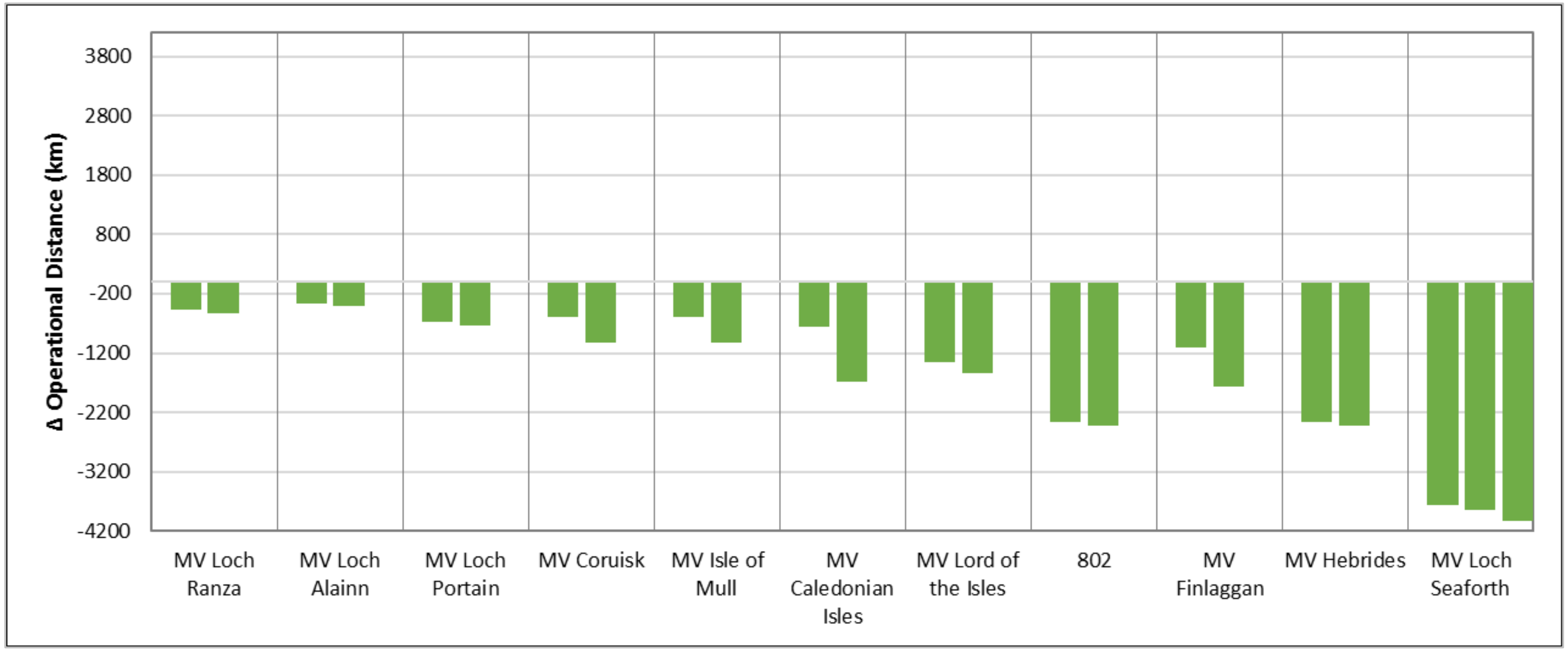


Figure 2-6 Dry Dock Versus Weekly Operational Distances

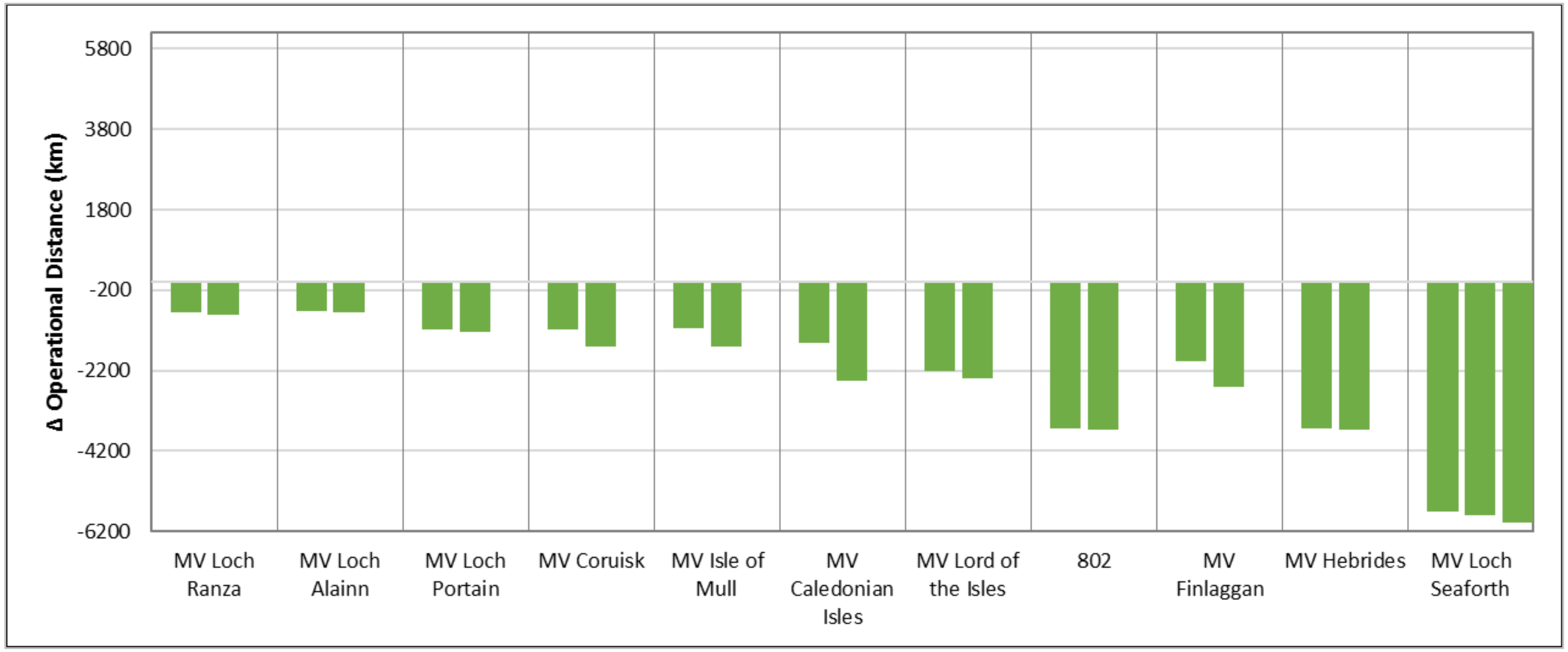


Figure 2-7 Dry Dock Versus 10-Day Operational Distances

2.2.2.3 Key Findings

The results above demonstrate how larger onboard stores of fuel provide adequate cover to reach even the farthest dry dock facility utilised by the CMAL fleet. For traditionally fuelled ferries this aspect may not prove to be a critical factor, but for a vessel design considering hydrogen as a fuel it may be necessary to reduce onboard storage capacity to accommodate the larger volumes required.

The results indicate that sizing onboard storage for daily bunkering reduces the range of all but three vessels to reach a suitable dry dock facility. Should the annual dry dock journey be considered on equal or greater weight as other design aspects, this may prove to be an unacceptable restriction.

A twice weekly bunkering frequency satisfies almost all dry dock options. However, a 100% hydrogen fuelled vessel requiring this quantity of onboard storage may prove to be technically challenging given the results of Section 2.2.1.2 which showed fuel volumes much larger than that of vessels used in operation today.

Findings suggest that bunkering at the intermediate thrice weekly frequency still enables nine vessels to reach at least one suitable dry dock facility each. Bunkering at this frequency may also fall within acceptable onboard fuel storage sizes as discussed in Section 2.2.

2.2.3 Hydrogen Content

Though a design objective for a purely hydrogen fuelled vessel is set in Section 2.2.1.1, a range of percentages of energy required to be delivered by hydrogen fuel has been modelled for reference. From a pure hydrogen delivery to a 10% hydrogen hybrid delivery. See Appendix B for details of the analysis undertaken and results obtained prior to a 100% hydrogen delivery system being decided by the Consortium.

2.2.4 Indicative Wind Farm Sizing

For each route converted to hydrogen with a given set of design parameters, a wind farm to provide sufficient power to run the hydrogen electrolyser(s) has been commensurately sized. These initial land-side findings are intended to be considered both in isolation and in conjunction with the naval architecture perspective.

2.2.4.1 Methodology

This analysis does not consider bunkering frequency as a variable as this relates to the size of onboard storage volume (buffer) required between refuelling events. The total quantity of hydrogen consumed over time remains the same for any bunkering frequency.

As such, this scenario is executed by changing the variable (P_h), the percentage energy demand to be delivered by hydrogen to provide a view on the indicative size of the wind farm required (number of WTGs) to supply the required demand. The design objective of the study is to implement a pure 100% hydrogen fuelled vessel, however hybrid deliveries have also been investigated and included in Appendix F for reference.

The feasibility model is designed to handle any input of WTG and AEP. For this scenario a SGRE SWT-DD-130 turbine has been selected (see Appendix E), however the precise configuration of WTGs will be site and cost variable.

Wind turbine technology innovations are continually being made and the ultimate turbine selection will be influenced not only by the route selected but also by the latest available technology.

Table 2-6 Wind Farm Key Design Inputs and Assumptions

Parameter	Variable / Setting
Fuel reserve (*R*)[7]	0.2
WTG model[8]	SGRE SWT-DD-130 (4.3 MW)
Generic Annual Energy Production	15,000 MWh (net of losses, P75)
Generic Capacity factor (C_p)	0.4
Electrolyser efficiency	55.52%

[7] Value recommended by CMAL.

[8] WTG characteristics recommended by SGRE.

2.2.4.2 Results

The following graph details the annual hydrogen demand and supply for each ferry and the minimum number of WTGs required to meet their respective demand profiles. The disparity between supply and demand arises through rounding up to the nearest integer number of wind turbines.

It is important to note that although the fuel reserve factor is applied, no redundancy relating to security of supply is considered other than rounding up of the number of WTGs to the nearest whole. This aspect should be considered at the next feasibility phase.

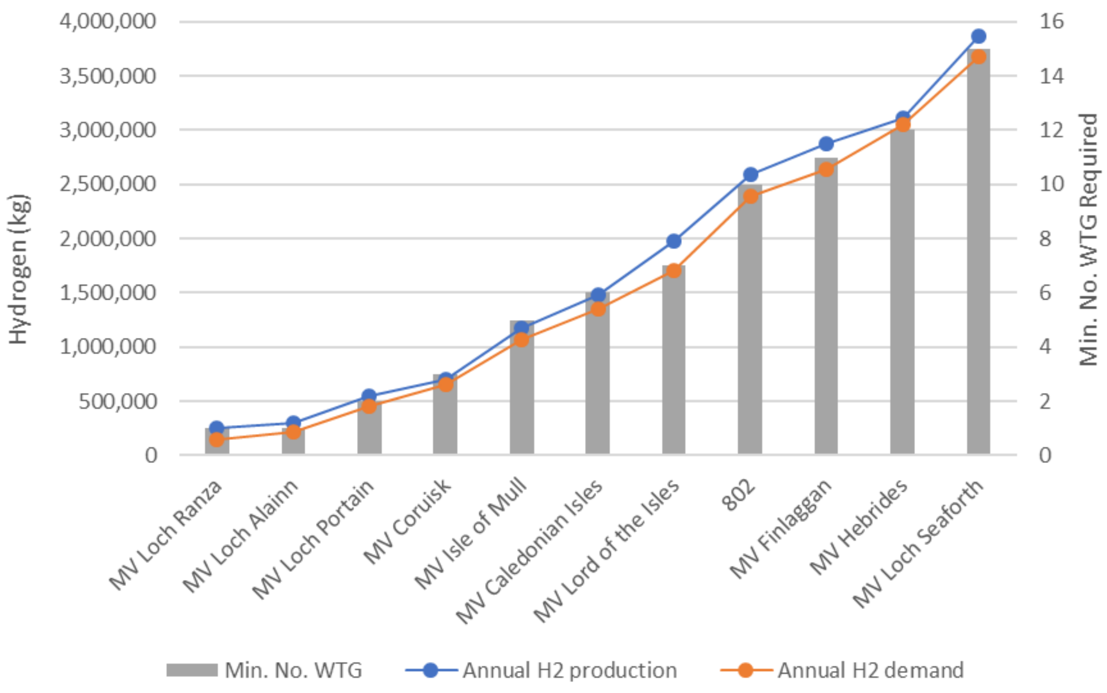


Figure 2-8 100% Hydrogen Delivery

2.2.4.3 Key Findings

The findings from this analysis present an indicative wind farm size required to meet each vessel's energy consumption for purely hydrogen fuelled energy delivery. These range from one WTG to supply the MV Loch Ranza to 15 WTGs to supply the MV Loch Seaforth, using the SWT-DD-130 (4.3 MW) model.

A key focus of this study is to analyse the land-side feasibility, including aspects relating to wind farm feasibility and security of hydrogen supply. However, early assumptions on the likely range of wind farm sizes to be considered can be made.

Natural wind variability will also need to be accounted for and the need to cover potential extended periods of low wind.

2.3 Vessel Equipment Assessment

Section 2.2 demonstrates the range of design options available to the project. In order to proceed with assessing the viability of a vessel, a number of design objectives have been set by the Consortium based on the findings above, alongside other commercial and operational requirements.

The following section sets out the design scenario and objectives for a vessel, the method of assessing the sizing of onboard physical infrastructure based on calculated energy requirements, and the results of the analysis. Each vessel has been assigned a score based on the practicality of implementing a hydrogen propulsion system.

This study does not cover individual aspects of the overall ship design. This report is based on a weight and volumetric comparison with regard to fuel, with no direct investigation into the effects associated with the physical capabilities of a future vessel to operationally service the current port infrastructures (length, breadth, depth, deadweight, etc).

This analysis has been undertaken to provide insights into onboard aspects based on available data. This data is intended only to provide a relativistic comparison between the different vessels to assist with scoring.

2.3.1 Design Scenario Objectives and Assumptions

In order to determine the viability of implementing a hydrogen propulsion system, the physical sizes to be installed onboard must be understood. This has been achieved by converting the calculated hydrogen / energy demand into ‘real’ sizes: the volume of space required for storage tanks and power plant.

This is a high level assessment not a detailed design and solely for the purposes of creating an additional criterion for the ferry route selection process. The aim is to determine which routes / vessels can be promoted in the selection process based on the required system weight and internal space occupied onboard each vessel.

To undertake this task, certain design characteristics have been set in order to limit the number of simulations run. The Consortium has agreed these as:

- A 100% pure hydrogen vessel.
- 520 bar compressed gaseous hydrogen (CGH2).
- 20% reserve fuel.
- Daily and thrice weekly bunkering.
- Type 4 cylinder storage is assumed as this type has the highest mass ratio of hydrogen stored, leading to optimized footprint and weight.

Additional operational preferences have been stipulated by CMAL:

- Range to drydock facilities is an important consideration as there would be no other infrastructure to bunker ships en route for ships further away.
- A low percentage content of hydrogen would not be ideal. A 100% hydrogen powered vessel is the ambition.
- Use of a fuel cell over a hydrogen internal combustion engine.

The results utilise data from appropriate suppliers (due to commercial confidentiality, company names have been redacted):

- Vendor A for CGH2 storage.
- Vendor B for LH2 storage.
- Vendor C and Vendor D for hydrogen fuel cell systems.

The following internal sizes which could be utilised for a hydrogen power system were provided by CMAL and comprise the combined engine room, generator room and machinery spaces of each ship:

Table 2-7 Vessel Engine Room Sizes

Vessel	Internal Available Volumes [m^3]
MV Loch Ranza	265.20
MV Loch Alainn	294.26
MV Loch Portain	207.36
MV Coruisk	428.40
MV Isle of Mull	700.00
MV Caledonian Isles	518.45
MV Lord of the Isles	657.44
802	1,071.00
MV Finlaggan	1,107.00
MV Hebrides	739.66
MV Loch Seaforth	1,570.00

2.3.2 Equipment Specifications

Marine applications for hydrogen propulsion systems are new. Technologies are mature but they cannot be found as off-the-shelf products at the scale required as yet and will need to be developed in close partnership with providers. Equipment items that have been selected for modelling are outlined in the following section. Items not included for initial weight and volumetric modelling include:

- Hydrogen gas reformers (where applicable).
- Propulsion motors.
- Batteries.
- Power management system.
- Auxiliaries.
- Other equipment.

It will be necessary to fully address the impact on ship design of installing all of the necessary components of a hydrogen propulsion system. For example, onboard batteries will be required to deliver fast-response power at times of high demand where fuel cell delivery would be insufficient (peak shaving). Current battery technology is relatively heavy, their exclusion from initial investigation is due to the time and resource intensity to model all scenarios under investigation. Detailed ship design incorporating the full set of necessary components of shortlisted options will be undertaken.

2.3.2.1 Vendor A: Type 4 Storage

Vendor A, a leader in storage equipment, has been considered based on the Consortium's good knowledge of their product range and competitive Type 4 Pressure Equipment Directive (PED) storage tanks for marine application.

Type 4 storage is the most suitable technology as it has the highest mass ratio of hydrogen stored, leading to optimized footprint and weight (key for the Project). PED has been chosen for the same reason. The Transportable Pressure Equipment Directive (TPED) classification has not been considered as the onboard storage does not need to be transported.

520 bar CGH2 has been considered as it is the highest pressure reachable in a Type 4 PED off-the-shelf product. The nearest product for 700 bar CGH2 storage is still under development for Type 4 PED and not yet commercially available. The 700 bar system exists for small storage capacities used by cars and can hold approximately 5 kg of hydrogen. This capacity is not suitable for the scale of this project.

A future phase of the SWIFTH$_2$ project can consider a wider range of potential vendors, including the possibility of customised co-development, if necessary. Table 2-8 below contains the technical specifications for the storage system used in the analysis.

Table 2-8 Vendor A Type 4 PED Storage

Type 4 PED 18.5' Composite Vessel	
Manufacturer	Vendor A
Pressure	520 bar
No. Vessels per Skid	9
Water Volume	19.138 m^3
Container Volume	36.32 m^3
Payload	612 kg
Container Tare Weight	9,150 kg
Container Loaded Weight	9,762 kg
Width, Height, Length	2.44m x 2.44m x 6.10m

2.3.2.2 Vendor B: Cryogenic Storage

Although a liquid hydrogen (LH2) storage system is not be the preferred technology of choice, the data and information has been included for reference. Dimensions have been used for a liquid nitrogen (LIN) storage system but modelled for hydrogen properties for the purposes of this simulation. This has been done due to lack of data regarding LH2 storage systems. Approximation with LIN cryogenic storage from Vendor B has been made as a reasonable first approach.

If liquid hydrogen is to be the storage state pursued, further investigation into the specific transportable equipment will need to be carried out. The table below details the cryogenic liquid nitrogen system offered by Vendor B.

Table 2-9 Vendor B LIN Cryogenic Vessel

18 Bar LIN Cryogenic Vessel	
Manufacturer	Vendor B
Pressure [bar]	18 bar
Hydrogen Gas Boil-off Rate*	1.2 % / day
Net Capacity	76.34 m^3
Approximate Volume (cylinder)	127.59 m^3
Payload	5,412.5 kg
Container Tare Weight	29,650 kg
Container Loaded Weight	35,062.5 kg
Diameter x Height	3.00m x 18.05m

*To be further confirmed and validated in the next project phase.

2.3.2.3 Vendor D: Electric Fuel Cell

Vendor D has been contacted by the Consortium and have supplied preliminary technical data to the Project corresponding to the spread of power requirements calculated for the CMAL fleet under investigation. Three main components have been considered: rack fuel cell, DC box, and power converter.

Table 2-10 Vendor D Fuel Cell Specification

Specification	
Weight of Stack	80 kg
Weight of x4 Stack, Compressor, Ancillary Equipment	470 kg
x4 Stack Length x Height x Width	0.8m x 2.1m x 0.8m
Stack Rated Power	25 kW
x4 Stack Rated Power	100 kW

For each peak power requirement considered a footprint has been estimated. Table 2-11 below itemises the peak power requirements of the ships and most appropriately sized Vendor D fuel cell system to meet the demands.

Table 2-11 Ship Peak Power Requirements

Vessel	Peak Power Requirement [kW]	Vendor D Power Supply [kW]
MV Loch Ranza	520	1,600
MV Loch Alainn	880	1,600
MV Loch Portain	1,610	1,600
MV Coruisk	2,000	2,000
MV Isle of Mull	3,323	3,300
MV Caledonian Isles	4,220	4,200
MV Lord of the Isles	5,992	6,000
802	6,100	6,100
MV Finlaggan	7,760	7,800
MV Hebrides	7,800	7,800
MV Loch Seaforth	7,050	7,000

The following quantities of hydrogen have been modelled based on information provided by Wood for operating the CMAL vessels on a daily and thrice weekly bunkering frequency, with a hydrogen compression of 520 bar.

Table 2-12 Hydrogen Quantities Modelled

Vessel	Geometric Hydrogen Volumes [m³ @ 520 Bar]	
	Daily Bunkering	Thrice Weekly Bunkering
MV Loch Ranza	10.95	25.55
MV Loch Alainn	17.36	40.52
MV Loch Portain	37.31	87.06
MV Coruisk	54.16	126.37
MV Isle of Mull	88.88	207.40
MV Caledonian Isles	113.07	263.83
MV Lord of the Isles	143.51	334.86
802	201.97	471.27
MV Finlaggan	223.02	520.39
MV Hebrides	257.64	601.15
MV Loch Seaforth	310.68	724.92

2.3.3 Methodology

The assessment of onboard equipment required on each of the vessels analysed has been undertaken based on information supplied and calculated by Consortium participants. Three major components have been modelled:

- Hydrogen fuel cell: combines the hydrogen supply fuel with atmospheric oxygen to produce electricity. This has been sized according to the vessel's peak power requirements (propulsion, hotel and ancillary loads). The weight penalty therefore varies with peak power demand not ferry range (e.g. quantity of onboard hydrogen fuel).
- Hydrogen fuel: calculated quantities of hydrogen for each ferry operating as per the design scenario described in Section 2.3.1. Hydrogen requirements vary with operational parameters, such as bunkering frequency (see Section 2). Two frequencies have been selected for assessment: daily and thrice weekly. The weight of hydrogen fuel has been calculated using the lower heating value.
- Fuel storage tanks: required to store the onboard fuel. Sizing varies with the quantities of hydrogen fuel required. Tanks carry a weight penalty which increases with higher quantities of hydrogen fuel required. Two states of hydrogen have been modelled: compressed gas (CGH2) at 520 bar and liquid (LH2).

The complete list of components which have been modelled for are shown in Table 2-3.

Table 2-13 Modelled Components

Modelled Components	Not Modelled
Hydrogen fuel cells	Engines
Hydrogen fuel	Gearboxes
Hydrogen storage tanks	Propeller motors
MGO fuel	Auxiliaries
MGO fuel storage tanks	Batteries
Engine / generator / machinery rooms	Power management
	Other equipment

The hydrogen propulsion systems have been sized for the ships under investigation using technical specifications from the suppliers reviewed in Section 2.3.2.

The weight and volume of each propulsion system have been calculated for each vessel, and bunkering frequency using a 520 bar fuel compression. The vessels and associated ferry routes have subsequently been assessed and scored by weight (comparing theoretical hydrogen propulsion systems to existing MGO fuel systems) and volume (expressing theoretical hydrogen systems as a percentage of the existing internal engine room volumes of the CMAL ships).

It is worth considering that when assessing the propulsions systems by weight, this has been done in reference to the figures supplied by CMAL on their existing fuel tanks: main, service and overflow where applicable. These figures therefore do not include the weights of existing main engines, generators and other components which were not supplied. The weight comparison of a hypothetical hydrogen propulsion system with the vessels existing MGO system can therefore be considered conservative.

Similarly, the volumetric comparison has been performed using figures from CMAL on the ship's existing engine room volumes and has not considered the available internal volumes of the generator rooms and machinery spaces which could be utilised. The volumetric analysis is also a conservative view.

2.3.4 Assessment Results

The following graphs illustrate the combined weight of fuel and equipment (fuel cell (FC) and storage tanks) required for each of the vessels analysed. This has been calculated for 520 bar CGH2.

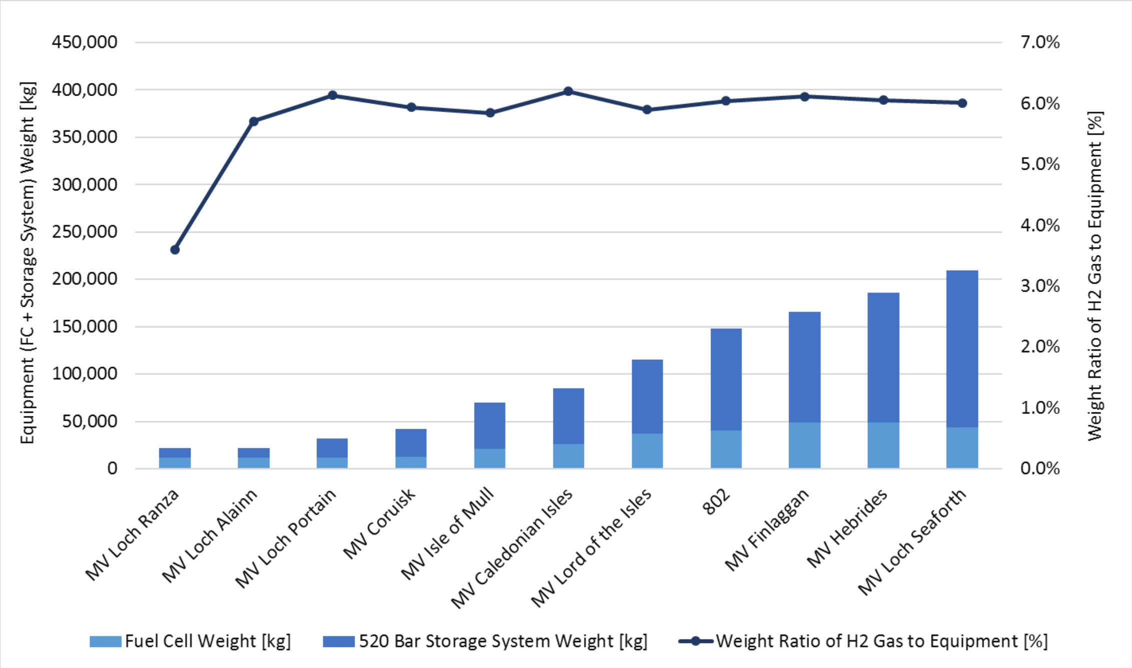


Figure 2-9 520 Bar CGH2 System Weight (Daily Bunkering)

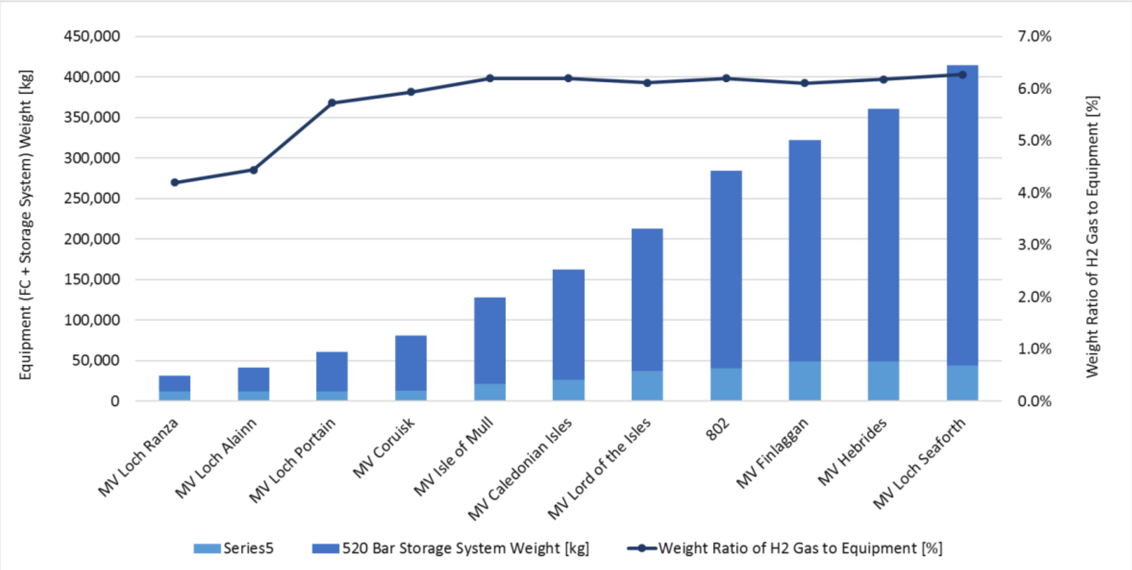


Figure 2-10 520 Bar CGH2 System Weight (Thrice Weekly Bunkering)

Table 2-14 System Weight Assessment (520 Bar CGH2)

Route	Vessel	Existing MGO System [t][9]	H2 System (Daily Bunker) [t]	Variance [%]	H2 System (Thrice Weekly Bunker) [t]	Variance [%]
Gigha – Tayinloan	MV Loch Ranza	9.56	21.83	228.35	31.59	330.44
Barra – Eriskay	MV Loch Alainn	19.76	21.83	110.48	41.36	209.31
Leverburgh – Berneray	MV Loch Portain	20.08	31.59	157.32	60.88	303.19
Craignure – Oban	MV Coruisk	52.00	42.09	80.94	81.13	156.02
	MV Isle of Mull	103.25	69.74	67.54	128.31	124.27
Ardrossan – Brodick	MV Caledonian Isles	79.45	84.71	106.62	162.81	204.92
Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	88.16	115.50	131.01	213.12	241.74
Kennacraig – Port Askaig / Port Ellen	MV Finlaggan	112.01	165.90	148.11	322.10	287.56
Uig – Tarbert – Lochmaddy	MV Hebrides	75.71	185.43	244.92	361.14	477.00
	802	117.81	147.75	125.41	284.42	241.42
Stornoway – Ullapool	MV Loch Seaforth	252.37	209.50	83.01	414.51	164.25

[9] Figures provided by CMAL include main, service and overflow fuel tanks filled to 95% capacity.

In order to assess the vessels in relation to all other criteria considered in this report (predominantly land-side aspects), the vessels have been mapped to one or more islands which they serve. Table 2-15 below details the vessel's weight ratios (hydrogen to MGO propulsion) for 520 bar CGH2 on a daily bunkering frequency.

For islands which are served by more than one ferry route (Lewis-Harris and Skye), the island in question is replicated to assess each route separately. Where more than one vessel operates on a ferry route, the vessel with the most favourable variance has been selected for scoring the performance of a hypothetical hydrogen propulsion system using the aforementioned parameters.

Table 2-15 System Weight Assessment (Islands)

Island	Route(s)	Vessel(s)	520 Bar CGH2 Variance [%]	Minimum Variance [%]
Arran	Ardrossan – Brodick	MV Caledonian Isles	106.62	106.62
Barra	Barra – Eriskay	MV Loch Alainn	110.48	110.48
Berneray	Leverburgh – Berneray	MV Loch Portain	157.32	157.32
Eriskay	Barra – Eriskay	MV Loch Alainn	110.48	110.48
Gigha	Gigha – Tayinloan	MV Loch Ranza	228.35	228.35
Islay	Kennacraig – Port Askaig / Port Ellen	MV Finlaggan	148.11	148.11

Island	Route(s)	Vessel(s)	520 Bar CGH2 Variance [%]	Minimum Variance [%]
Lewis & Harris	Stornoway – Ullapool	MV Loch Seaforth	83.01	83.01
	Uig – Tarbert – Lochmaddy	802	125.41	125.41
		MV Hebrides	244.92	
	Leverburgh – Berneray	MV Loch Portain	157.32	157.32
Mull	Craignure – Oban	MV Coruisk	80.94	67.54
		MV Isle of Mull	67.54	
North Uist	Uig – Tarbert – Lochmaddy	802	125.41	125.41
		MV Hebrides	244.92	
Skye	Uig – Tarbert – Lochmaddy	802	125.41	125.41
		MV Hebrides	244.92	
	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	131.01	131.01
South Uist	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	131.01	131.01

The following graphs illustrate the systems in terms of volume occupied and expressed as a percentage of the internal volume of the engine rooms of the vessels:

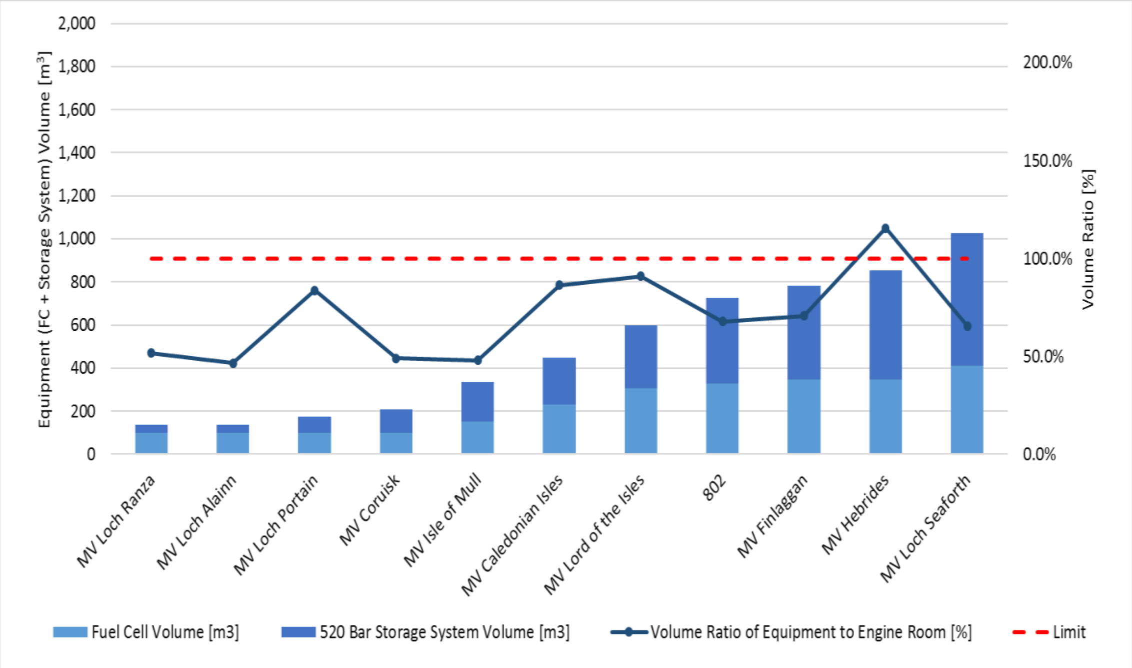


Figure 2-11 520 Bar CGH2 System Volume (Daily Bunkering)

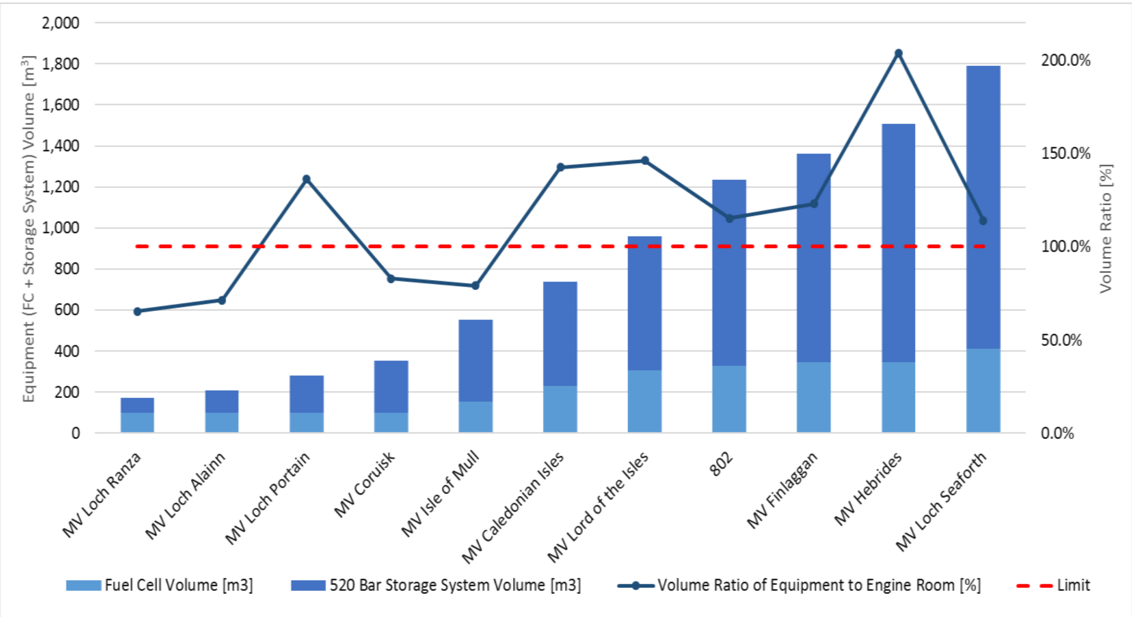


Figure 2-12 520 Bar CGH2 System Volume (Thrice Weekly Bunkering)

Table 2-16 System Volumetric Assessment (520 Bar CGH2)

Route	Vessel	Existing Volume [m³]	H2 System (Daily Bunker) [m³]	Variance [%]	H2 System (Thrice Weekly Bunker) [m³]	Variance [%]
Gigha – Tayinloan	MV Loch Ranza	265.20	137.12	51.70	173.43	65.40
Barra – Eriskay	MV Loch Alainn	294.26	137.12	46.60	209.75	71.28
Leverburgh – Berneray	MV Loch Portain	207.36	173.43	83.64	282.38	136.18
Craignure – Oban	MV Coruisk	428.40	209.75	48.96	355.02	82.87
	MV Isle of Mull	700.00	335.18	47.88	553.09	79.01
Ardrossan – Brodick	MV Caledonian Isles	518.45	448.30	86.47	738.84	142.51
Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	657.44	597.74	90.92	960.91	146.16
Kennacraig – Port Askaig / Port Ellen	MV Finlaggan	1,107.00	781.40	70.59	1,362.47	123.08
Uig – Tarbert – Lochmaddy	MV Hebrides	739.66	854.04	115.46	1,507.74	203.84
	802	1,071.00	725.89	67.78	1,234.32	115.25
Stornoway – Ullapool	MV Loch Seaforth	1,570.00	1,027.79	65.46	1,790.44	114.04

The vessels have been mapped to one or more islands which they serve as per Section 2.3.4. Table 2-17 below details the vessel's volumetric ratios for 520 bar CGH2 on a daily bunkering frequency.

For islands which are served by more than one ferry route (Lewis-Harris and Skye), the island in question is replicated to assess each route separately. Where more than one vessel operates on a ferry route, the vessel with the most favourable variance has been selected for scoring the performance of a hypothetical hydrogen propulsion system using the aforementioned parameters.

Table 2-17 System Volumetric Assessment (Islands)

Island	Route(s)	Vessel(s)	520 Bar CGH2 Variance [%]	Minimum Variance [%]
Arran	Ardrossan – Brodick	MV Caledonian Isles	86.47	86.47
Barra	Barra – Eriskay	MV Loch Alainn	46.60	46.60
Berneray	Leverburgh – Berneray	MV Loch Portain	83.64	83.64
Eriskay	Barra – Eriskay	MV Loch Alainn	46.60	46.60
Gigha	Gigha – Tayinloan	MV Loch Ranza	51.70	51.70
Islay	Kennacraig – Port Askaig / Port Ellen	MV Finlaggan	70.59	70.59

Island	Route(s)	Vessel(s)	520 Bar CGH2 Variance [%]	Minimum Variance [%]
Lewis & Harris	Stornoway – Ullapool	MV Loch Seaforth	65.46	65.46
	Uig – Tarbert – Lochmaddy	802	67.78	67.78
		MV Hebrides	115.46	
	Leverburgh – Berneray	MV Loch Portain	83.64	83.64
Mull	Craignure – Oban	MV Coruisk	48.96	47.88
		MV Isle of Mull	47.88	
North Uist	Uig – Tarbert – Lochmaddy	802	67.78	67.78
		MV Hebrides	115.46	
Skye	Uig – Tarbert – Lochmaddy	802	67.78	67.78
		MV Hebrides	115.46	
	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	90.92	90.92
South Uist	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	90.92	90.92

2.3.5 Scoring

The following section is a weight evaluation of the vessels as mapped to the respective islands which they operate. For islands with more than one vessel operating, the vessel with the lightest system has been selected. This evaluation is based on the vessel's percentage weight ratio of a 520 bar CGH2 propulsion system to the vessel's existing MGO system. A daily bunkering frequency has been selected for the evaluation.

The range between the highest and lowest deviation in weight ratios has been divided into three portions to reflect the scoring range chosen as shown in Figure 2-13. Each route is scored in Table 2-18 below according to the position it lies in.

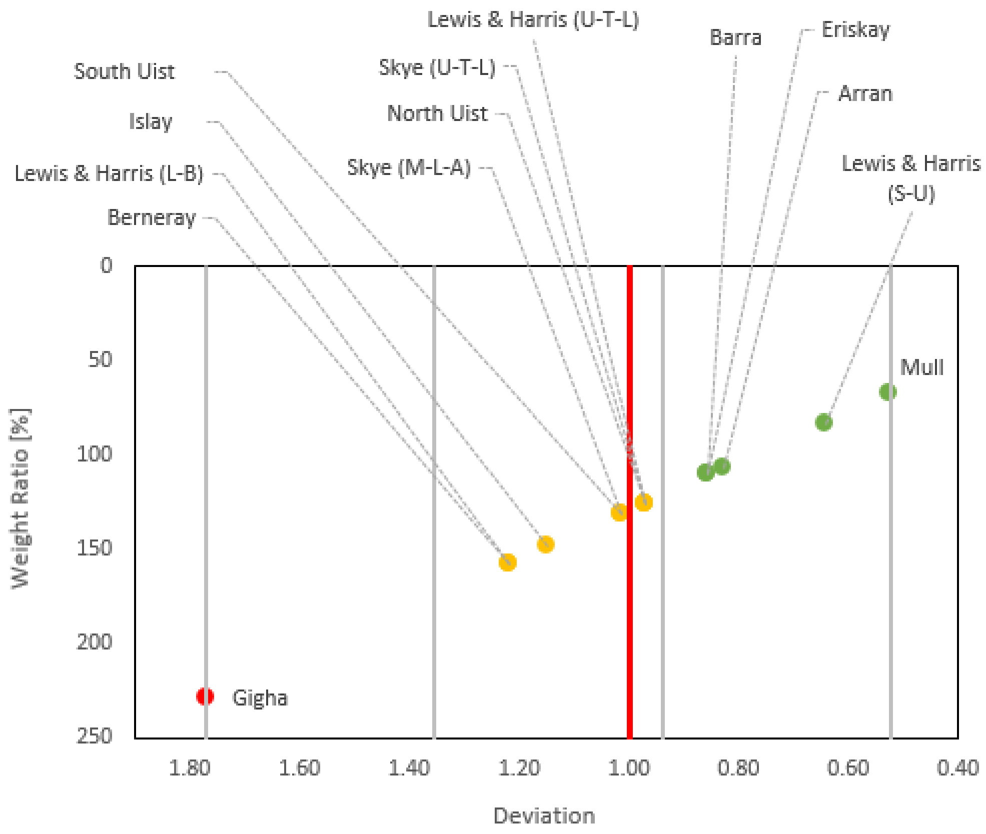


Figure 2-13 Hydrogen System Weight Average Deviations

Table 2-18 System Weight Scoring

Route	Variance[10] [%]	Score
Gigha	228.35	1
Berneray	157.32	2
Lewis & Harris (Leverburgh - Berneray)	157.32	2
Islay	148.11	2
Skye (Mallaig - Lochboisdale - Armadale)	131.01	2
South Uist	131.01	2
Lewis & Harris (Uig - Tarbert - Lochmaddy)	125.41	2
North Uist	125.41	2
Skye (Uig - Tarbert - Lochmaddy)	125.41	2
Barra	110.48	3
Eriskay	110.48	3
Arran	106.62	3
Lewis & Harris (Stornoway - Ullapool)	83.01	3
Mull	67.54	3

[10] Where ferry route has more than one vessel operating, the best result has been selected.

The following section is a volumetric evaluation of the vessels as mapped to the respective islands which they operate. For islands with more than one vessel operating, the vessel with the smallest system has been selected. This evaluation is based on the vessel's percentage volumetric ratio of a 520 bar CGH2 propulsion system to the vessel's existing MGO system. A daily bunkering frequency has been selected for the evaluation.

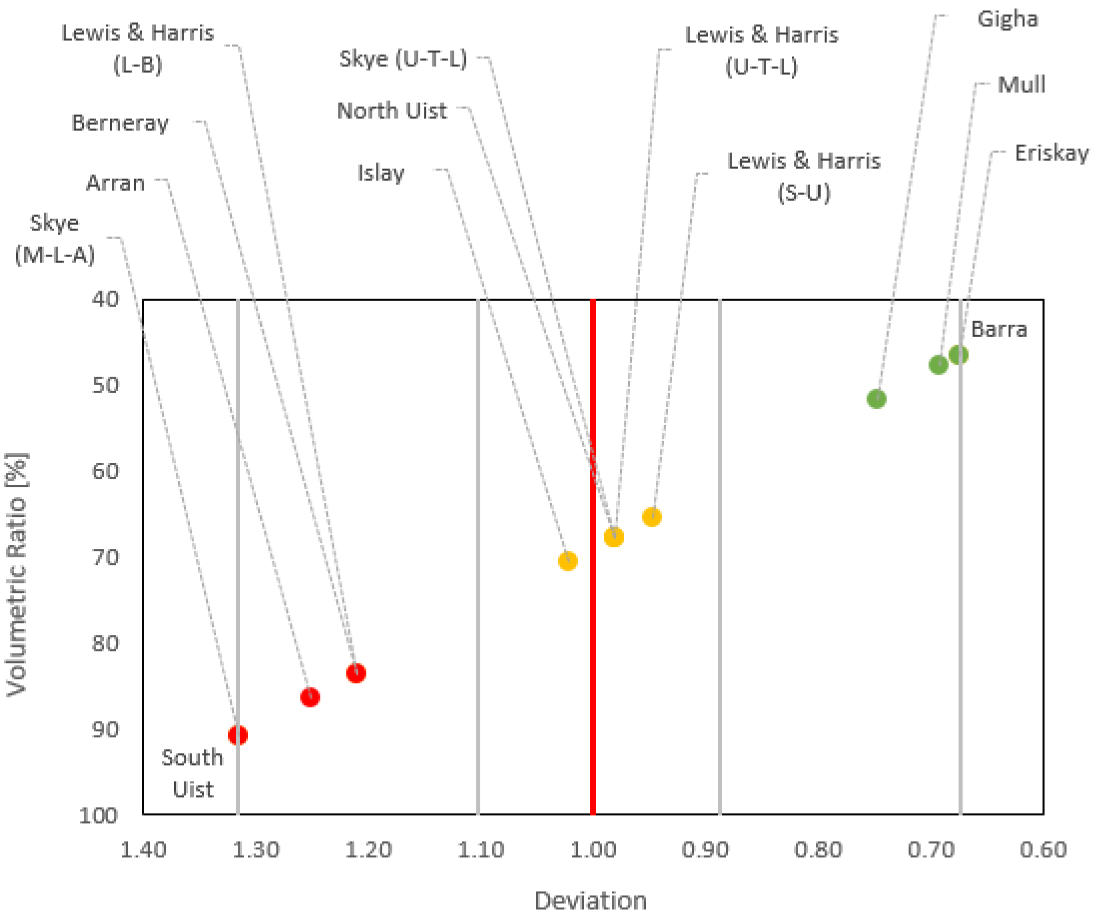


Figure 2-14 Hydrogen System Volume Average Deviations

Table 2-19 System Volume Scoring

Route	Variance[11] [%]	Score
Skye (M-L-A)	90.92	1
South Uist	90.92	1
Arran	86.47	1
Berneray	83.64	1
Lewis & Harris (L-B)	83.64	1
Islay	70.59	2
Lewis & Harris (U-T-L)	67.78	2
North Uist	67.78	2
Skye (U-T-L)	67.78	2
Lewis & Harris (S-U)	65.46	2
Gigha	51.7	3
Mull	47.88	3
Barra	46.6	3
Eriskay	46.6	3

[11] Where ferry route has more than one vessel operating, the best result has been selected.

2.3.6 Key Findings

The results of the vessel feasibility analysis on required onboard equipment show that a hydrogen propulsion system could be comparable to existing MGO fuelled propulsion systems when considering the design and modelling assumptions used for this report.

The majority of results indicate a CGH2 propulsion systems would generally be heavier and larger than the MGO systems they have been measured against, but the size of the variances indicates that this may not be technically prohibitive if optimisation is pursued. In some examples, such as the MV Loch Seaforth, MV Coruisk, and MV Isle of Mull for a daily bunkering frequency using 520 bar CGH2, hydrogen systems have been calculated as being lighter than MGO comparators. Hydrogen stored at higher compressions or in a liquid state would incur smaller weight and volume penalties.

The bunkering frequency chosen also has a significant impact on the practicalities of installing a hydrogen propulsion system onboard a vessel, with initial evidence suggesting a daily or thrice weekly bunking frequency most likely to stay within the physical limits of the existing ship dimensions.

The results of this section indicate that a suitability of a hydrogen propulsion system does not intrinsically relate to the size of the existing vessel being used as a modelling reference. It is important to recognise that if a new build hydrogen vessel is being considered then the naval architecture aspects will be unconstrained by existing vessel dimensions, but will need to conform to limitations imposed by port infrastructure.

Although analysis of vessel onboard equipment is a crucial factor in determining whether any future development would be successful, a holistic assessment of all the available localities and ferry routes needs to be maintained. This requires the assessment of the land-based aspects that are involved in successful wind farm and hydrogen plant delivery.

As the proposed development (as outlined in Section 1.1.3) consists of both land-side hydrogen production and utilisation at sea, determining the most favourable ferry routes based solely on naval architecture aspects alone is insufficient.

Hence, the following section appraises the island locations under investigation on a number of criteria. Together with the vessel feasibility aspects, these land-side criteria are fed into a decision matrix in Section 4. In instances where islands and their associated ferry routes perform well in one assessment criterion and well in competing criterion, a weighting system determines priority (see Section 4.1).

3 Land-side Feasibility

The islands and associated ferry routes under investigation have been individually assessed against the following criteria:

- Hydrogen plant infrastructure.
- Preliminary wind resource.
- Wind farm land-use and planning.
- Wind farm accessibility.
- Preliminary solar resource.

3.1 Hydrogen Plant Infrastructure Assessment

In addition to vessel equipment sizing, footprint sizes have been produced for the land-side infrastructure necessary to produce the required quantities of hydrogen for each vessel and the associated equipment to store hydrogen at a port and dispense the fuel to a vessel.

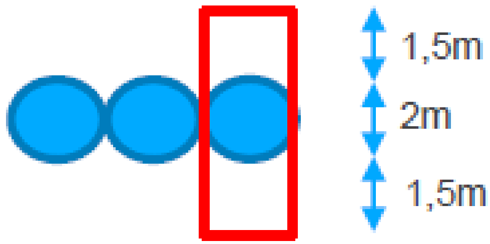
Two models have been created in order to represent the upper and lower bounds of plant footprint at the ports. The necessary space for access and maintenance is taken into consideration in the footprint estimation (but not safety distances). The footprints have been calculated based on information provided by available suppliers and in conjunction with Consortium participants.

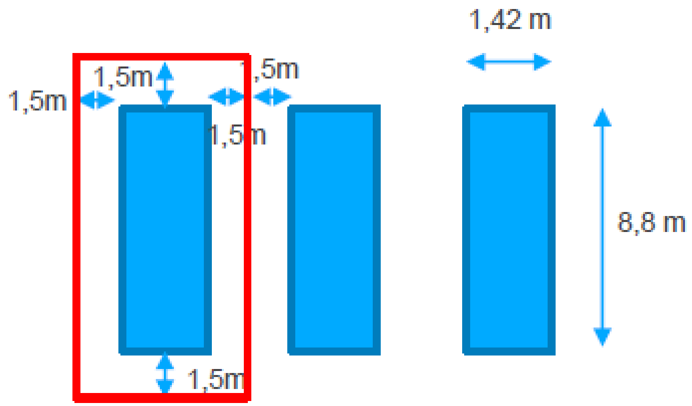
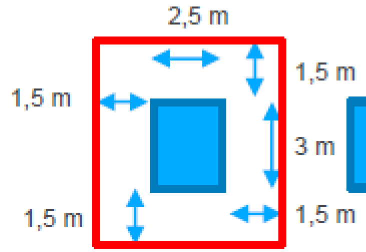
3.1.1 Equipment Specifications

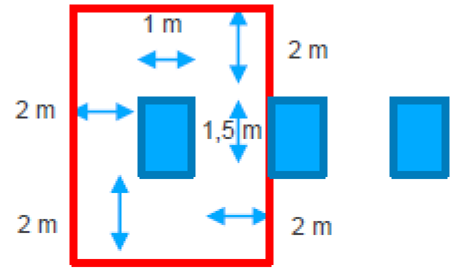
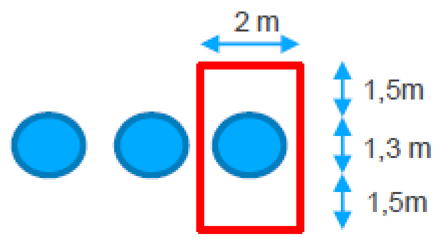
3.1.1.1 Component Dimensions

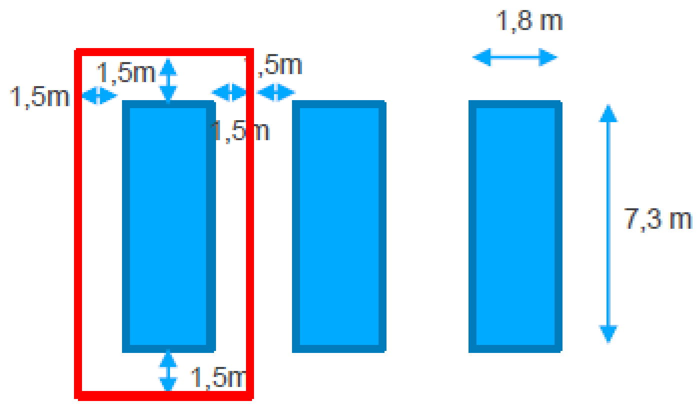
The following dimensions have been compiled for the components required for each of the models outlined Section 3.1.1.2 and Section 3.1.1.3.

Table 3-1 Land-side Equipment Dimensions

Dimension		Top View Diagram
20 Bar Storage (Tower Tank)		
Height	9.0 m	
Outside Diameter (including support)	2.0 m	
Maintenance Space	1.5 m	
Water Volume	15 m^3	
10 to 1,000 Bar Compressor (24h / 24 + Spare)		
Vendor	Vendor E	-
Rated Power Consumption (Footprint)	70 kWe (10m^2)	
	300 kWe (30 m^2)	

Dimension		Top View Diagram
1,000 Bar CGH2 Type 2 Storage Vessel		
Vendor	Vendor A	
Length	8.8 m	
Outside Diameter (including support)	0.4064 m	
Maintenance Space (all sides)	1.5 m	
Water Volume	0.721 m^3	
No. Tubes per Trailer	9	
Hydrogen Cooling Equipment		
Length	2.5 m	
Breadth	3.0 m	
Maintenance Space (all sides)	1.5 m	

Dimension		Top View Diagram
Dispenser		
Length	1.5 m	
Breadth	1.0 m	
Maintenance Space (all sides)	2.0 m	
20 (30) Bar CGH2 Buffer Storage (15 minutes)		
Vendor	Vendor F	
Height	1.8 m	
Outside Diameter (including support)	1.3 m	
Water Volume	0.85 m^3	

Dimension		Top View Diagram
200 (193) Bar CGH2 Type 1 Tube Vessel		
Vendor	Vendor A	
Length	7.3 m	
Outside Diameter	0.6 m	
Water Volume	1.7 m^3	
Maintenance Space (all sides)	1.5 m	
Electrolyser		
Footprint values have been provided by ITM Power. These are estimates and include space for equipment, maintenance and access. The values assume the electrolysers produce hydrogen continuously over a 24 hour period with no integrated redundancy.		
Instrumentation		
Instrumentation can be expressed as a percentage of the main equipment required.		

3.1.1.2 Model 1 (Upper Limit)

This model assumes cascade dispensing through pressure equalisation from a high-pressure land-side storage vessel (1,000 bar) to the onboard storage (520 bar). This is usual practice for standard hydrogen refuelling station but has implications for the size of footprint, such issues include:

- 20 bar storage: high quantity of hydrogen in low-pressure storage. This results in a high number of 20 bar storage vessels and subsequent overall plant footprint.
- 1,000 bar storage: transfer from 1,000 bar to the onboard storage at 520 bar allows only a certain percentage of the stored hydrogen to be available for bunkering ('dead volumes') even when cascade banks are considered for optimization. Therefore high-pressure storage would be to be sized accordingly.

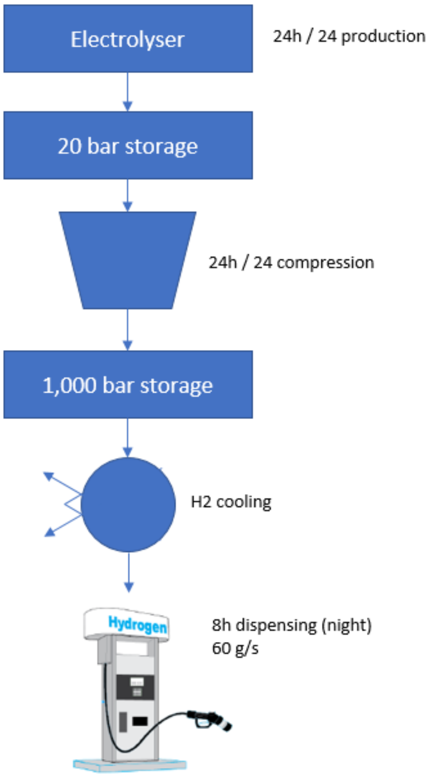


Figure 3-1 Model 1 Process

The equipment list for Model 1 is as follows:

- Electrolyser.
- 20 bar storage (tower tanks).
- Compressor 10 to 1,000 bar (24h/24 + spare).
- 1,000 bar storage vessel.
- Hydrogen cooling equipment.
- Multiple dispensers at pier for simultaneous bunkering of vessel.
- Instrumentation.

3.1.1.3 Model 2 (Lower Limit)

Model 2 (lower limit) assumes dispensing is done directly from a compressor. This involves a medium-pressure land-side storage vessel with direct compression into the onboard storage. An optimized footprint is anticipated for this model.

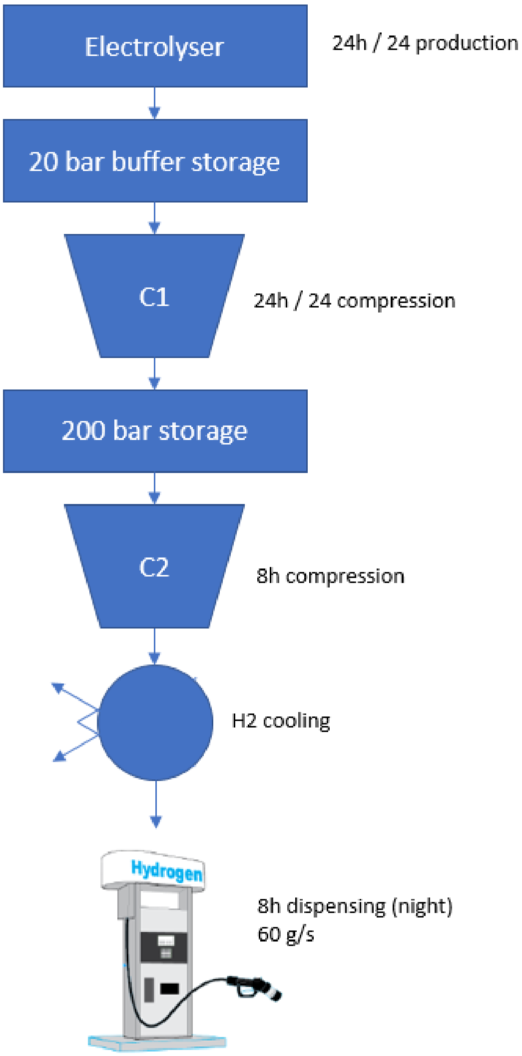


Figure 3-2 Model 2 Process

The equipment list for Model 2 is as follows:

- Electrolyser.
- 20 bar buffer storage (15 minute).
- Compressor 1: 10 to 200 bar (24h/24 + spare).
- Compressor 2: atmospheric pressure to 520 bar (8h + spare).
- 200 bar storage.
- Hydrogen cooling equipment.
- Multiple dispensers at pier for simultaneous bunkering of vessel.
- Instrumentation.

3.1.2 Methodology

The resultant footprints of hydrogen production plants have been modelled for four bunkering frequencies as detailed in Table 3-2 and Table 3-3 below. The footprints are generated by appropriately scaling the equipment footprints detailed in Section 3.1.1 for required hydrogen quantities which were provided by Wood. The resulting footprints are provided for each vessel's required hydrogen consumption.

3.1.3 Analysis Results

Model 2 has been created to optimize the plant footprint and therefore to store the hydrogen produced continuously by the electrolyser at a higher pressure (200 bar at first stage compression). The hydrogen then needs to undergo second stage compression to dispensed the hydrogen to the ship in question at the requested onboard storage pressure (520 bar in the design scenario set out in Section 2.3.1).

This method is not technically possible for all vessels analysed due to the volumetric flows required of the direct refuelling compressor which become excessive for twice weekly, thrice weekly, and weekly bunkering frequencies. Therefore, results have been omitted from Table 3-3 for dispensing requirements deemed technically unviable. An arbitrary physical limit has been set at 40 compressors of 300 kW. The vessels itemised in Table 3-2 below have been ordered by size.

Table 3-2 Model 2 Compressors Required

Vessel	No. 300 kW Compressors per Bunkering Frequency			
	Weekly	Twice	Thrice	Daily
MV Loch Ranza	12	6	4	2
MV Loch Alainn	18	10	6	4
MV Loch Portain	36	18	12	6
MV Coruisk	>40	26	18	8
MV Isle of Mull		>40	28	12
MV Caledonian Isles			36	16
MV Lord of the Isles			>40	20
802				28
MV Finlaggan				30
MV Hebrides				36
MV Loch Seaforth				>40

Table 3-3 Hydrogen Plant Footprints (Vessels)

Vessel	Weekly Bunkering		Twice Weekly		Thrice Weekly		Daily Bunkering	
	Model 1 [m^2]	Model 2 [m^2]	Model 1 [m^2]	Model 2 [m^2]	Model 1 [m^2]	Model 2 [m^2]	Model 1 [m^2]	Model 2 [m^2]
MV Loch Ranza	2,750	1,540	1,560	970	1,210	790	790	620
MV Loch Alainn	4,140	2,130	2,300	1,330	1,690	980	980	760
MV Loch Portain	8,670	4,380	4,760	2,660	3,440	2030	1,920	1,400
MV Coruisk	-	-	6,610	3,530	4,680	2730	2,520	1,760
MV Isle of Mull	-	-	10,350	5,210	7,200	3830	3,620	2,230
MV Caledonian Isles	-	-	12,910	-	8,860	4700	4,400	2,760
MV Lord of the Isles	-	-	16,320	-	11,280	-	5,470	3,310
802	-	-	23,040	-	15,900	-	7,740	4,770
MV Finlaggan	-	-	25,380	-	17,510	-	8,570	5,250
MV Hebrides	-	-	29,410	-	20,370	-	9,970	6,090
MV Loch Seaforth	-	-	35,390	-	24,450	-	11,900	7,250

The following is an evaluation of the islands according to the size of land-side hydrogen plant required to supply servicing vessels as per the design assumptions set out in Section 2.3.1. A daily bunkering frequency using Model 2 dispensing has been selected for the evaluation. Where an island has been modelled with more than one vessel, the vessel with the smallest plant footprint has been selected.

Table 3-4 Hydrogen Plant Footprints (Islands)

Island	Route(s)	Vessel(s)	Plant Footprint [m^2]	Min Plant Footprint [m^2]
Arran	Ardrossan – Brodick	MV Caledonian Isles	2,760	2,760
Barra	Barra – Eriskay	MV Loch Alainn	760	760
Berneray	Leverburgh – Berneray	MV Loch Portain	1,400	1,400
Eriskay	Barra – Eriskay	MV Loch Alainn	760	760
Gigha	Gigha – Tayinloan	MV Loch Ranza	620	620
Islay	Kennacraig – Port Askaig / Port Ellen	MV Finlaggan	5,250	5,250

Island	Route(s)	Vessel(s)	Plant Footprint [m^2]	Min Plant Footprint [m^2]
Lewis & Harris	Stornoway – Ullapool	MV Loch Seaforth	7,250	7,250
	Uig – Tarbert – Lochmaddy	802	4,770	4,770
		MV Hebrides	6,090	
	Leverburgh – Berneray	MV Loch Portain	1,400	1,400
Mull	Craignure – Oban	MV Coruisk	1,760	1,760
		MV Isle of Mull	2,230	
North Uist	Uig – Tarbert – Lochmaddy	802	4,770	4,770
		MV Hebrides	6,090	
Skye	Uig – Tarbert – Lochmaddy	802	4,770	4,770
		MV Hebrides	6,090	
	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	3,310	3,310
South Uist	Mallaig – Lochboisdale – Armadale	MV Lord of the Isles	3,310	3,310

3.1.4 Scoring

The islands have been scored as per the scenario discussed in Section 3.1.3. The range between the highest and lowest deviation in plant footprint ratios has been divided into three portions to reflect the scoring range chosen as shown below.

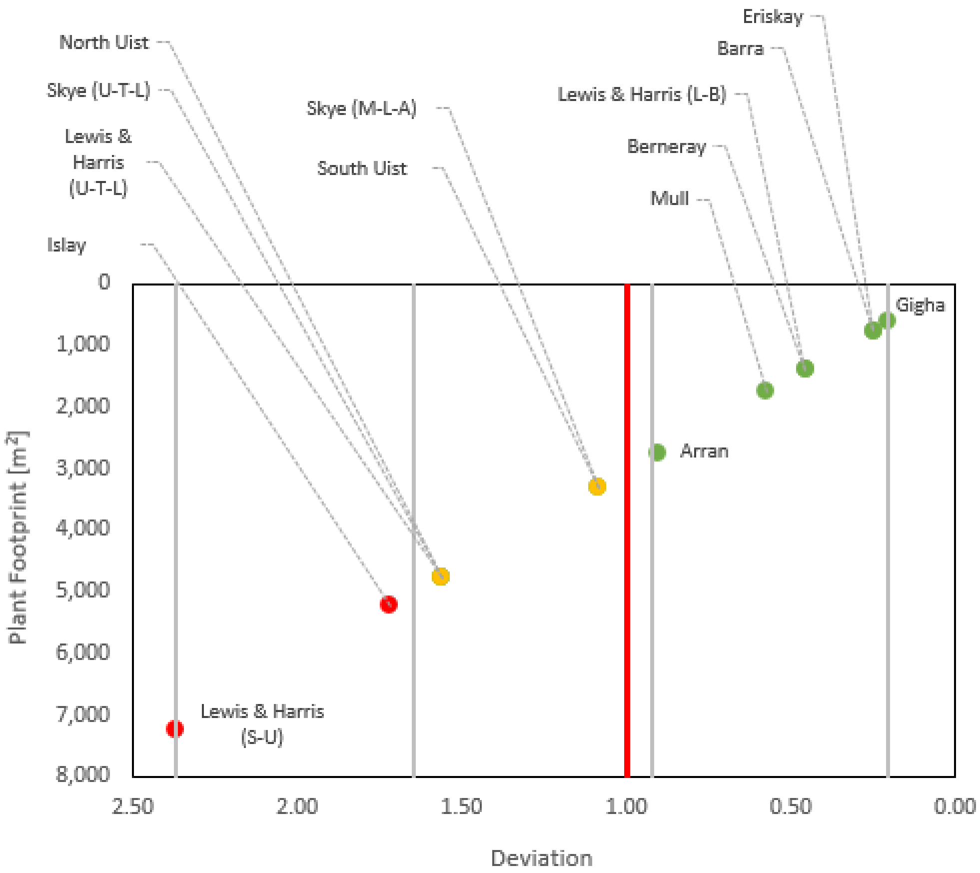


Figure 3-3 Hydrogen Plant Footprint Average Deviations

Table 3-5 Hydrogen Plant Footprint Scoring

Island	Minimum Plant Footprint [m^2]	Score
Lewis & Harris (S-U)	7,250	1
Islay	5,250	1
Lewis & Harris (U-T-L)	4,770	2
North Uist	4,770	2
Skye (U-T-L)	4,770	2
Skye (M-L-A)	3,310	2
South Uist	3,310	2
Arran	2,760	3
Mull	1,760	3
Berneray	1,400	3
Lewis & Harris (L-B)	1,400	3
Barra	760	3
Eriskay	760	3
Gigha	620	3

3.1.5 Key Findings

Direct dispensing (without high-pressure storage) can lead to very high volumetric flows for some scenarios, which can only be performed by several compression units (300 kW membrane compressor packages are considered based on the largest existing products). For availability purposes each compressor has a backup unit. This implies for some scenarios a large number of units to be installed, thus leading to possibly unacceptable plant footprints.

A detailed study should be undertaken once sites have been earmarked for further investigation. This should include a review of larger compressor packages using different technologies, or specific development could be planned with a vendor.

3.2 Preliminary Wind Resource Assessment

The success of the project will rest upon the installation of a suitable wind farm to generate the quantities of hydrogen required for the ferry operating on the route deemed most feasible.

As such, 20 island-side nodes have been selected across the region for modelling and clustered according to their island locations (see Figure 3-4 and Figure 3-5). For inter-island routes, either terminus is deemed available to host the wind farm and hydrogen infrastructure.

The following is a long term indicative wind distribution and energy field assessment of the areas under consideration in the Scottish Western Isles.

3.2.1 Methodology

This preliminary energy yield assessment is based on ConWx reference data from the closest node to each location of interest. ConWx data was chosen for its high consistency and has data coverage across Europe for long periods of historical data.

Mesoscale data products, such as ConWx, are initialised with reanalysis data and additional atmospheric physics modelling to downscale climate information to a higher resolution using terrain and roughness information. The ConWx mesoscale model is run at a high spatial resolution of 0.03° x 0.03°, approximately 3 × 3 km with hourly temporal resolution[12].

The data is scaled to finer resolutions than other reference sources such as MERRA2. The long term trending was considered for the selected node dataset. As a result of the assessment, the period January 1999 to December 2017 was selected as the most suitable long term reference data period.

Caveats:

- The indicative P50 energy yield has been calculated based on power curve data on the SGRE SWT-DD-130 4.3 MW turbine (for technical specifications see Appendix D).
- A hub height (HH) of 100m has been assumed.
- The average wind speed obtained for some sites is over 10 m/s and hence above that recommended for a Class 1A WTG.
    - New Siemens Gamesa technology will be available by the time the project is contracted, which will be IEC Class 1A and is expected to generate greater AEP than the SWT-DD-130 at lower capex.
- Considering the remote locations, any repairs could take longer, and hence the warranted availability would be less.

[12] https://www.emd.dk/windpro/mesoscale-data/subscribe/emdconwx-mesoscale-data/

- Wood typically consider ConWx reference data to correct short term site data to a longer period. The use of ConWx data as a direct measure of wind speed at a location is not advisable and should be updated using measured site data where possible.
- A number of the losses applied are nominal and should be updated with appropriate site specific losses where possible.

The locations for the wind model nodes were chosen using the following criteria:

- Island-side ports: based on the rationale that any future wind farm development should ideally be located as close to associated port infrastructure as possible where hydrogen electrolysis and ferry refuelling will likely take place. Locating the wind farm as close as possible to port infrastructure is not yet a fixed decision but is an acceptable assumption at this stage. This setup could minimise energy transmission losses whilst minimising the number of landowners requiring to be involved in laying pipeline and/or cables between the wind farm and port infrastructure.
- Undeveloped consented wind farms: There are several consents for wind farms in the region that have remained undeveloped at the time of writing this report. These locations for wind modelling have been selected in order to take advantage of existing third party measurement campaigns and energy yield assessments that could be made available to the project in any future collaboration.
- Wood have calculated losses based on a comparison with the Beinn Ghrideag wind farm losses and carried out some additional checks using the wind flow model from our assessment undertaken in 2011.
- The capacity factors are relatively high, most likely because the turbines selected in this report are considered to be IEC-Class 2, however the sites are considered to be IEC-Class 1, due to the very high average wind speeds. Wood therefore recommend that the site suitability of the turbines is confirmed in the next phase.

Figure 3-4 and Figure 3-5 below show the geographical locations of these nodes.

Figure 3-4 Wind Node Locations (Outer Hebrides and Skye)

Figure 3-5 Wind Node Locations (Inner Hebrides and Arran)

3.2.2 Assessment Results

Table 3-6 Wind Resource Assessment of Nodes

Node	ConWx Node Latitude	ConWx Node Longitude	Average Wind Speed @ 100m [m/s]	Indicative Energy Yield Value[13] [MWh/annum]	Indicative Capacity Factor [%]
Armadale Port	57.08	-5.89	8.82	14,371.7	38.20
Barra Port (Ardmhor)	56.99	-7.42	10.60	17,619.3	46.80
Berneray Port	57.71	-7.18	10.21	16,982.5	45.10
Brodick Port	55.58	-5.14	8.91	14,764.0	39.20
Craignure Port	56.48	-5.71	8.58	14,084.8	37.40
Druim Leathann Wind Farm	58.34	-6.22	9.65	16,249.7	43.10
Eriskay Port	57.08	-7.30	10.42	17,295.2	45.90
Gigha Port	55.67	-5.74	9.24	15,379.2	40.80
Leverburgh Port	57.77	-7.03	10.18	16,919.7	44.90
Lochboisdale	57.14	-7.30	10.26	17,083.9	45.40

[13] Indicative P50 energy yield value based on power curve data provided by SGRE for the SWT-DD-130-4.3 MW WTG

Node	ConWx Node Latitude	ConWx Node Longitude	Average Wind Speed @ 100m [m/s]	Indicative Energy Yield Value[13] [MWh/annum]	Indicative Capacity Factor [%]
Lochcarnan Wind Farm	57.35	-7.30	10.18	16,957.1	45.00
Lochmaddy Port	57.59	-7.15	10.19	16,964.7	45.00
Muaitheabhal Wind Farm	58.01	-6.55	9.36	15,562.1	41.30
Port Askaig	55.85	-6.10	9.29	15,681.2	41.60
Port Ellen	55.64	-6.19	9.45	15,983.3	42.40
Stornoway Port	58.22	-6.40	9.26	15,485.2	41.10
Stornoway Wind Farm	58.22	-6.49	9.23	15,434.0	41.00
Tarbert Port	57.89	-6.79	9.80	16,308.0	43.30
Uig Port	57.59	-6.37	9.46	15,771.6	41.90
Vatersay	56.93	-7.54	10.63	17,655.9	46.90
		Average	**9.7**	**16,127.66**	**42.82**
		Minimum	**8.6**	**14,084.80**	**37.40**
		Maximum	**10.6**	**17,655.90**	**46.90**

Table 3-7 Wind Resource Assessment of Islands

Node	Node Indicative EY [MWh/annum]	Island	Averaged Indicative EY [MWh/annum]
Brodick Port	14,764.0	Arran	14,764.0
Barra Port (Ardmhor)	17,619.3	Barra	17,637.6
Vatersay	17,655.9		
Berneray Port	16,982.5	Berneray	16,982.5
Eriskay Port	17,295.2	Eriskay	17,295.2
Gigha Port	15,379.2	Gigha	15,379.2
Port Askaig	15,681.2	Islay	15,832.3
Port Ellen	15,983.3		
Druim Leathann Wind Farm	16,249.7	Lewis & Harris	15,993.12
Leverburgh Port	16,919.7		
Muaitheabhal Wind Farm	15,562.1		
Stornoway Port	15,485.2		
Stornoway Wind Farm	15,434.0		
Tarbert Port	16,308.0		
Craignure Port	14,084.8	Mull	14,084.8
Lochmaddy Port	16,964.7	North Uist	16,964.7
Armadale Port	14,371.7	Skye	15,071.65
Uig Port	15,771.6		
Lochboisdale	17,083.9	South Uist	17,020.50
Lochcarnan Wind Farm	16,957.1		

3.2.3 Scoring

Based on the above preliminary wind resource assessment the islands have been scored according to the deviation of each island's (node average) indicative energy yield from the mean average of all islands.

Using this method, the range between the highest and lowest deviation in island average energy yield can be divided into three portions to reflect the scoring range chosen. Each island is scored in Table 3-8 below according to the position it lies in.

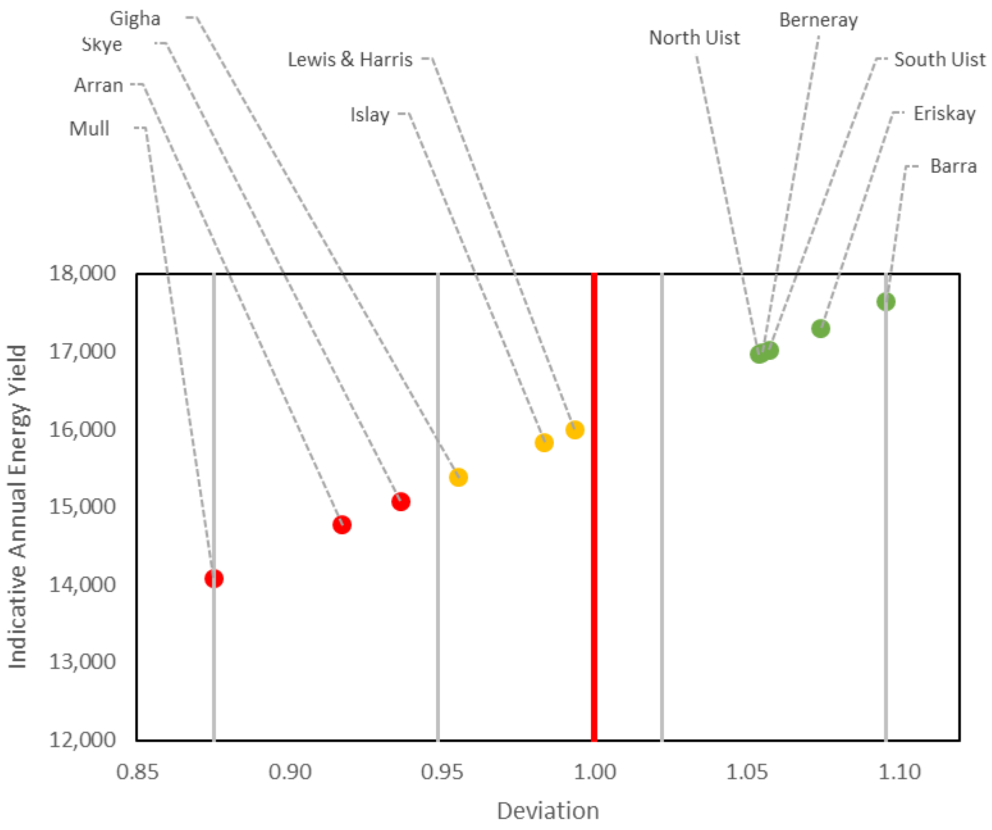


Figure 3-6 Island Wind Resource Average Deviations

Table 3-8 Wind Resource Scoring

Island	Island Average Energy Yield Value[8] (MWh / annum)	Score
Mull	14,084.80	1
Arran	14,764.00	1
Skye	15,071.65	1
Gigha	15,379.20	2
Islay	15,832.30	2
Lewis & Harris	15,993.12	2
North Uist	16,964.70	3
Berneray	16,982.50	3
South Uist	17,020.50	3
Eriskay	17,295.20	3
Barra	17,637.60	3

3.2.4 Key Findings

The results of the preliminary wind resource assessment indicate that the region as a whole has a good resource with indicative capacity factors averaging 42.82% across all nodes modelled with a maximum capacity factor of 46.90% occurring at the Vatersay node.

These results confirm Wood's positive expert opinion of the region and reinforce the argument for exploring alternative methods to harness the islands' abundant wind resource.

Generally, capacity factors in excess of 40% are seen as favourable. The minimum recorded factor in this dataset is 37.40%, indicating good resource in every island under investigation. A high capacity factor is beneficial to any future development as costs can be spread across a greater quantity of energy output for the same generating assets.

3.3 Wind Farm Land-use and Planning Assessment

The islands have been subjected to high-level screening in relation to potential WTG development. This has focussed on spatial guidance from local planning authorities (LPAs) and information with regard to other potential key constraints including aviation interests and key environmental designations.

The key constraints considered at this high-level screening assessment stage include:

- Aviation:
  - Proximity to airports.
  - National Air Traffic Services (NATS) Primary Surveillance Radar Potential Impact Zones.
  - Ministry of Defence (MoD) Radar Potential Impact Zones.
- Environmental designations:
  - Special Areas of Conservation (SAC) - strictly protected sites designated under the European Commission Habitats Directive.
  - Special Protection Area (SPA) - strictly protected sites classified in accordance with Article 4 of the European Commission Birds Directive.
  - Ramsar - a wetland site designated of international importance under the Ramsar Convention. Ramsar sites typically incorporate elements of bird conservation.

Further detailed assessment of potential constraints and opportunities should be undertaken to confirm potential for WTG development at a particular site and/or to guide the site identification process.

Successfully obtaining planning consent for a new wind farm development anywhere in the study area is likely to be challenging and would be considered to represent one of the higher risks facing the overall project. This high-level screening assessment is undertaken to provide an indication of relative potential for development across the different islands/island groups, within the context of high planning risk overall.

3.3.1 Methodology

Geographic Information Systems (GIS) software was used to undertake the screening exercise, incorporating publicly available spatial data representing each of the potential constraints listed above.

Spatial planning guidance from LPAs was digitised and incorporated into the GIS screening process. The guidance identified areas where the respective LPA is likely to look favourably on proposed WTG development, areas where WTG development would only be possible if it can be demonstrated that potential impacts on significant constraints can be mitigated and areas where WTG development will not be accepted. The LPA spatial guidance was used as the principal consideration in the screening exercise.

WTGs in proximity to an airport (within up to 15 km in some cases) have the potential to represent a physical obstacle/safety risk to aircraft taking off and landing. Safeguarding zones are adopted by airports within which obstacles above a certain height are prohibited. Areas within airport safeguarding zones are considered to have no potential for WTG development.

In addition, WTGs can present a potential aviation safety risk through interference with radar systems within a 30 km radius (impacts can extend beyond 30 km in some instances). The National Air Traffic Services (NATS) and the Ministry of Defence (MoD) publish GIS datasets which illustrate areas within which WTGs of a given tip height would impact on their radar systems. Radar impacts can often be mitigated but this typically entails considerable expense. Consequently, identified aviation radar impact zones are considered to have medium potential for WTG development.

The areas within the key environmental designations included in the screening exercise are not suitable for WTG development. Special Protection Areas (SPAs) and Ramsar sites[14] are designated due to important bird interests. Consequently, as a result of the potential for birds to collide with WTGs (leading to injury or death), the areas adjacent to these designations are considered to have low potential for WTG development.

The overall level of potential for new WTG development at each island/island group was categorised as reasonable, medium or low to no potential using professional judgement informed by the LPA spatial guidance, supplemented by the key aviation and environmental constraints. As stated earlier, these categories are relative to allow comparison between islands/island groups and that level of planning risk across the entire study area is considered to be relatively high, even where an LPA has indicated that some potential may exist.

Some key issues such as landscape and visual impacts, noise, shadow flicker, ornithology and ecology cannot be fully considered in such a high-level screening exercise and more detailed assessment would be required once potentially suitable routes are selected. These issues may have a significant effect on the potential for WTG development. Where Wood has specific industry insight in relation to the effects of such issues on the potential for WTG development, this has been taken into account in the categorisation of the islands/island groups, supplementing the initial GIS-based screening exercise.

[14] https://www.ramsar.org/

3.3.2 Assessment Results

The following table details the results of the land-use and planning assessment of the Western Isles localities under investigation. Where appropriate, individual islands have been grouped together to assess constraints.

Table 3-9 Land-use and Planning Potential

Island / Group	Screening Comments	Level of Potential
Skye	LPA Spatial Guidance: The Highlands Council's *Spatial Framework for Onshore Wind Energy* (August 2016 - West Highland and Islands Local Development Plan Area) indicated that approximately 133 km^2 of Skye would potentially be suitable for WTG development (approximately 8% of the total island area). An area of approximately 1,240 km^2 (approximately 75% of total island area) was identified as being subject to potential constraint and is therefore considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. A further 275 km^2 (approximately 17% of total island area) was illustrated to have no potential for WTG development. Key Aviation Constraints: Areas of potential impact on NATS primary surveillance radar and MoD radar were identified in relation to WTGs of the scale being considered. Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed in these areas. A number of areas identified by	Reasonable

	the Local Planning Authority (LPA) as having potential for WTG development remain unconstrained by these key aviation constraints. Key Designations: One large SPA and a number of SACs present on the island. These primarily coincide with no or low / medium potential areas as per LPA Spatial Guidance. However, the SPAs are located adjacent to some areas identified by the LPA as having potential for WTG development. Developing WTGs adjacent to SPAs, or other bird-related designations, can increase the planning risk. A number of relatively large areas of reasonable potential are not located within or adjacent to these key environmental designations.	
Gigha	LPA Spatial Guidance: The *Argyll and Bute Spatial Framework for Windturbines over 50 metres to blade tip* (Appendix F) identifies that approximately 5 km^2 of Gigha would potentially be suitable for WTG development, approximately 34% of the total area of the island. The remainder is identified as being areas of significant protection and are considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. Key Aviation Constraints: No potentially significant aviation issues were identified. Key Designations: No SAC, SPA or Ramsar sites on the island.	Reasonable
Lewis & Harris	LPA Spatial Guidance: The Western Isles Council's *Map 1 - Comhairle Spatial Strategy for Wind Farms* (December 2016) indicates that Lewis and Harris has an area of approximately 7 km^2 that may potentially be suitable for WTG development (approximately 0.3% of total island area). An area of approximately 1,341 km^2 (approximately 61% of total island area) is shown to be subject to potential constraint and is therefore considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG	Medium

	development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. A further 848 km^2 (approximately 39% of total island area) is shown to have no potential for WTG development. Key Aviation Constraints: A large area of Lewis would be within a 15 km radius safeguarding zone around Stornoway Airport. Any WTGs within this area could represent a potential safety risk to aircraft using this airport. This only affects areas already identified as being subject to potential constraint by the LPA. There are also areas of potential impact in relation to MoD radar, however, these are in areas already identified by the LPA as having no potential for WTG development. Key Designations: A large part of Lewis is designated as SPA, SAC and / or Ramsar sites. These designations would likely prohibit WTG development within or adjacent to these areas. Some of the areas identified by the LPA as being potentially suitable for WTG development (roughly half of the combined area identified as having potential) are immediately adjacent, and in some cases surrounded by, these important international designations. Consequently, even within these areas of potential, it is considered that obtaining planning consent for a WTG development could be a significant challenge However, even considering these key potential environmental designations and aviation constraint, relatively large areas with low to medium potential and some small areas with reasonable potential for WTG development remain available (subject to detailed investigation of other constraints).	
Mull	LPA Spatial Guidance: *Argyll and Bute Spatial Framework for Windturbines over 50 metres to blade tip* identifies that approximately 255 km^2 of Mull is potentially suitable for WTG development (approximately 29% of the total island area). An area of approximately 537 km^2 (approximately 61% of the total island area) is shown to be subject to potential constraint and is therefore considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG	Medium

	development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. A further 96 km^2 (approximately 11% of total island area) is shown to have no potential for WTG development. Key Aviation Constraints: Some areas, primarily in the west of Mull, are within an area of potential impact on NATS primary surveillance radar in relation to WTGs of the scale being considered. Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed in these areas. A relatively high proportion of the areas identified by the LPA as having potential for WTG development are situated outside the potential radar impact areas. Key Designations: One large SPA and a number of SACs are present on the island. These coincide with no or low / medium potential areas as per LPA Spatial Guidance. However, the SPAs are located adjacent to some areas identified by the LPA as having potential for WTG development. Developing WTGs adjacent to SPAs, or other bird-related designations, can increase the planning risk. A number of relatively large areas of reasonable potential are not located within or adjacent to these key environmental designations. Although the initial GIS-based screening exercise would suggest that Mull has reasonable potential for new WTG development, Wood's industry experience indicates that, primarily due to the presence of sea eagles and landscape and visual sensitivities, the level of potential is considered to be lower.	
Arran	LPA Spatial Guidance: The *Ayrshire Planning Guidance on Wind Farm Development* document indicates that the island of Arran has approximately 29 km^2 of land that would potentially be suitable for WTG development (approximately 7% of the total area of the Island. A further 96 km^2 (approximately 22% of the total area) is identified as being subject to potential constraint and is considered to have low to medium potential for WTG development. The remainder is identified as having no potential for development (71% of total area).	Low / None

	In addition, a landscape sensitivity study presented in Appendix A of the aforementioned document indicates that the entire island would have high sensitivity to medium-scale wind farm development (3 to 7 WTGs with installed capacity of less than 20 MW) from a landscape and visual impact perspective. Key Aviation Constraints: Large areas of the island are within an area of potential impact in relation to NATS Primary Surveillance Radar for WTGs of the scale being considered. Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed in these areas. Key Designations: There is one large SPA identified on the island. This coincides with an area already identified by the LPA as having no potential for WTG development.	
Barra	LPA Spatial Guidance: The Western Isles Council's *Map 1 - Comhairle Spatial Strategy for Wind Farms* (December 2016) indicates that Barra has an area of approximately 1 km^2 (approximately 1% of the total island area) that would potentially be suitable for WTG development. The remainder is shown to be subject to potential constraint and to have low to medium potential. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. Key Aviation Constraints: The majority of the area identified by the Western Isles Council to have potential for WTG development is within a 5 km radius of the Barra Airfield and as such any WTGs within this area are likely to represent a potential risk to aircraft taking-off and landing. In addition, the majority of the island is also within a potential impact zone in relation to MoD Radar and NATS primary surveillance radar for WTGs of the scale being considered. Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed across the majority of the island. Key Designations: No SAC, SPA or Ramsar sites on the island.	Low / None

Berneray, Uist & Eriskay	LPA Spatial Guidance: The Western Isles Council's *Map 1 - Comhairle Spatial Strategy for Wind Farms* (December 2016) indicates that this island group has an area of approximately 14 km^2 that may potentially be suitable for WTG development (approximately 2% of the total area). An area of approximately 497 km^2 (approximately 68% of the total area) is shown to be subject to potential constraint and is therefore considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. A further 223 km^2 (approximately 30% of total island area) is shown to have no potential for WTG development. Key Aviation Constraints: Roughly half of the island group is within a 15 km radius safeguarding zone around Benbecula Airport. WTGs within this area would potentially represent a risk to aircraft using this airport. In addition, almost all of the island group is within potential impact zones in relation to aviation radar issues (NATS primary surveillance radar and MoD radar). Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed across the majority of the island. Key Designations: There are a number of SPA, SAC and Ramsar sites on the island group. Although these coincide with areas identified as having no or low / medium potential for WTG development based on the LPA Spatial Guidance, there are identified areas of potential adjacent to important bird-related designations. Development of WTGs in these areas is likely to have relatively high planning risk. Only a small number of areas identified as having reasonable potential are not located immediately adjacent to these key environmental designations.	Low / None

Islay	LPA Spatial Guidance: *Argyll and Bute Spatial Framework for Windturbines over 50 metres to blade tip* identifies that approximately 132 km^2 of Islay would potentially be suitable for WTG development (approximately 21% of total island area). An area of approximately 487 km^2 (79% of total island area) was shown to be subject to potential constraint and is considered to have low to medium potential for WTG development. Additional studies would be required to fully understand the constraints present in these areas and the implications for WTG development. In addition to higher planning risks, it is considered likely that development costs will also be higher for a WTG development in these constrained areas. Key Aviation Constraints: A large proportion of the island would be within a 15 km radius of Islay Airport and consequently any WTG development within this area could potentially represent a safety risk to aircraft taking-off and landing at the airport. In addition, a large part of the island is also within an area of potential impact in relation to NATS primary surveillance radar for WTGs of the scale being considered. Radar mitigation, which can be prohibitively expensive, may be required for any WTG development proposed in these areas. Key Designations: There is one large SPA and a number of Ramsar and SAC sites on the island. Although these coincide with areas identified as having low / medium potential for WTG development based on the LPA Spatial Guidance, there are identified areas of potential amidst and adjacent to important bird-related designations. Development of WTGs in these areas is likely to have relatively high planning risk. A number of relatively large areas of reasonable potential are not located within or adjacent to these key environmental designations. Although the initial GIS-based screening exercise would suggest that Islay has Medium potential for new WTG development, Wood's industry experience indicates that, primarily due to the presence of protected geese, the airport and landscape and visual sensitivities, the level of potential is actually considered to be lower.	Low / None

Table 3-10 Land-use and Planning Potential Summary

Island	Planning Group	Island Level of Potential
Arran	Arran	Low / None
Barra	Barra	Low / None
Berneray	Berneray, Uist & Eriskay	Low / None
Eriskay	Berneray, Uist & Eriskay	Low / None
Gigha	Gigha	Reasonable
Islay	Islay	Low / None
Lewis & Harris	Lewis & Harris	Medium
Mull	Mull	Medium
North Uist	Berneray, Uist & Eriskay	Low / None
Skye	Skye	Reasonable
South Uist	Berneray, Uist & Eriskay	Low / None

3.3.3 Scoring

Scoring for this criterion has been undertaken on a simple ranking scale as follows:

Table 3-11 Land-use and Planning Scoring

Route	Island Level of Potential	Score
Arran	Low / None	1
Barra	Low / None	1
Berneray	Low / None	1
Eriskay	Low / None	1
Islay	Low / None	1
North Uist	Low / None	1
South Uist	Low / None	1
Lewis-Harris	Medium	2
Mull	Medium	2
Gigha	Reasonable	3
Skye	Reasonable	3

3.3.4 Key Findings

The results of the land-use and planning review highlight the constrained nature of much of the land masses under review. In total, seven islands have been determined to have either low or no potential to develop new wind farm developments which is a significant portion of the area under investigation.

Conversely, four islands have been determined to have a medium to reasonable chance of securing planning permission for a future wind farm, and have been scored positively as a result.

Successfully obtaining planning consent for a new wind farm development anywhere in the study area, even where an LPA has indicated that there may be potential, is likely to be challenging and would be considered to represent one of the higher risks facing the overall project.

This high-level desktop screening assessment was undertaken to provide an indication of relative potential for development across the different islands/island groups, against the generally high planning risk background.

It should also be noted, that local planning authorities have not been contacted as part of this feasibility study to canvas professional opinion. Future investigation should consider re-appraising the islands by approaching LPAs with specific developmental proposals for opinions.

3.4 Wind Farm Accessibility Assessment

Many of the islands proposed for hosting the hydrogen production wind farm are remote locations with all but one (Skye) requiring access by sea for construction purposes. Indeed, many of the islands now fall within the UK government's updated definition of remote island wind (RIW) resource.

A preliminary access study has been undertaken to evaluate the accessibility of potential wind farm locations under investigation across the Western Isles. This has been performed using specifications for the SWT-DD-130 4.3 MW WTG. This model of wind turbine is of a large scale. Thus, a location scoring poorly on accessibility may benefit from employing a smaller turbine such as the SG 2.6-114 which is also being considered for SWIFTH$_2$.

There are no standard specifications for ports for the purposes of offloading WTG components. A selected port will be surveyed and then a suitable vessel found for the infrastructure. In the few circumstances where a port has insufficient draft, or the tidal range impacts offloading, then alternatives are sought such as roll-on/roll-off vessels or barges.

3.4.1 Methodology

The access study includes a review of the existing port infrastructure available, the suitability of the port to receive and offload WTG components, and whether a purpose built landing area would be required to be constructed to facilitate this.

The accessibility of local trunk roads available to transport components from ports to a hypothetical wind farm site was also reviewed, with particular consideration given to weight loading and length of oversized components. The blade transporters themselves will be approximately 70m long (approximately the length of six double decker buses) which while utilising rear wheel steering will still require road widening on tight bends.

Caveats:

- Discussions with relevant council road engineers have not been undertaken as a specific site for a wind farm development has yet to be identified.
- It is recommended that a detailed access study is commissioned once a site or sites have been selected for further investigation.
- The study was undertaken with regard to the suitability for the transportation of abnormal loads associated with the proposed SWT-DD-130 WTG. The impact of construction traffic has not been considered.

This desktop assessment does not include site visits to assess infrastructure. The term 'tentative' has been used below to caution that further site specific investigation should be undertaken.

3.4.2 Assessment Results

The following tables detail the results of the access study. Islands linked together by road bridges have been grouped together as it is expected a suitable port facility could potentially open up the entire island group to the delivery of WTG components.

Each island / island group has been assessed on a number of access criteria which have each been assigned a status of either 'tentative' or 'restricted', with the number of restrictions totalled in Table 3-20 below.

Further information on port characteristics used to determine criteria status can be found in Appendix L.

Table 3-12 Arran Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Brodick Ferry Terminal.	Tentative
Port upgrade requirements	As neither port is suitable for ship deliveries, a purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island.	Restricted
Access to road network from port	There is no direct access from either port.	Restricted
Existing road network suitability	• 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required.	Tentative

Table 3-13 Barra Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Castle Bay Ferry Terminal. A LTM1220 5.2 (220 tonne) crane, weighing 60 tonnes with an axle load of 12 tonnes per axle was used to erect the community owned Enercon E-44 wind turbine on Barra.	Tentative
Port upgrade requirements	Neither port suitable for ship deliveries of the WTG model discussed. A purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island via towed barge from the mainland. Note, Barra has previously received a 900 kW turbine delivered by a landing craft type vessel close to the selected site rather than via harbour. In this case, the port was suitable for delivery of the Enercon E-44 WTG but a tug and barge were required as the road from the port to the site were not suitable.	Restricted
Access to road network from port	There is no direct access from either port.	Restricted
Existing road network suitability	6m wide 'A' class roads suitable for oversize loads with localised widening in places as required.	Tentative

Table 3-14 Berneray / Uist / Eriskay Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Lochmaddy or Lochboisdale ferry terminals.	Tentative
Port upgrade requirements	Lochmaddy and Lochboisdale both have quays witch could possibly be suitable for ship deliveries provided they did not interfere with ferry movements. Otherwise a purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island via towed barge from the mainland.	Tentative
Access to road network from port	There is no direct access from Berneray, Otternish, Kallin or Eriskay, however there is a good connection to the existing road network form both Lochmaddy and Lochboisdale terminals.	Tentative
Existing road network suitability	<u>Berneray Ferry Terminal</u> • 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required. <u>Lochboisdale South Uist Ferry Terminal</u> • 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required. <u>Eriskay Ferry Terminal</u> • 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required.	Tentative

Table 3-15 Gigha Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Ardminish Ferry Terminal	Tentative
Port upgrade requirements	As the ports are not suitable for ship deliveries, a purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island.	Restricted
Access to road network from port	There is no direct access from the current port.	Restricted
Existing road network suitability	3m wide 'B' class roads would require widening on bends as required.	Restricted

Table 3-16 Islay Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Port Ellen and Port Askaig ferries terminals.	Tentative
Port upgrade requirements	As the ports are not suitable for ship deliveries, a purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island.	Restricted
Access to road network from port	• There is good access to the local road network from the Port Ellen. • The roads from Port Askaig are of suitable quality however the presence of two tight switchback bends together with steep grades involved are not suitable for WTG components.	Tentative

Criteria	Issue	Status
Existing road network suitability	• 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required.	Tentative

Table 3-17 Lewis & Harris Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via Stornoway Port.	Tentative
Port upgrade requirements	Stornoway Port could feasibly take WTG deliveries, however Arnish Point is the preferred offloading location by the Stornoway Ports Authority as it has been utilised in the past for WTG components. The ports of Leverburgh and Tarbert are not suitable for ship deliveries as there is no areas for quayside crane or laydown operations.	Tentative
Access to road network from port	• As Arnish point has been used previously for WTG deliveries, the local roads have been widened at bends to accommodate oversized vehicles. • There is no direct access from the other ports.	Tentative

Criteria	Issue	Status
Existing road network suitability	• 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required. • Stornoway streets would be very difficult for larger blades to negotiate however Arnish has been used for that purpose previously and can be customised further.	Tentative

Table 3-18 Mull Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Fishnish Ferry Terminal.	Tentative
Port upgrade requirements	As the ports are not suitable for ship deliveries, a purpose built landing area would need to be constructed to facilitate the landing of WTG components onto the island.	Restricted
Access to road network from port	There is no direct access from either ports.	Restricted
Existing road network suitability	• 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required.	Tentative

Table 3-19 Skye Accessibility

Criteria	Issue	Status
Crane / transporter accessibility	Cranes and transporters could be delivered via the Skye bridge from the Kyle of Lochalsh. Alternatively the ports at Uig or Armadale could be utilised.	Tentative
Port upgrade requirements	As the ports are not suitable for ship deliveries the Skye bridge from the Kyle of Lochalsh should be used to facilitate the deliveries of WTG components onto the island.	Tentative
Access to road network from port	There is no direct access from the current ports. Access to road network via the Skye bridge from the Kyle of Lochalsh.	Tentative
Existing road network suitability	• 6m wide 'A' class roads suitable for oversize loads with localised widening in places as required. • 3m wide 'B' class roads would require widening on bends as required.	Tentative

Table 3-20 Island Accessibility Summary

Island	Accessibility Group	Accessibility Criteria				No. Restricted Criteria
		Crane transport accessibility	Port upgrade requirements	Access to road network from port	Existing road network suitability	
Arran	Arran	Tentative	Restricted	Restricted	Tentative	2
Barra	Barra	Tentative	Restricted	Restricted	Tentative	2
Berneray	Berneray / Uist / Eriskay	Tentative	Tentative	Tentative	Tentative	0
Eriskay	Berneray / Uist / Eriskay	Tentative	Tentative	Tentative	Tentative	0
Gigha	Gigha	Tentative	Restricted	Restricted	Restricted	3
Islay	Islay	Tentative	Restricted	Tentative	Tentative	1
Lewis & Harris	Lewis & Harris	Tentative	Tentative	Tentative	Tentative	0
Mull	Mull	Tentative	Restricted	Restricted	Tentative	2
North Uist	Berneray / Uist / Eriskay	Tentative	Tentative	Tentative	Tentative	0
Skye	Skye	Tentative	Tentative	Tentative	Tentative	0
South Uist	Berneray / Uist / Eriskay	Tentative	Tentative	Tentative	Tentative	0

3.4.3 Scoring

The islands as reviewed by the access study have been scored in Table 3-21 below. In the absence of an objective metric, such as associated cost of infrastructure upgrades, the islands have been scored on a simple ranking basis. Islands incurring restrictions on two or more access criteria have been scored least favourably. A score of '3' does not foresee no access problems, merely that major restrictions that prohibit development have not been identified.

Table 3-21 Wind Farm Accessibility Scoring

Island	No. Restricted Criteria	Score
Gigha	3	1
Arran	2	1
Barra	2	1
Mull	2	1
Islay	1	2
Berneray	0	3
Eriskay	0	3
Lewis & Harris	0	3
North Uist	0	3
Skye	0	3
South Uist	0	3

3.4.4 Key Findings

The results of the wind farm accessibility review demonstrate a wide variety of issues to consider. Many of the constraints identified can be mitigated against by infrastructure upgrades. However other requirements, such as major port improvements, may prove cost prohibitive. In general, suitable infrastructure follows island industrial and commercial development, and population levels. The Isle of Skye scored particularly well owing to the bridge connection to the mainland which would greatly benefit WTG component transport to site. This assessment has been undertaken as a desktop study. Surveying infrastructure as part of a site visit is recommended for a more detailed understanding of access constraints.

3.5 Preliminary Solar Resource Assessment

Though not originally tasked with investigating the solar resource of the region, the Consortium expanded the remit of this study to opine on this area. This was done for two principal reasons:

Firstly, to assess the viability of providing any future development with additional security of hydrogen supply for what are lifeline ferry services to the Western Isles should the proposed wind farm be subject to unacceptably high periods of outage. Note, other forms of system redundancy are available (see Section 7.1).

Secondly, a notable feature of the perceived supply-demand profile of the project is such that the ferry busy period is in the summer season, whilst the greatest available wind resource tends to be in the winter months. Solar resource however aligns well with the ferry busy period.

This second reason can be considered moot as hydrogen as an energy carrier can be stored for later utilisation, decoupling demand from supply and negating the requirement for energy to be utilised as soon as it is available (energy time-shifting).

Periods of low wind resource in the summer months can be compensated for by producing more hydrogen during winter and storing sufficient quantities to meet forecast demand. What an additional solar-PV supply could offer, however, is the ability to downscale the overall size of the on-shore buffer storage as hydrogen could be produced at a steadier rate throughout the year rather than seasonally in bulk.

3.5.1 Methodology

To preliminarily assess the available solar resource in the region, SolarGIS database was employed. SolarGIS is a solar meteorological model which has the ability to serve data for any location with a continuous history of 10 to more than 20 recent years. The model serves data in real time for monitoring and forecasting. To achieve high reliability and low uncertainty the models are calibrated and validated using high quality ground measurements.

Key features of SolarGIS resource data include:

- Tim representation since 1994/1999/2006 depending on the satellite data coverage.
- Primary data resolution 3 to 6 km (depending on the latitude). Enhanced resolution by downscaling up to ~250 m (~90 m) in some regions.
- Original 10/15/30 minutes depending on the satellite region aggregated into hourly, daily, monthly and yearly data products.

The same 20 island-side node locations as assessed by the wind resource assessment in Section 3.2 have been selected for modelling and averaged each island (see Table 3-24Table 3-24). The following is a long term indicative solar resource and energy field assessment of the areas under consideration in the Scottish Western Isles.

Caveats:

- The indicative P50 energy yield has been calculated based on the solar-PV characteristics have been selected for the model are detailed in Table 3-22 below.
- The nodes selected coincide with those for the preliminary wind resource assessment as detailed in Section 3.2.1.

Table 3-22 Solar-PV Modelling Characteristics

PV Characteristic	Type / Value
Type of modules	JA – 6,456 x JAM6-60-270 (270 Wp)
Pitch (distance between arrays)	8.65 m
Module Orientation	Portrait
No. Modules in Column	3
Mounting system	Fixed mounting, free standing
Azimuth/inclination	180° South / 30°
DC / AC losses	5.5% / 1.5%
Availability	99.0%
MWp Per hectare	0.56
MWp for 4 hectares	2.24

3.5.2 Assessment Results

Table 3-23 Solar Resource Assessment of Nodes

Node	Node Latitude	Node Longitude	Energy Output (kWh / kWp)	Indicative Energy Yield Value (MWh / annum)[15]	Indicative Performance Ratio[16] (%)
Armadale Port	57.063	-5.896	1,021	1,873.1	81.9
Barra Port (Ardmhor)	57.000	-7.420	1,062	1,926.9	81.0
Berneray Port	57.710	-7.180	1,013	1,862.9	82.1
Brodick Port	55.574	-5.141	1,045	1,889.0	80.7
Craignure Port	56.469	-5.708	1,008	1,795.0	79.5
Druim Leathann Wind Farm	58.344	-6.233	988	1,825.8	82.5
Eriskay Port	57.073	-7.299	1,060	1,911.4	80.5
Gigha Port	55.678	-5.742	1,085	1,985.6	81.7
Leverburgh Port	57.766	-7.017	1,001	1,827.4	81.5

[15] P50 estimated capacity for a 4 hectare solar farm

[16] Actual yield / theoretical maximum yield the system could have been produced

Node	Node Latitude	Node Longitude	Energy Output (kWh / kWp)	Indicative Energy Yield Value (MWh / annum)[15]	Indicative Performance Ratio[16] (%)
Lochboisdale	57.160	-7.316	1,057	1,943.9	82.1
Lochcarnan Wind Farm	57.359	-7.295	1,038	1,906.6	82.0
Lochmaddy Port	57.600	-7.165	1,012	1,854.3	81.8
Muaitheabhal Wind Farm	58.010	-6.537	980	1,782.5	81.2
Port Askaig	55.849	-6.110	1,065	1,958.6	82.1
Port Ellen	55.634	-6.185	1,113	2,051.8	82.3
Stornoway Port	58.209	-6.371	983	1,805.6	82.0
Stornoway Wind Farm	58.206	-6.464	977	1,794.6	82.0
Tarbert Port	57.897	-6.789	957	1,751.4	81.7
Uig Port	57.586	-6.376	976	1,784.0	81.6
Vatersay	56.930	-7.540	1,064	1,961.5	82.3
		Average	**1,025.3**	**1,874.6**	**81.6**
		Minimum	**957.0**	**1,751.4**	**79.5**
		Maximum	**1,113.0**	**2,051.8**	**82.5**

Table 3-24 Solar Resource Assessment of Islands

Node	Node Indicative EY [MWh/annum]	Island	Averaged Indicative EY [MWh/annum]
Brodick Port	1,889.0	Arran	1,889.0
Barra Port (Ardmhor)	1,926.9	Barra	1,944.2
Vatersay	1,961.5		
Berneray Port	1,862.9	Berneray	1,862.9
Eriskay Port	1,911.4	Eriskay	1,911.4
Gigha Port	1,985.6	Gigha	1,985.6
Port Askaig	1,958.6	Islay	2,005.2
Port Ellen	2,051.8		
Druim Leathann Wind Farm	1,825.8	Lewis & Harris	1,797.9
Leverburgh Port	1,827.4		
Muaitheabhal Wind Farm	1,782.5		
Stornoway Port	1,805.6		
Stornoway Wind Farm	1,794.6		
Tarbert Port	1,751.4		
Craignure Port	1,795.0	Mull	1,795.0
Lochmaddy Port	1,854.3	North Uist	1,854.3
Armadale Port	1,873.1	Skye	1,828.6
Uig Port	1,784.0		
Lochboisdale	1,943.9	South Uist	1,925.3
Lochcarnan Wind Farm	1,906.6		

3.5.3 Scoring

The solar resource has been scoring using the same regime as with the wind resource assessment in Section 3.3.

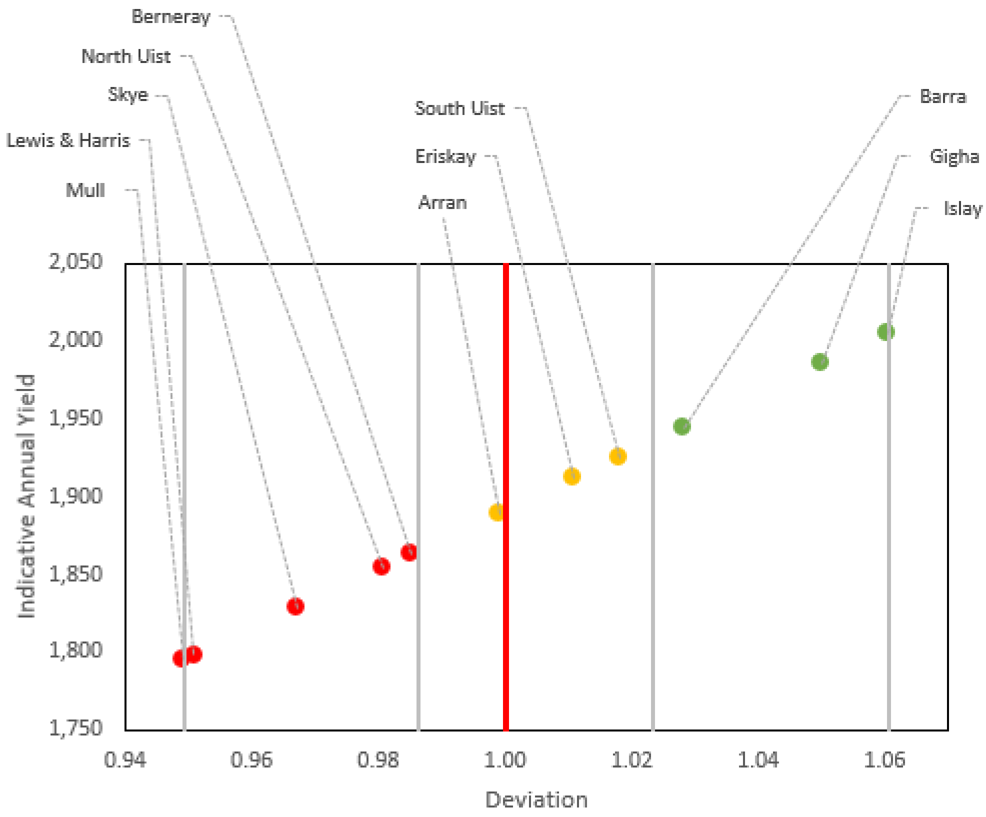


Figure 3-7 Island Solar Resource Average Deviations

Table 3-25 Solar Resource Scoring

Island	Island Average Energy Yield Value (MWh / annum)[12]	Score
Mull	1,795.0	1
Lewis & Harris	1,797.9	1
Skye	1,828.6	1
North Uist	1,854.3	1
Berneray	1,862.9	1
Arran	1,889.0	2
Eriskay	1,911.4	2
South Uist	1,925.3	2
Barra	1,944.2	3
Gigha	1,985.6	3
Islay	2,005.2	3

3.5.4 Key Findings

The results of the solar resource assessment show a fairly uniform spread across the region, with southern islands generally performing above average. Northern islands have scored generally below average for the dataset, in line with expectations.

4 Selection Result and Examination

This feasibility study seeks to determine which island and ferry route demonstrate the greatest viability for deployment of a hydrogen fuelled vessel using the design options stipulated in Section 2.3.1 as a basis.

To assess viability, eight criteria have been examined in relation to both vessel design (Section 2) and the necessary land-based infrastructure required for hydrogen production (Section 3). Though not an exhaustive set of criteria, the aim of this report is to address the most substantive aspects facing a future SWIFTH$_2$ development.

4.1 Methodology

To arrive at a view on the most viable developmental options, a decision matrix has been created to compile all of the assessment criteria and scores for the islands into a single evaluation. This approach benefits from providing a transparent methodology and can accommodate additional or revised criteria with ease should the need arise.

Each criterion has been assigned a score from 1 to 3 (least to most favourable) based on either empirical data or professional judgement where appropriate. The scoring regime's for each criterion can be found in the relevant sections itemised in Table 4-1 below.

As each assessment criterion cannot be considered to hold equal standing in the decision making process, a weighting value is used to differentiate the criteria by importance. The multiplication of each score with an assigned weighing value produces weighted scores:

$$Weighted\ Score = \ Score \ \cdot \ Weighting\ Value$$

The weighting for each criterion is based on professional judgement and is subjective. Table 4-1 details the weighting values agreed by Consortium based on the collective experience of the parties. A higher weighting value indicates greater importance. The rationale for the weightings chosen are included below.

Section 4.2 below shows the assessment criteria and associated weighted values (WV), along with scores (S) and weighted score (WS). Islands with the highest weighted scores can be considered the most viable. Islands with more than one ferry route are incorporated as separate entries to allow both the most suitable island to be determined but also the most suitable ferry route in the case of the islands of Lewis-Harris and Skye.

Table 4-1 Criteria Score Weighting

Criteria	Weighting	Scoring Regime
Preliminary Solar Resource Assessment As not part of the original project scope, this aspect is considered of least importance.	1	Section 3.5.3
Hydrogen Plant Infrastructure As limits to plant footprint not yet fully developed criteria assessment can be considered less critical.	3	Section 3.1.4
Preliminary Wind Resource Assessment Key to successful wind farm development is the available wind resource.	6	Section 3.2.3
Wind Farm Accessibility Transportation of components to any site (regardless of all other positive aspects) is a critical metric as upgrades to port and/or road infrastructure could be cost prohibitive. Existing infrastructure should be considered to be highly beneficial.	7	Section 3.4.3
Wind Farm Land-use and Planning Potential Securing planning permission in a region with significant restrictions will be critical to project success and will drive many of the other site selection decisions.	8	Section 3.3.3
Vessel Equipment Assessment This criterion is effectively scored twice by weight (weighting of 5) and by volume (also 5). The equal weighting indicates the equal importance of considering both measurements. As such, the double measurement produces an effective weighting of 10.	10 (5 + 5)	Section 2.3.5

4.2 Decision Matrix Results

Table 4-2 Decision Matrix

Criteria	WV	Arran		Barra		Berneray		Eriskay		Gigha		Islay		Lewis-Harris[17]						Mull		North Uist		Skye[23]				South Uist	
														(L-B)		(U-T-L)		(S-U)						(M-L-A)		(U-T-L)			
		S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS
Preliminary Solar Resource	1	2	2	3	3	1	1	2	2	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
Hydrogen Plant Infrastructure	3	3	9	3	9	3	9	3	9	3	9	1	3	3	9	2	6	1	3	3	9	2	6	2	6	2	6	2	6
Vessel Equipment Assessment (Volume)	5	1	5	3	15	1	5	3	15	3	15	2	10	1	5	2	10	2	10	3	15	2	10	1	5	2	10	1	5
Vessel Equipment Assessment (Weight)	5	3	15	3	15	2	10	3	15	1	5	2	10	2	10	2	10	3	15	3	15	2	10	2	10	2	10	2	10
Preliminary Wind Resource	6	1	6	3	18	3	18	3	18	2	12	2	12	2	12	2	12	2	12	1	6	3	18	1	6	1	6	3	18
Wind Farm Accessibility	7	1	7	1	7	3	21	3	21	1	7	2	14	3	21	3	21	3	21	1	7	3	21	3	21	3	21	3	21
Wind Farm Land-use and Planning	8	1	8	1	8	1	8	1	8	3	24	1	8	2	16	2	16	2	16	2	16	1	8	3	24	3	24	1	8
TOTALS		**13**	**52**	**18**	**75**	**15**	**72**	**19**	**88**	**17**	**75**	**14**	**60**	**17**	**74**	**17**	**76**	**17**	**78**	**15**	**69**	**15**	**74**	**15**	**73**	**16**	**78**	**15**	**70**

[17] Leverburgh-Berneray (L-B), Uig-Tarbert-Lochmaddy (U-T-L), Stornoway-Ullapool (S-U), Mallaig – Lochboisdale – Armadale (M-L-A)

4.3 Weighted Scores

From the results obtained in the decision matrix in Section 4.2 the ferry routes have been ranked by order of the highest weighted score to lowest as follows:

Table 4-3 Route Selection Results

Island	Score	Weighted Score	Ferry Route
Eriskay	19	88	Barra - Eriskay
Lewis & Harris (S-U)	17	78	Stornoway - Ullapool
Skye (U-T-L)	16	78	Uig - Tarbert - Lochmaddy
Lewis & Harris (U-T-L)	17	76	Uig - Tarbert - Lochmaddy
Barra	18	75	Barra - Eriskay
Gigha	17	75	Gigha - Tayinloan
Lewis & Harris (L-B)	17	74	Leverburgh - Berneray
North Uist	15	74	Uig - Tarbert - Lochmaddy
Skye (M-L-A)	15	73	Mallaig - Lochboisdale - Armadale
Berneray	15	72	Leverburgh - Berneray
South Uist	15	70	Mallaig - Lochboisdale - Armadale
Mull	15	69	Oban - Craignure
Islay	14	60	Kennacraig - Port Askaig / Port Ellen
Arran	13	52	Ardrossan - Brodick

4.4 Ferry Route Shortlist

As per Table 4-3 above, it can be shown that the most favourable islands and their associated ferry routes to pursue a hydrogen vessel are Barra-Eriskay (with land-side infrastructure on Eriskay) and Stornoway-Ullapool (with land-side infrastructure located on Lewis & Harris). These weighted scores are the result of the collective assessment of a range of criteria. The scoring for the two highest performing islands is summarised in Table 4-4 below:

Table 4-4 Route Selection Findings

Criteria	Lewis-Harris (S-U)		Eriskay	
	Score	Weighted Score	Score	Weighted Score
Preliminary Solar Resource Assessment	1	1	2	2
Hydrogen Plant Infrastructure	1	3	3	9
Vessel Equipment Assessment (Volume)	2	10	3	15
Vessel Equipment Assessment (Weight)	3	15	3	15
Preliminary Wind Resource Assessment	2	12	3	18
Wind Farm Accessibility	3	21	3	21
Wind Farm Land-use and Planning Potential	2	16	1	8
TOTALS	**17**	**78**	**19**	**88**

4.4.1 Barra – Eriskay (MV Loch Alainn)

This section addresses some of the key implications of implementing a hydrogen vessel on the Barra – Eriskay route of the scale of the MV Loch Alainn, pictured below in Figure 4-1. Many of these aspects will require close consideration by key stakeholders who will be required to determine the next phase of the SWIFTH$_2$ project.

Figure 4-1 MV Loch Alainn

4.4.1.1 Power Train Replacement

The existing power delivery system (power train) of the MV Loch Alainn is detailed in Table 4-5 and illustrated in Figure 4-2 below. The system is comprised of two 485 kW main engines drawing from the MGO fuel tank each feeding a Voith Schneider propeller, one fore and aft, intermediated by gearboxes and couplings.

Electrical power is provided by two 91 kW engine-generator sets drawing from the MGO fuel tank to deliver electricity for the hotel requirements of the ship. Power management and other ancillary equipment regulate the electrical grid.

The total peak power demand (hotel and propulsion) of the ship is 880 kW. To deliver the same demand using a fuel cell system operating at 40% efficiency, would require 16x 100 kW fuel cell PAC racks.

Table 4-5 MV Loch Alainn Power Train Specifications

MGO System	
MGO fuel tank	24.2 m^3
Hotel Load	60 kW (2 x 91 kW generators)
Propulsion Load	820 kW (2 x 485 kW main engines)
Total Load	880 kW
Equivalent Hydrogen Fuel Cell Power Delivery	
Indicative fuel cell delivery	100 kW (x4 25 kW PAC rack)
No. fuel cell PAC racks required	16
Fuel cell weight	12.07 t
Fuel storage weight (loaded)	9.76 t (x1 520 bar skid)
Total daily energy demand (propulsion + hotel)	134.10 MWh
Indicative fuel cell efficiency	40%
Total daily hydrogen fuel required	335.25 MWh

Figure 4-3 below illustrates a proposed hydrogen power train design for the MV Loch Alainn. Here, the power delivery of the ship would be entirely electrical, with motors replacing MGO fed engines. Fuel cells would convert the store of onboard hydrogen fuel to electricity. As the response times for fuel cells tend to be inadequate for immediate peak demand, a battery will be employed to deliver fast response electricity (peak shaving).

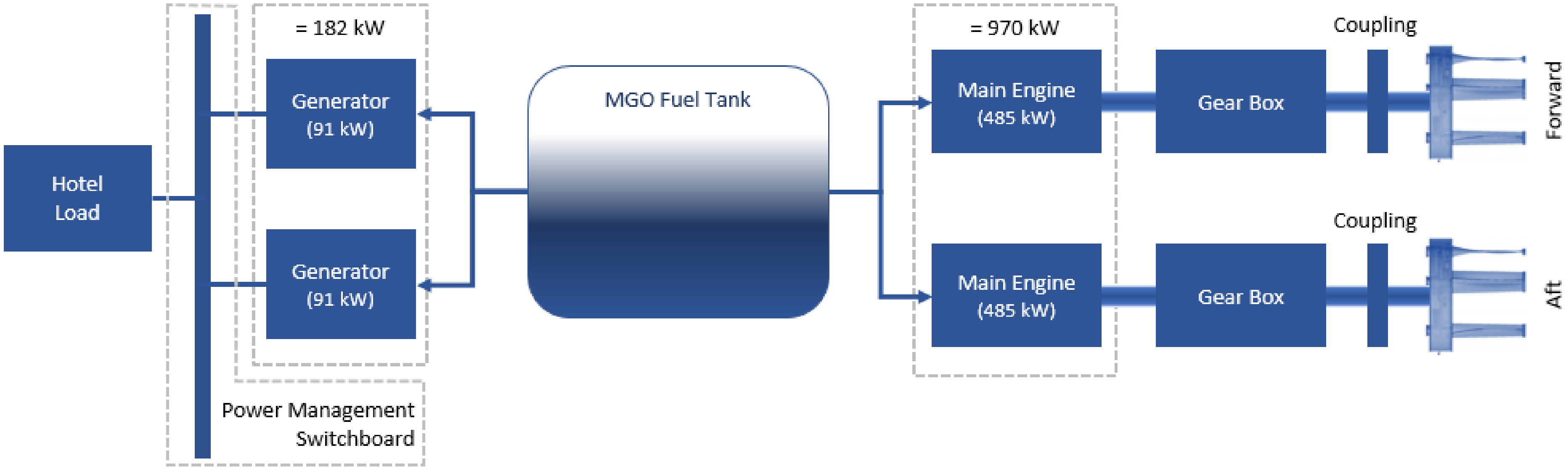


Figure 4-2 MV Loch Alainn MGO Power Train

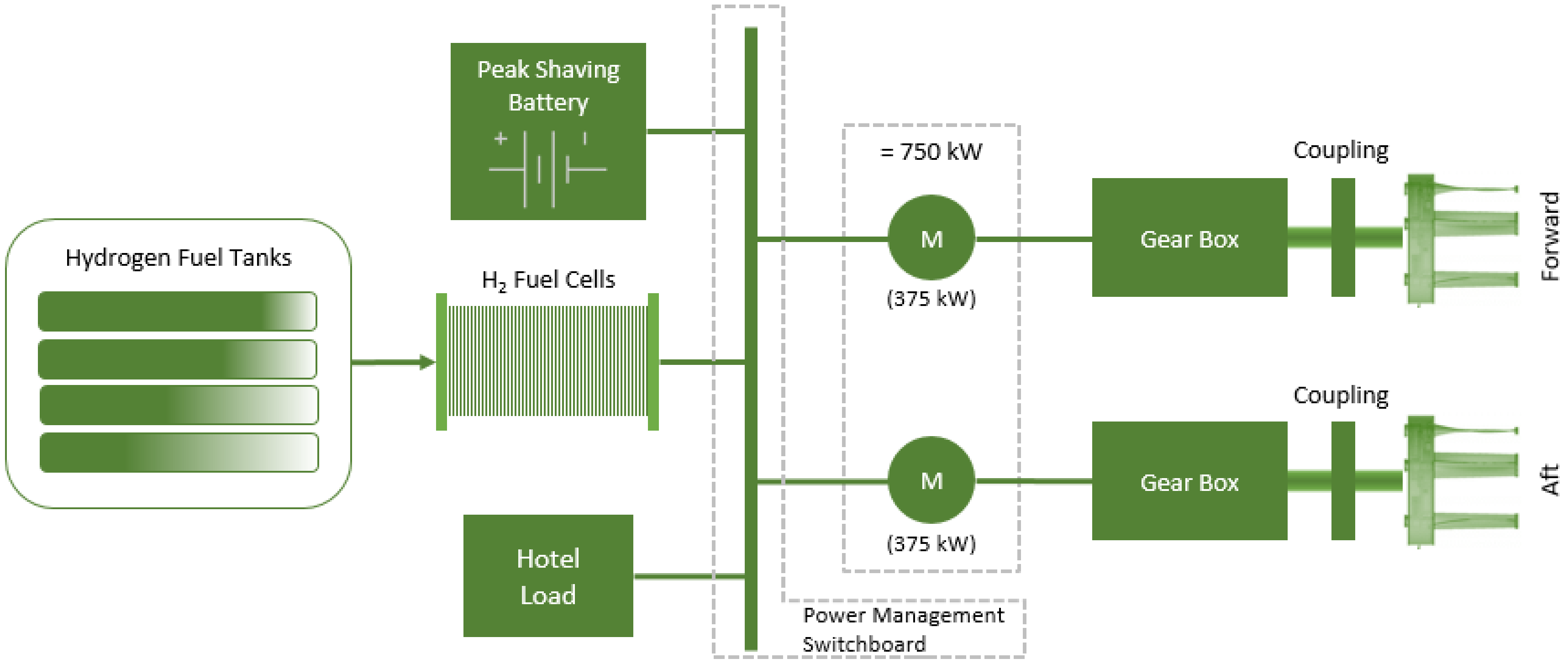


Figure 4-3 Proposed MV Loch Alainn H2 Power Train

4.4.1.2 Emissions Reduction

Using data from the UK government's 2018 greenhouse gas reporting conversion factors[18], it is possible to provide indicative figures on the reduction in greenhouse gasses resulting from operating a hydrogen ship on the Barra – Eriskay ferry route.

These have been calculated by analysing the present hourly consumption of MGO fuel on the MV Loch Alainn and converting the resulting annual quantities of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) to a carbon dioxide equivalent (CO_2e). These emissions can be assumed to be abated as the only by-product of a replacement hydrogen fuel cell vessel is water vapour.

The consumption rate has been provided by CMAL, which is assumed to be applicable during periods of peak power output (e.g. the time the vessel is at sail including hotel load). Therefore, the figures in Table 4-6 are conservative as they do not incorporate MGO fuel consumed when docked. The 675.70 tCO_2e per annum quoted is approximately equivalent to taking 147 cars off the road in a year. Given that the reported number of cars on the island of Eriskay is in the region of 30, this represents nearly a five times reduction of emissions from road transport on the island.

Table 4-6 Barra-Eriskay Annual Emissions Reduction

MGO Consumption [L/hr]	Propulsion/ Hotel Load [hr/day]	MGO Consumption [L/annum]	Emissions Reduction [tonne/annum]	
100	6.67	243,515	666.70 CO_2 0.17 CO_2e CH_4 8.83 CO_2e N_2O	675.70 CO_2e

4.4.1.3 Refuelling Time

Assuming a daily bunkering period and other parameters set in Section 2.2, the daily consumption of hydrogen has been calculated as 599 kg per day. By assuming a gaseous dispensing rate of 120 grams per second, the total dispensing time required is calculated as 83 minutes. Indicative dispenser connection and disconnection times result in a total refuelling time of 91 minutes each day. It is assumed that refuelling can be undertaken before or after the daily timetable each day.

[18] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018

4.4.1.4 Summary of Hydrogen System Characteristics

Below is a summary of the proposed vessel and land-side system characteristics for the Barra – Eriskay ferry route referenced against relevant report sections.

Table 4-7 Barra – Eriskay Hydrogen System Characteristics

Characteristic	Value	Section
Vessel Characteristics		
Ferry route	Barra – Eriskay	Appendix A
Bunkering frequency	Daily	n/a
Daily hydrogen required	599 kg	2.2.1.2
Annual hydrogen required	218,851 kg	
Refuelling time	91 min	4.4.1.3
Fuel system weight	21.83 t	2.3.4
Fuel system volume	137.12 m^3	
Annual emissions reduction	675.70 CO_2e	4.4.1.2
Land-side Characteristics		
Site (island)	Eriskay	Appendix A
WTG reference model	SWT-DD-130	2.2.4.3
Wind farm size (WTGs)	1	
Wind farm size (MW)	4.3 MW	
Hydrogen plant footprint	760 m^2	3.1.3
Wind resource assessment	17,637.6 MWh/annum	3.2.2
Planning assessment	Low / no potential	3.3.2
Accessibility assessment	No access restrictions	3.4.2
Island population	2,995	n/a
Solar resource assessment	1,911.4 MWh/annum	3.5.2

4.4.2 Stornoway – Ullapool (MV Loch Seaforth)

The Stornoway – Ullapool ferry route has proven to be competitive amongst the range of options provided by CMAL for investigation. However, it should be noted that the vessel currently servicing this route, the MV Loch Seaforth, is a relatively new vessel (launched March 2014) and not due for replacement in the near term. Furthermore, the MV Loch Seaforth was designed specifically for the ferry route it operates on, severely limiting the possibility of re-commissioning the vessel on another route to make room for a hydrogen replacement.

It should also be noted that this feasibility study makes no reference to, or has any interface with CMAL's current ferry replacement programme. The existing fleet of CMAL vessels used in this study are for indicative purposes only.

Figure 4-4 MV Loch Seaforth

4.4.2.1 Power Train Replacement

The existing power train of the MV Loch Seaforth is more substantial than that of the MV Loch Alainn. The system is comprised of two 4,000 kW main engines drawing from the MGO fuel tanks feeding twin aft propellers, intermediated by gearboxes and power take off/in motors. Table 4-8 and Figure 4-5 below provide further information.

Electrical power is provided by three 1,600 kW engine-generator sets drawing from the MGO fuel tanks to deliver electricity for the hotel requirements of the ship and bow thrusters. Power management and other ancillary equipment regulate the electrical grid.

The total peak power demand (mechanical and electrical) of the ship is 12,800 kW. As an example, to deliver this same demand using a bank of 100 kW fuel cells operating at 80% efficiency, would require 160 fuel cells. Note, this example differs from the specifications used in Section 2.3 where fuel cells of a higher rated output have been used, thus producing differing weight values.

Table 4-8 MV Loch Seaforth Power Train Specifications

MGO System	
MGO fuel tank	308.9 m^3
Hotel Load	550 kW (3 x 1,600 kW generators)
Propulsion Load	6,500 kW (2 x 4,000 kW main engines)
Total Load	7,050 kW
Equivalent Hydrogen Fuel Cell Power Delivery	
Indicative fuel cell delivery	100 kW (x4 25 kW PAC rack)
No. fuel cell PAC racks required	70
Fuel cell weight	43.55 t
Fuel storage weight (loaded)	165.95 t (x17 520 bar skids)
Total daily energy demand (propulsion + hotel)	7.98 MWh
Indicative fuel cell efficiency	40%
Total daily hydrogen fuel required	19.96 MWh

Figure 4-6 below illustrates a proposed hydrogen power train design for the MV Loch Seaforth. Here, the power delivery of the ship would be entirely electrical, with motors replacing MGO fed engines. The bow thrusters would also draw electrical power from the grid. Fuel cells would convert the store of onboard hydrogen fuel to electricity. As the response times for fuel cells tend to be inadequate for immediate peak demand, a battery will be employed to deliver fast response electricity (peak shaving).

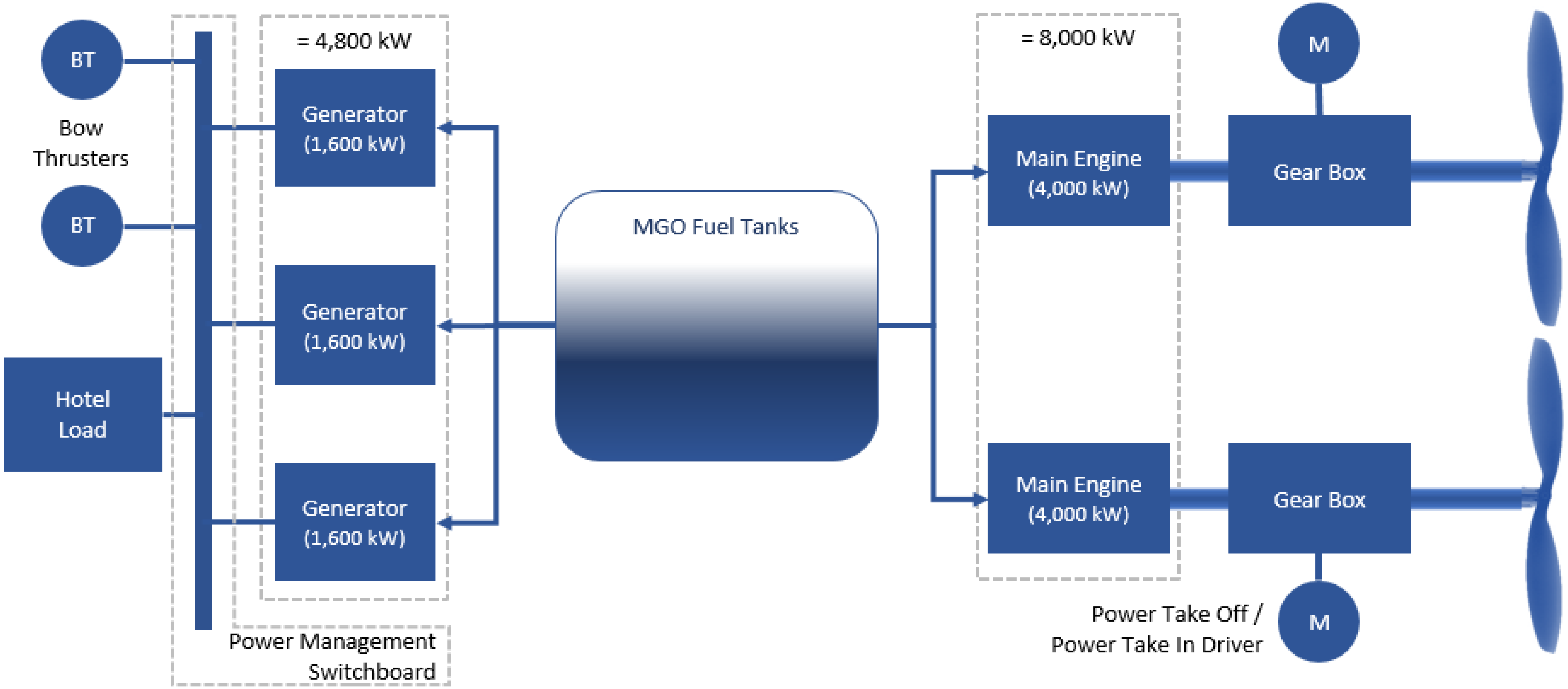


Figure 4-5 MV Loch Seaforth MGO Power Train

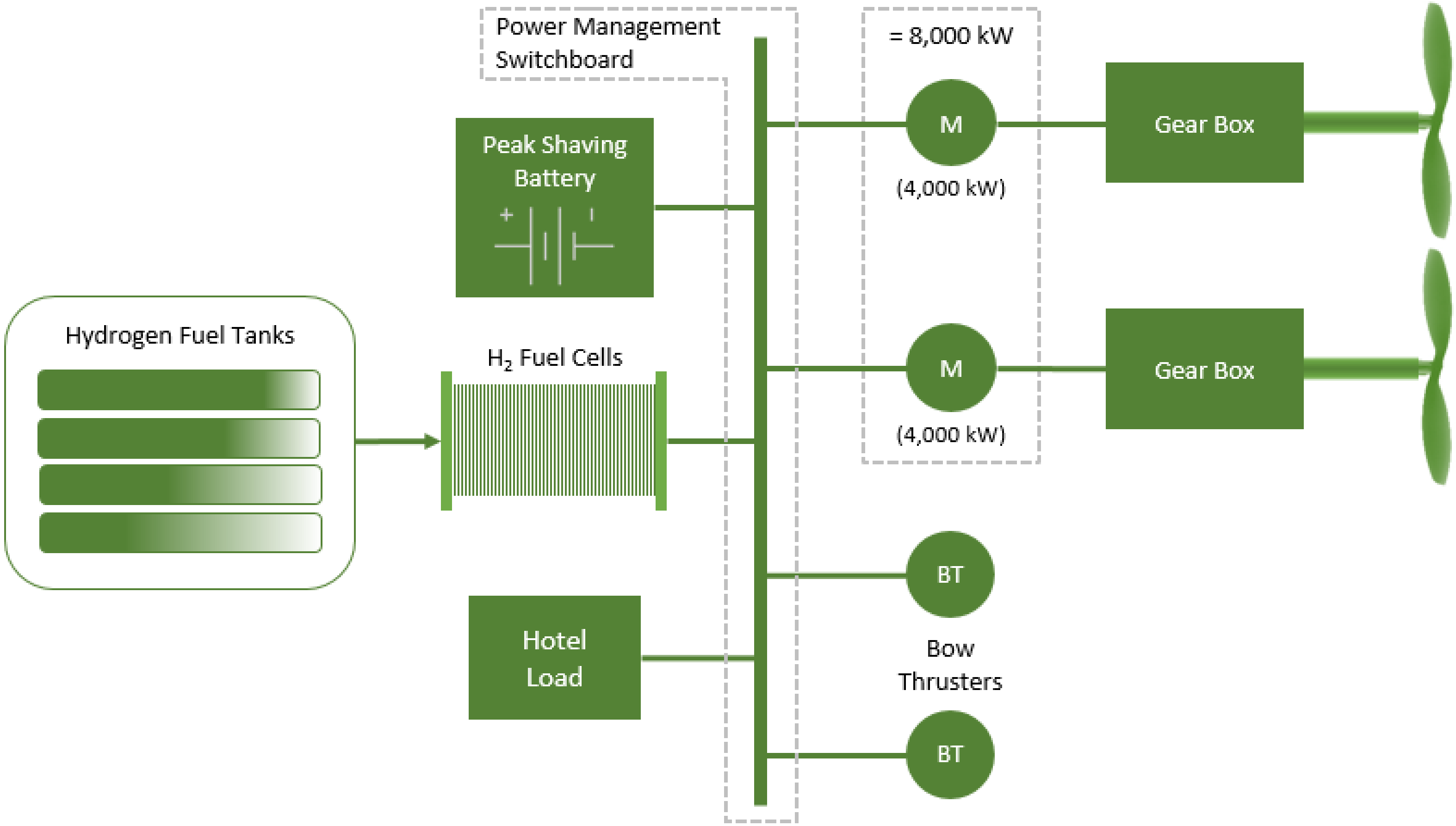


Figure 4-6 Proposed MV Loch Seaforth H2 Power Train

4.4.2.2 Emissions Reduction

Using data from the UK government's 2018 greenhouse gas reporting conversion factors[20], it is possible to provide indicative figures on the reduction in greenhouse gasses resulting from operating a hydrogen ship on the Stornoway – Ullapool ferry route.

These have been calculated by analysing the present hourly consumption of MGO fuel on the MV Loch Seaforth and converting the resulting annual quantities of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) to a carbon dioxide equivalent (CO_2e). These emissions can be assumed to be abated as the only by-product of a replacement hydrogen fuel cell vessel is water vapour.

The consumption rate has been provided by CMAL, which is assumed to be applicable during periods of peak power output (e.g. the time the vessel is at sail including hotel load). Therefore, the figures in Table 4-9 are conservative as they do not incorporate MGO fuel consumed when docked. The 21,815 tCO_2e per annum quoted is approximately equivalent to taking 4,742 cars off the road in a year.

Table 4-9 Stornoway-Ullapool Annual Emissions Reduction

MGO Consumption [L/hr]	Propulsion/ Hotel Load [hr/day]	MGO Consumption [L/annum]	Emissions Reduction [tonne/annum]	
1,435	15.00	7,862,006	21,524.76 CO_2 5.50 CO_2e CH_4 285.15 CO_2e N_2O	21,815.42 CO_2e

4.4.2.3 Refuelling Time

Assuming a daily bunkering period and other parameters set in Section 2.2, the daily consumption of hydrogen has been calculated as 10,063 kg per day. By assuming a gaseous dispensing rate of 120 grams per second, the total dispensing time required is calculated as 1,398 minutes. Indicative dispenser connection and disconnection times result in a total refuelling time of 1,406 minutes (~23.5 hours).

As the time required would be unacceptably high using a single dispenser, alternative refuelling methods will be required. Simultaneous refuelling of manifolded tanks from multiple dispensers could provide a solution (e.g. four dispensers refuelling simultaneously could refuel the vessel in approximately 6 hours overnight). Swapping out spent fuel storage tanks with filled tanks at the dock is another alternative. It is assumed that refuelling can be undertaken before or after the daily timetable.

4.4.2.4 Summary of Hydrogen System Characteristics

Below is a summary of the proposed vessel and land-side system characteristics for the Stornoway – Ullapool ferry route referenced against relevant report sections.

Table 4-10 Stornoway - Ullapool Hydrogen System Characteristics

Characteristic	Value	Section
Vessel Characteristics		
Ferry route	Stornoway - Ullapool	Appendix A
Bunkering frequency	Daily	n/a
Daily hydrogen required	10,063 kg	2.2.1.2
Annual hydrogen required	3,675,646 kg	
Refuelling time	1,406 min (or 4 x 352 min)	4.4.2.3
Fuel system weight	209.50 t	2.3.4
Fuel system volume	1,027.79 m^3	
Annual emissions reduction	21,815.42 CO_2e	4.4.1.2
Land-side Characteristics		
Site (island)	Lewis & Harris	Appendix A
WTG reference model	SWT-DD-130	2.2.4.3
Wind farm size (WTGs)	15	
Wind farm size (MW)	64.5 MW	
Hydrogen plant footprint	7,250 m^2	3.1.3
Wind resource assessment	15,993.12 MWh/annum	3.2.2
Planning assessment	Medium potential	3.3.2
Accessibility assessment	No access restrictions	3.4.2
Island population	21,000	n/a
Solar resource assessment	1,797.9 MWh/annum	3.5.2

4.4.2.5 Ullapool Freight Ferry

It was not within the scope of this report to analyse freight-only vessels. Though CMAL do not own any freight carriers, they do however charter two ships to operate on the Northern Isles routes. There could be merit in investigating a freight-only route as part of a future study as the following characteristics may prove advantageous:

- Lower construction or conversion costs due to the absence of passenger facilities other than that required for lorry drivers.
- Lower operational costs due to the absence of normal passenger facilities.
- Lower operational costs owing to fewer overall journeys and slower cruising speeds.
- Lower regulatory hurdles due to the absence of normal passenger traffic.

A freight vessel would carry greater cargo and therefore would require a greater (deadweight) capability. This in turn would require a greater installed power requirement and therefore a greater number of fuel cells. This is the “tipping point” between the weight of installed power capacity against the deadweight (ability to carry the weight of cargo). For example; in order to power the ship to carry more cargo it must increase in size. This increase in ship size consequently requires more power capability to propel it – an escalating sequence of design requirements.

Fuel cell technology remains at a very early readiness level for marine applications. Uncertainty exists as to whether large numbers of fuel cells can operate in group formations and be controlled in a fashion that would provide a suitable solution to address the large powering requirements of a vessel such as a freight carrier.

In order to consider such a vessel, a detailed technical study by a specialised naval architecture and advanced ship design house would need to be conducted.

The project Consortium would be willing to undertake an assessment of a freight-only option upon request. However, it is also important to note that the technical challenges of designing a freight vessel would be significant.

5 Financial Modelling

Financial modelling has been undertaken for the study. The Barra to Eriskay and the Stornoway to Ullapool routes are the two most technically or practically viable for further investigation based on the assessment criteria used for conversion to hydrogen and consequently our financial modelling has been focussed on these two routes.

The purpose of the financial modelling is to forecast future cashflows to determine the indicative price that H2 could be sold to the ferry operator. The vessels on the two routes are currently fuelled by MGO. The indicative hydrogen price has been compared against the price paid for MGO per kWh and some suggestions are made at Section 6.1 as to how the 'price gap' identified could be narrowed.

The modelled assumptions are high level given the early stage of the feasibility study. The next stage would involve a more detailed feasibility study (development stage) which would seek to advance the project design and produce more refined assumptions.

For both routes two scenarios have been modelled:

1. Base Case: Modelling the assumptions provided by the Key Partners; and
2. RTFO Case: Modelling the assumptions provided by the Key Partners and assuming the Project is eligible for Renewable Transport Fuel Obligation ("RTFO").

RTFO is a support regime incentivising the production of renewable fuels for use in the transport industry. Marine transport is not currently eligible to participate, even though the hydrogen production method would qualify it as a fuel of 'non-biological origin'. Our financial modelling has, nevertheless, included and quantified the impact of introducing the RTFO on the price hydrogen could be sold to the ferry operator in the hope that it can inform future debate.

Table 5-1 details the indicative price that hydrogen could viably be sold to the ferry operator. All prices have a base date of April 2018. It should be noted that the financial modelling assessed the cost per unit of energy supplied to each vessel (bunkered fuel) rather than the end demand.

Table 5-1 Comparison of Fuel Cost to Ferry Operator

Route	Base Case	RTFO Case	MGO
Barra to Eriskay (£ / kWh)	£0.17	£0.12	£0.05
Barra to Eriskay (£ / kg)	£5.60	£4.00	n/a
Stornoway to Ullapool (£ / kWh)	£0.11	£0.09	£0.05
Stornoway to Ullapool (£ / kg)	£3.70	£2.90	n/a

The financial modelling confirms that the cost of fuelling the vessels with hydrogen is more expensive compared with MGO. It also suggests that the introduction of RTFO income could make a significant contribution to bridging the gap in cost between MGO and H2 and this would be an important area of study for the development stage of the project.

Another way to bridge the ‘price gap’ would be to reduce the capital costs of the project and the financial modelling has considered at a high level the reduction that would be required to achieve this. The results have been summarised in Table 5-2.

Table 5-2 Capital Cost Reduction Required to Achieve Price Parity

Route	Base Case	RTFO Case
Barra to Eriskay	£9.18m	£8.55m
Stornoway to Ullapool	£82.43m	£67.03m

The results in Table 5-2 indicate that a significant capital cost reduction would be required in both the wind farm company and electrolyser company to enable the cost of hydrogen to be brought down to a level comparable to the current cost of MGO.

Section 6.1 outlines other opportunities to bridge the gap. In addition, it should be noted that hydrogen produced from a local wind farm would provide long term price certainty for CMAL, unlike the substantial annual variations in the price of MGO. This price certainty has an economic value for CMAL which can be quantified in more detail in the development stage of the project.

Finally, liquified natural gas (LNG) is now being introduced as a cleaner Marine Transport fuel, including by CMAL, and that its use is likely to grow in the near future. LNG is more expensive than MGO and its increasing use, including in hybrid formats, will make it a better comparator for hydrogen in the long term than the current price of MGO. Unfortunately, there is no available data on the price of marine LNG on the west coast of Scotland, so we were unable to include this in our model. It is anticipated that the use of LNG will close the ‘price gap’ but it cannot be said by how much without this data. This will be another area of study for the development stage.

In summary, the high-level financial modelling has shown that:

- Hydrogen is more expensive than MGO per kWh of fuel supplied.
- The reclassification of ‘Marine Transport’ as an eligible fuel use within the RTFO support regime has the potential to significantly bring down the cost of hydrogen.

- Increasing use of Marine LNG rather than MGO is also expected to close the 'price gap' with hydrogen but the data is not currently available to allow this to be modelled.
- The Stornoway to Ullapool route can produce hydrogen at a lower cost than the Barra to Eriskay route but the Stornoway to Ullapool route would require a larger reduction in capital cost in cash terms to achieve price parity.
- A significant capital cost reduction is required on both routes to enable price parity to be reached.
- There is value to the ferry operator in having a fixed long-term fuel cost and this is easier to achieve using hydrogen rather than using MGO.
- There are several other options to close the price gap. Time should be spent at the development stage refining the design of the project and exploring the areas identified in Section 6.1, which have the potential to make hydrogen a more viable alternative.

5.1 Methodology and Optimisation

5.1.1 Methodology

The key objective of the financial modelling was to determine the following for both routes:

a. The price at which hydrogen could be sold to the ferry operator whilst meeting optimisation criteria – the Base Case;
b. The price at which hydrogen could viably be sold to the ferry operator as above but assuming that the electrolyser company is eligible for Renewable Transport Fuel Certificates (RTFC's) – the RTFO Case; and
c. The gap between the price for H2 in the Base Case and the RTFO Case above and the price currently paid by the ferry operator for MGO.

To achieve the objectives, the project partners provided financial modelling assumptions for both routes (summarised in Appendix G to Appendix J). Where there was a lack of information available, a perceived prudent position has been modelled. It has been assumed for both routes that the wind farm company and the electrolyser company will be separately owned to enable income and cost profiles to be separately identified. Two financial models were therefore prepared for each route. Alternative ownership structures can be considered at the development stage.

The wind farm financial model was populated with the assumptions provided by the project partners. Once populated the financial model was optimised. The aim of optimisation is to determine the lowest possible price that electricity can be sold whilst meeting the optimisation criteria. This is an iterative process which is documented at Section 5.1.2. The sale price is ultimately a balancing figure to meet the established optimisation criteria.

The optimised price per MWh for electricity sold from the wind farm feeds into the electrolyser financial model as a cost assumption which is then combined with the electrolyser specific assumptions detailed at Appendix G.

The aim of the optimisation process for the electrolyser company is consistent with the wind farm company in that we are seeking to identify the sale price for a commodity, in this case hydrogen, that enables all optimisation criteria to be met.

In addition, a scenario was modelled assessing the impact that RTFO eligibility would have on the hydrogen sales price. In this scenario, all assumptions are the same as the Base Case with the only changes being additional assumptions relating to the RTFO (see Appendix G). The same optimisation process was followed.

It would be useful to be able to compare the Base Case and RTFO Case prices with the price of LNG as well as the price of MGO. However, the current lack of suppliers of Marine LNG on the west coast of Scotland meant that the price of LNG could not be calculated. This will be an important area of analysis for the development stage of the $SWIFTH_2$ project

5.1.2 Optimisation

The aim of wind farm model optimisation is to sell electricity at the lowest price possible subject to the constraint that the wind farm company remains a going concern. More specifically, the wind farm company is deemed to be a going concern where the following criteria are met:

- All operational costs and liabilities are met as they fall due.
- No overdraft position in any period.
- Senior Debt and Subordinated Debt are repaid on time.
- Senior Debt covenants are met i.e. Gearing, Debt Service Cover Ratio (DSCR) and Loan Life Cover Ratio (LLCR).
- Equity is repaid at the end of the project.

The electricity sales price assumption in the model is flexed until an optimised position is achieved where all optimisation criteria are met and any further reduction in the sales price would lead to one of the optimisation criteria not being met.

The aim of the electrolyser model optimisation is to sell hydrogen at the lowest price possible subject to the constraint that the electrolyser company remains a going concern. The going concern criteria is as outlined above.

The hydrogen sales price assumption in the model is flexed until an optimised position is achieved where all optimisation criteria are met and any further reduction in the sales price would lead to one of the optimisation criteria not being met.

The models are not being solved to achieve any profitability targets, this can be considered at the development stage.

Optimisation for the RTFO scenario follows the same process as the Base case electrolyser model. The only difference is that the RTFO scenario has an additional revenue stream which means the hydrogen price can be reduced further than the Base Case scenario and not breach the optimisation criteria.

5.1.3 Fuel Cost Price Parity Optimisation

One way of illustrating, at a high-level, the price gap between the indicative hydrogen price and current MGO is to estimate the amount by which the initial capital cost of the wind farm and electrolyser would have to be reduced to achieve fuel cost parity.

The electrolyser company's biggest overhead is electricity which is purchased from the wind farm company. The price it pays for electricity impacts the price it can charge for hydrogen. Reducing electrolyser capital costs without a reduction in its electricity cost will mean there is limited ability to achieve fuel cost price parity. Therefore, a capital cost reduction is also required in the wind farm to reduce the cost of electricity to the electrolyser.

The process for identifying the total capital cost reduction required is outlined below:

1. The capital cost is firstly reduced in the wind farm financial model. This enables the sale price of electricity to the electrolyser company to be reduced.
2. The wind farm financial model is optimised as outlined at Section 5.1.2. The aim is to reduce the sale price of electricity as far as possible, by reducing capital costs, whilst still ensuring the wind farm remains a going concern.
3. The revised electricity price flows through to the electrolyser model as a cost. The electrolyser financial model is optimised and the price gap between MGO and hydrogen is assessed.
4. After optimisation, if hydrogen is more expensive than MGO then the electrolyser capital costs are reduced until MGO and hydrogen achieve fuel cost parity.

5.2 Key Assumptions

5.2.1 General

5.2.1.1 Structure

The wind farm company and electrolyser company have been separately modelled and assumed to operate as two separate companies with the wind farm being community owned and the electrolyser being commercially owned. The main benefit of this approach is that we can separately identify the income and cost streams for both installations. This requires two separate models for each route. There are a variety of possibilities for ownership and company structure which can be considered at the development stage.

5.2.1.2 Vessel

No attempt has been made to model the financial viability of constructing the hydrogen powered vessel. At this stage the financial modelling is limited to modelling the wind farm company and the electrolyser company to establish the price at which hydrogen can be sold to the ferry operator.

5.2.2 Wind farm

5.2.2.1 Wind Generation

The annual energy generation figures (MWh) for both potential wind farms have been produced as part of this study. The generation figures are based on P50. We believe that a P50 equity assumption is the most appropriate to be used at this stage of the feasibility study to determine the minimum commercial basis of the project.

This feasibility study determined the size of the wind farm required on each route to meet hydrogen demand from the ferry operator. The electricity generated on both routes exceeds that which is required by the ferry operator due to the inability to exactly match the installed capacity to demand when working with turbines that are required to be purchased in whole units. Based on the hydrogen demand values circa. 74% of the electricity generated by the Barra site and circa. 92% of the electricity generated by the Stornoway site would be utilised by the electrolyser.

With insufficient available capacity on the local grid to sell any surplus electricity, alternative options would need to be explored. These could include but are not limited to:

- Use surplus electricity to generate hydrogen for sale to third parties.
- Use surplus electricity to generate hydrogen to top up SWIFTH$_2$ buffer and/or back-up systems.
- Build a battery on the site of the wind farm to feed the grid at peak times.

For the financial modelling, it has been assumed that there will be one turbine installed on the Barra wind farm site. This creates a risk to supply if the turbine goes offline. However, there are multiple forms of system redundancy available for consideration. These include:

Employing as a minimum two WTGs to ensure downtime in one turbine can be compensated for. Where only a single 4.3 MW WTG would be required in the first instance, consideration should be given to using smaller more numerous WTGs to deliver the same power requirement.

- The proposed wind farm could be supplemented with a co-located solar farm to ensure an additional generating capability.
- Sizing of the hydrogen storage at port to incorporate a suitable period of outage such that hydrogen dispensing can continue for a defined period without new production.

- Power import to the electrolyser from local grid and/or other generating capacity such as diesel gensets.

5.2.2.2 Revenue

The price charged for electricity sold to the electrolyser company is derived through the optimisation process. The price has a base date of April 2018. The price is indexed annually at 2.5%.

5.2.2.3 Operating Costs

All costs have a base date for inflation purposes of April 2018 and are inflated annually at 2.5%.

5.2.2.4 Rates

The estimated business rates have been calculated based on the Scottish Assessors Association (SAA) '2017 Practice Notes' for on-shore wind farms. As the wind farm is proposed to be 100% owned by a community organisation we have calculated the business rates on the assumption that the site is eligible for 'Renewable Energy Generation relief'. As the rateable value of the Barra site is Projected to fall below £145,000, 100% relief is available. The Stornoway sites projected rateable value is between £860,001 and £4m thus is eligible for 10% relief.

The actual cost will depend on the business rate regime and relief available at the time the project is operational.

5.2.2.5 Capital Expenditure

The Base case cost per MW for the Barra to Eriskay route, based on the high-level assumptions is £1.13m/MW installed and on the Stornoway to Ullapool route is £1.05m/MW installed.

The cost per MW for both sites is in the range typically observed on wind farm projects. It appears reasonable that economies of scale would make Stornoway a cheaper project per MW installed.

In the absence of construction cost profiles, construction costs have been modelled to be evenly incurred over the construction phase. This can be reconsidered at the development stage.

5.2.2.6 Funding

With the wind farm modelled to be community owned it has been assumed that the wind farm will be funded by senior debt up to a maximum gearing level of 80%, with the balance being funded by a social investor in the form of subordinated debt. This has been based on the funding structure of the Beinn Ghrideag Community Wind Farm on the Isle of Lewis. Key senior and subordinated debt assumptions have been based on Beinn Ghrideag.

Whilst prudent assumptions have been made in relation to funding, the actual amount of funding available and the terms of the funding will depend on the final design of the project thus are indicative and should be reconsidered at the development stage.

5.2.3 Electrolyser

5.2.3.1 Revenue

Revenue for the electrolyser company is a function of the demand for hydrogen from the ferry operator. This demand figure also determines the required installed capacity of the wind farm. The daily hydrogen demand (kg) is calculated based on the power requirement of the vessel (kWh) which is converted to a daily hydrogen requirement. The daily power requirement for a new hydrogen vessel has been calculated based on the power requirement for the existing MGO fuelled vessel, provided by CMAL, with the addition of a power requirement for auxiliary functions relating to the hydrogen as well as a 20% daily reserve.

The modelling assumption for the feasibility study is that all hydrogen produced by the electrolyser company to meet the daily demand (which includes a daily 20% reserve) is sold to the ferry operator and that all the hydrogen purchased by the ferry operator is used. This represents a prudent position as it is possible that once enough reserves are built up the ferry operator is unlikely to purchase a daily hydrogen amount that includes a reserving element. If the ferry operator’s actual daily demand is less than that which is modelled, then the electrolyser company would have excess hydrogen which it could sell to third parties. However, it may be that the actual demand is such that there may be a need to reappraise the installed capacity of the wind farm required to meet demand. The daily demand figure should be reconsidered at the development stage to more accurately reflect the reserving requirements of the shipping company.

The price per kg of hydrogen sold to the ferry operator is derived through the optimisation process. The price per kg has a base date of April 2018. The price is indexed annually at 2.5%.

5.2.3.2 Operating Costs

The two main operating costs for the electrolyser are water and electricity.

The electricity cost was determined by hydrogen demand. Based on hydrogen demand, the amount of electricity required to meet the demand was calculated. The electricity cost is the required electricity to meet hydrogen demand in MWh multiplied by the price per MWh charged by the wind farm company.

An estimate of water consumption was provided by ITM Power and an estimate of water price was provided by Wood.

Most of the other operating costs modelled have been provided by Wood and ITM Power. Due to the uniqueness of this study, accurate costings on insurance, rent and rates were not available. A cost has been modelled for each of these areas for prudence. These costs should be reconsidered at the development stage once more detailed information is available.

All costs are assumed to have a base date of April 2018 and are indexed annually at 2.5%.

5.2.3.3 Capital Expenditure

Estimates on capital expenditure have been provided by Wood and ITM Power.

In the absence of construction cost profiles, construction costs have been modelled to be evenly incurred over the construction phase. This can be reconsidered once more detailed information is available at the development stage.

5.2.3.4 3.3.4 Funding

As the Electrolyser is assumed to be commercially owned it has been assumed that the electrolyser company will be funded up to a maximum of 80% by senior debt with the balance being funded by off balance sheet capital.

As this is a developing technology there is not a data set of funding terms from similar projects. The modelled financing costs for the electrolyser are assumed to be higher than the wind farm to reflect the additional risk that funders may perceive.

The debt structure and assumptions are indicative and should be revised at The development stage.

5.2.4 Renewable Transport Fuel Obligation (RTFO) Scenario

5.2.4.1 Overview of Assumptions

The Marine sector is not currently eligible to receive RTFO but for this scenario it has been assumed that the Project qualifies and is categorised as a Renewable Fuel of Non-Biological Origin (RFNBO). The consequence of this assumption is that the Project would be eligible to receive RTFC's at a rate of 9.16 RTFC's per kg of hydrogen sold, as it produces hydrogen from a renewable source.

All fuel suppliers earn a number of RTFC's (the amount depends on the fuel) for each litre of green fuel supplied. Each supplier has a target depending on the fuel. All fuel certificates earned in excess of the target can be traded, typically to suppliers who are unable to meet their own obligation.

The electrolyser company would generate revenue by selling any certificates in excess of those that it must keep to demonstrate compliance with the RNFBO target in an obligation period. The 'RTFO guidance', which is issued by the government annually, sets out the obligation. The first 450,000 litres of RNFBO fuel sold is not subject to the obligation which means that the company can sell all certificates earned on the first 450,000 litres of fuel sold. Anything sold above that is subject to the obligation.

The buy-out price, the amount that a supplier must pay to purchase a certificate if it fails to meet its obligation, is set at 80p per RTFC for Development fuels. With this project hydrogen is derived from a renewable source thus it would be categorised as a Development Fuel. These certificates can be traded on the open market; thus, it is not uncommon for the price that they are traded for to be lower than the buy-out price. To maintain a prudent position, it has been assumed that the price achieved is 40p per RTFC and that the price of the certificates will not be subject to inflation.

The obligation targets have been set out to 31 December 2032. It has been assumed that there will be RTFO post this date as there is no certainty that there will be an RTFO after this date and as such this represents a prudent position.

5.3 Results

5.3.1 Pricing and Output

Table 5-3and Table 5-4 detail the energy requirement for both modelled routes, documents the quantity of fuel required by the ferry operator and provides the cost of hydrogen to the ferry operator. The sales price of electricity from the wind farm company to the electrolyser company is also stated. Where relevant, equivalent information is provided for MGO to facilitate a comparison. Note that the values are based on high-level assumptions that will be refined at the development stage.

The 'Energy used per day' values represent the propulsion and hotel (communications, air conditioning, electricity) loads. The hydrogen fuelled vessel makes auxiliary power demands of the fuel cells which means that the energy requirement per day is higher than the MGO powered vessel.

The sales price per unit represents the price at which hydrogen is sold to the ferry operator. The methodology underpinning the calculation of this figure is detailed in Section 5.1.

This study assesses the cost per unit of energy supplied to each vessel (bunkered fuel) rather than the end demand. This enables a comparison between the cost of energy to supply the vessel, which has been indicatively priced at £0.50 per litre with a base date of April 2018 for MGO, for approximately the same ship energy demand profile.

Table 5-3 Barra– Loch Alainn Vessel Financial Output Summary

	MGO	H2 - Base Case	H2 - RTFO
Price Paid for Electricity from Wind farm (Base Date 2018). Converted from MWh to kg based on Lower Heating Value of 119.93 MJ / kg	-	£42.00 / MWh = £2.52 / kg H2	£42.00 / MWh= £2.52 / kg H2
Fuel Used per day	2,400 L	599 kg	599 kg
Power Energy Supply (kWh / day)	25,393	19,955	19,955
Fuel usage per supply kWh (unit / kWh)	0.10 L / kWh	0.03 kg / kWh	0.03 kg / kWh
Cost to Ferry Operator per Unit of Fuel Supplied	£0.50 / L	£5.60 / kg	£4.00 / kg
Cost to Ferry Operator per kWh fuel supplied (Base Date 2018)	£0.05	£0.17	£0.12

Table 5-4 Stornoway– Loch Seaforth Vessel Financial Output Summary

Parameter	MGO	H2 - Base Case	H2 - RTFO
Price Paid for Electricity from Wind farm (Base Date 2018) Converted from MWh to Kg based on Lower Heating Value of 119.93 MJ / kg	-	£36.70 / MWh = £2.20 / kg H2	£36.70 / MWh = £2.20 / kg H2

Parameter	MGO	H2 - Base Case	H2 - RTFO
Fuel Used (kg / day)	34,440 L	10,063 kg	10,063 kg
Power Energy Supply (kWh / day)	364,395	335,238	335,238
Fuel usage per supply kWh (unit/kWh)	0.095 L / kWh	0.03 kg / kWh	0.03 kg / kWh
Cost to Ferry Operator per Unit of Fuel	£0.50 / L	£3.70 / kg	£2.90 / kg
Cost to Ferry Operator per kWh fuel supplied (Base Date £ 2018)	£0.05	£0.11	£0.09

5.3.2 Capital Cost Reduction

Table 5-5 provides a summary of the indicative reduction in capital cost that would be required for hydrogen to achieve price parity with MGO as described in Section 5.1.2 above. The table shows the reduction in capital cost necessary for both the wind farm and electrolyser on both routes and under both the Base and RTFO cases.

Table 5-5 Reduction in Capital Cost to Achieve Price Parity

Parameter	Base Case	RTFO Case
Barra		
Wind Farm Capital Cost Reduction	£4.59m	£4.59m
Electrolyser Capital Cost Reduction	£4.59m	£3.96m
Total Barra Capital Cost Reduction	**£9.18m**	**£8.55m**
Stornoway		
Wind Farm Capital Cost Reduction	£48.83m	£48.83m
Electrolyser Capital Cost Reduction	£33.60m	£18.20m
Total Stornoway Capital Cost Reduction	**£82.43m**	**£67.03m**

The analysis indicates that on both routes there would need to be a significant amount of capital cost reduction to achieve price parity. RTFO brings both routes closer to price parity.

6 Conclusion

Section 4.4.1 and Section 4.4.2 have outlined the particular viability of hydrogen vessels on two ferry routes. The advantages of a hydrogen vessel in general also merits consideration.

This report has provided an overview of the quantities of hydrogen involved in operating equivalent ferry services with the same timetables as exists at present. For the MV Loch Alainn (Barra – Eriskay) and the MV Loch Seaforth (on the Stornoway – Ullapool route) this amounts to 218,851 kg and 3,675,646 kg of hydrogen per annum respectively. For either case, having such a large and long-term single user of hydrogen would provide significant impetus to develop the required production, storage and dispensing infrastructure.

An important economic advantage of hydrogen as a marine fuel, as opposed to conventional marine oil, is that it can be produced in Scotland from green, renewable resources. Indeed, the same remote islands which have the greatest dependence on marine transport for lifeline ferry services have some of the best renewable resources in Europe, especially in wind.

The emissions savings from either shortlisted option are also significant. Using the conversion measure used in the aforementioned sections, these would amount to 676 tCO_2e on the Barra – Eriskay route and 21,815 tCO2e on the Stornoway – Ullapool route per annum respectively. The combined equivalent of taking 4,889 petrol cars off the road in the same period. This outcome would contribute to both cleaner air locally, and to reductions in national emissions. The abatement of noise pollution, a noticeable advantage to employing fuel cells over internal combustion engines, would also be a significant benefit to local communities along affected routes.

A further advantage of local renewable hydrogen is shelter from fluctuations in global oil prices which would no longer be a major economic facet required to be forecast and mitigated against. The key variable in the proposed hydrogen production chain would be the local wind (and potentially solar) resource, which can be adequately modelled for and anticipated. This presents an huge opportunity to remove financial shocks to operators, customers and the Scottish Government who all have exposure to oil price volatility in this area.

The proposed development opens up the potential of the hydrogen fuel for future West Coast ferry services being produced within - and by - the same communities which depend on said services. If the potential can be realised, the green, carbon-saving gain from hydrogen marine transport can be matched by an equally important economic gain for those local communities and for the Scottish economy as a whole.

6.1 Closing the Price Gap

Based on the current high-level assumptions, hydrogen is a more expensive fuel than MGO for the ferry operator. This is not an unexpected result, consequently it is important to look at this gap as a 'worse case' scenario with there being several areas for exploration at the development stage that could play a part in bridging that gap. These are considered at a high level below:

RTFO

Including 'Marine Transport' as a fuel eligible for RTFO could go a long way to bridging the gap, which has been indicatively demonstrated in this Report. Changing 'Marine Transport's' status within the RTFO will require the consent of the UK Government but it represents a significant opportunity for the Government to facilitate and expedite the transition from dirty MGO to renewable and sustainable hydrogen.

Change in the Fuel Mix

New cleaner fuel such as LNG is being introduced onto the CMAL routes. LNG's introduction will also close the price gap with hydrogen as LNG will be priced higher than MGO. The information required to do a more detailed assessment of the likely impact on the gap of a change in fuel mix is not currently available. A more detailed analysis and further financial modelling will be undertaken at the development stage.

This report details the cost of marine hydrogen fuel from renewable sources as compared to the current cost of MGO. As anticipated, there is currently a significant price gap. However, the analysis also shows that the gap can be closed substantially if hydrogen from renewable sources is included as an RTFO-eligible fuel. The price gap would be closed further by comparing the cost of hydrogen with LNG or with an LNG/MGO fuel mix, but the data is not available at present to quantify this more precisely.

This is an important area of study for the development stage. It is also clear that there are other routes to closing the current price gap such as reducing the capital costs of the wind farm and electrolyser and by the adoption of new technologies to make the vessel more fuel-efficient which would also be an important area of study for the development stage.

Capital Cost

The impact of reducing the initial capital cost to be funded by the project has been modelled within this report. This requires further analysis in the development stage to determine what form of capital cost reduction can be achieved and how this could work with other solutions.

Technology

The adoption of the most advanced available technology on the vessels could reduce the hydrogen required. For example, a Flettner rotor has been modelled on the Stornoway route and the initial estimates are that it could produce fuel savings of over 10%.

Price Certainty

Purchasing hydrogen from the electrolyser company offers the ferry operator the opportunity to have more certainty over its fuels costs by entering into a fixed price Power Purchase Agreement (PPA). Whilst this does not necessarily close the gap it has significant benefits in terms of budgeting and planning. MGO pricing is subject to movements in the markets which can be volatile. For example, based on the 'Global 20 ports Average' the price of MGO increased 46% between October 2017 and October 2018. This is a high-level example as it only considers one year in isolation but demonstrates the volatility that can have a major bearing on the profitability of the ferry operator.

Revenue from Excess Supply

The electrolyser company will utilise circa. 74% of the electricity generated by the wind farm on the Barra route and circa. 92% on the Stornoway route. We have outlined in Section 3 some uses for this excess supply which could bring alternative revenue streams to the project. This should be considered in more detail at the development stage where final designs will identify a more exact amount of excess capacity.

Electrolyser Efficiency

The financial modelling has been predicated on an electrolyser efficiency level of 55%. It has been suggested by ITM Power than this is a prudent position as the possibility does exist to specify a larger electrolyser that can then run at a more efficient point giving lower operating expenditure cost and improving the overall economics of the hydrogen production. This is an area that can be revisited at the development stage as with finalised sites and routes there is the ability to start sizing components to more accurately fit the project requirements.

6.2 Options for Next Phase

Following from the conclusions of this report, it is recommended that the key stakeholders engaged with the SWIFTH$_2$ feasibility study reflect on the next phase of the project. Figure 6-1 below illustrates the processes undertaken thus far, and sets out three branches of options for future exploration of the opportunity:

- **Option 1 – Single Candidate Selection:** Section 4.4 has shortlisted two top scoring ferry routes as per guidance agreed by the Consortium. Rather than proceeding with detailed feasibility of one or both routes (option 3), it may be desirable to first initiate a secondary selection process to arrive at a single candidate route, guided by objective assessment. This may be beneficial if time and/or resources will be too constrained to undertake detailed feasibility on both shortlisted routes and stakeholders remain uncertain as to which to take forward to the detailed feasibility phase.
- **Option 2 – Detailed Feasibility:** Should relevant stakeholders agree to proceed to the detailed feasibility phase, this can be undertaken on one or both of the two shortlisted ferry routes. Detailed feasibility should involve aspects pertaining to both specific site selection of a wind farm and port infrastructure, and detailed vessel design. Section 7 provides advisory recommendations on areas that should be addressed at the detailed feasibility phase.
- **Option 3 – Re-analysis:** The SWIFTH$_2$ feasibility study has been undertaken in a modular fashion, such that new or updated assessment criteria can be integrated to provide improved filtering to the selection process. This holds true for any updates or additions to the ferry routes investigated. As such, any stakeholder decision to re-analyse the ferry routes can be met with relative ease. This may be beneficial should technical or commercial information not available to the Consortium at the time of undertaking this study be forthcoming post-publication. Re-analysis may therefore result in a new shortlist of ferry routes on which to consider further options.

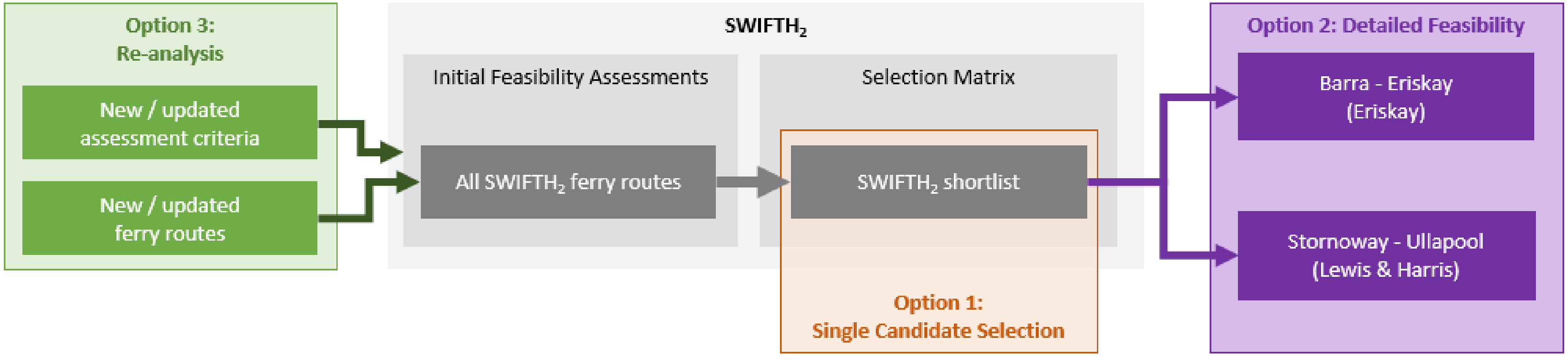


Figure 6-1 Next Phase Options

7 Recommended Future Areas of Investigation

This report examines aspects identified by the Consortium and Wood as crucial to the successful deployment of a renewable-hydrogen powered vessel in the region. Given the large number of developmental aspects to consider, both complementary and competing, it has been necessary to present the variety of options which could be pursued to key stakeholders for evaluation, guided by the findings of this report.

Going forward, commercial and technical objectives will be required to be refined to allow for site-specific feasibility work to commence. The following areas are recommended to be investigated in detail as part of the next phase of the SWIFTH_2 project.

7.1 Vessel Architecture

It has been agreed during the course of this Project that the Consortium should aspire to deliver a vessel entirely powered by hydrogen and not be of a hybrid (duel-fuelled) design unless said preferred starting position proves unviable.

It is recommended that a ferry fuelled purely by hydrogen should employ a fuel cell and battery power delivery system rather than a hydrogen internal combustion engine (HICE) to take advantage zero nitrogen oxide emissions, potentially greater energy efficiencies, and noise pollution abatement. CMAL have indicated that this design should be realised within a purpose built ferry as opposed to retrofitting an existing ship.

These initial design specifications will allow a naval architect to propose a solution incorporating the above requirements sized for the ferry route and operating model chosen. Many of the components of a hydrogen fuel cell marine propulsion system differ from those installed in a typical MGO gas engine vessel.

It is expected that the components required for a new power train will be of bespoke design, to be subjected to a suitable testing regime. It is recommended that an initial electrical design is undertaken as part of the next phase of the SWIFTH_2 programme.

7.2 Land-side System Architecture

There are a wide range of available system designs for the onshore portion of the proposed development that have been considered. The minimum system requirements identified for the supply of hydrogen to a port are:

- Wind farm.
- Electrolyser(s).
- Hydrogen storage.
- Compressor(s).
- Dispenser(s).

In order to provide system redundancy and security of hydrogen supply to what are lifeline ferry services, it is necessary to consider back-up systems that could be implemented.

A number of designs have been outlined below which each advance a form of system redundancy. The following variables are first considered as part of system redundancy:

Renewable Energies

Depending on the emplacement the proposed development and the available resources of the site (such as wind, temperature or global irradiance), the renewable energies configuration should be appropriate for the location chosen. The design should take into account additional factors such as the “inrush current” and the black start strategy. The option to add solar-PV should also be explored further.

Electrolyser Characteristics

The electrolyser is the principal land-side device of the development, thus the plant size will be determined by its nominal power. Additional characteristics will be taken into account such as performance and minimum load.

Ancillary Services

The possibility to supply ancillary services from different generation sources, depending of the capabilities of the development and if the plant will be grid connected.

Hydrogen Production Plant Location

Depending on the distance between the hydrogen production plant and the power production plant, there can be three possible arrangements:

- Locating the hydrogen production plant next to the wind farm and transport the hydrogen to the port using pipes or trucks.
- Locating the hydrogen production plant next to the port and supply the plant using a power line from the wind farm.
- Locating the hydrogen production plant at an intermediary location between the wind farm and the hydrogen production plant.

Minimum Hydrogen Supply Guarantee

To ensure a guaranteed supply of hydrogen for the ferry, the following forms of back-up power are considered:

- Photovoltaic plant: additional power supply to complement the wind farm.
- Diesel genset: maintain electricity supply via diesel genset.
- Grid connection: maintain electricity supply by importing electricity from the grid. Review of corporate power purchase agreements is recommended.
- Energy storage: maintain electricity supply via an energy storage system that may accept charge from the wind farm and/or local distribution grid.
- Fuel cell: maintain the electricity supply of the ancillary services by ‘cannibalising’ a portion of the hydrogen produced via an onshore fuel cell.

7.2.1 Proposed Layouts

There are multiple alternatives depending on the combination of the different design variables. Some of the possible configurations that can be realized are explained below.

7.2.1.1 Case 1: Hydrogen Production at Wind Farm with Strong Grid Back-up

Power plant based on a wind farm, solar-PV farm, and a strong grid connection which would be used to supply the ancillary services, maintain the electrical stability of the plant, and the hydrogen generation in case of a lack of renewable resources (depending on the energy cost). The electrolyser and the hydrogen tank would be installed next to the power plant and the hydrogen could be transported to the harbour using trucks or pipes.

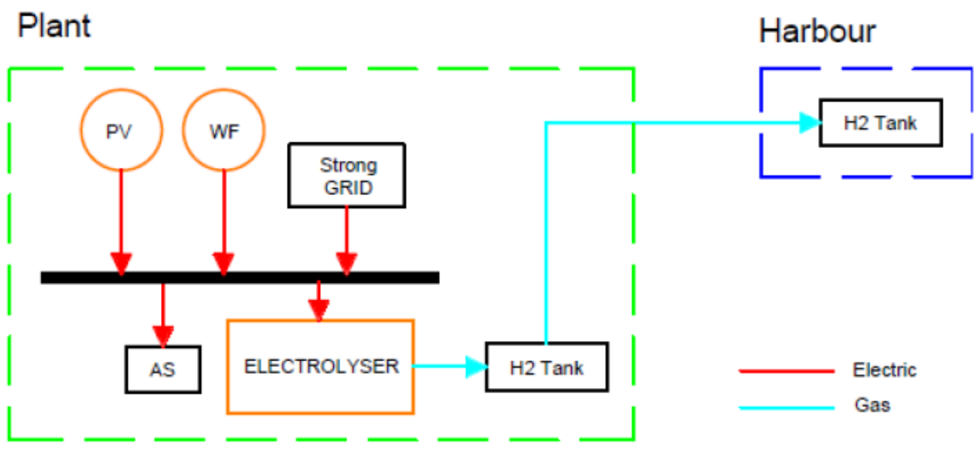


Figure 7-1 Case 1

7.2.1.2 Case 2: Hydrogen Production at Wind Farm with Weak Grid Back-up

Power plant based on a wind farm, solar-PV farm, and a weak grid which would be used to supply the ancillary services. The electrolyser and the hydrogen tank would be installed next to the power plant and the hydrogen could be transported to the harbour using trucks or pipes.

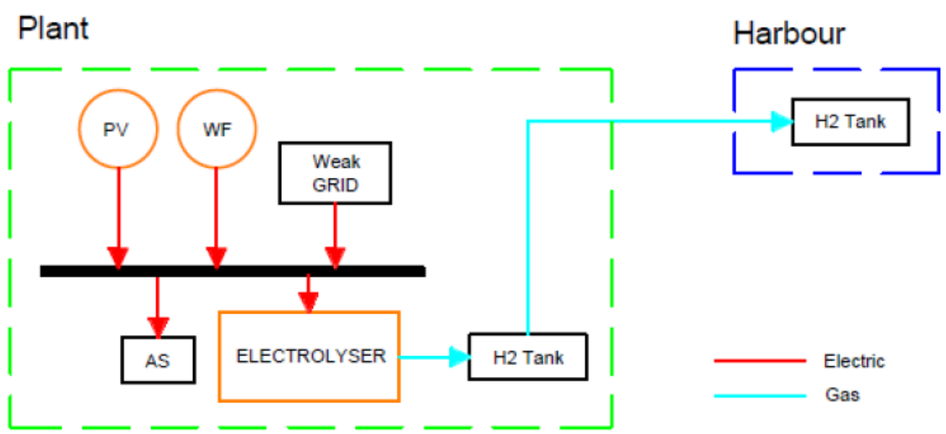


Figure 7-2 Case 2

7.2.1.3 Case 3: Hydrogen Production at Wind Farm with Fuel Cell Back-up

Power plant based on a wind farm, solar-PV farm, without any grid connection. The power production of the plant would be intended to supply the hydrogen production and the ancillary services. The hydrogen storage would comprise two tanks, one for supplying hydrogen to the port and the other for supplying hydrogen to an onshore fuel cell which would supply the ancillary services of the whole system when the renewable energies are not available.

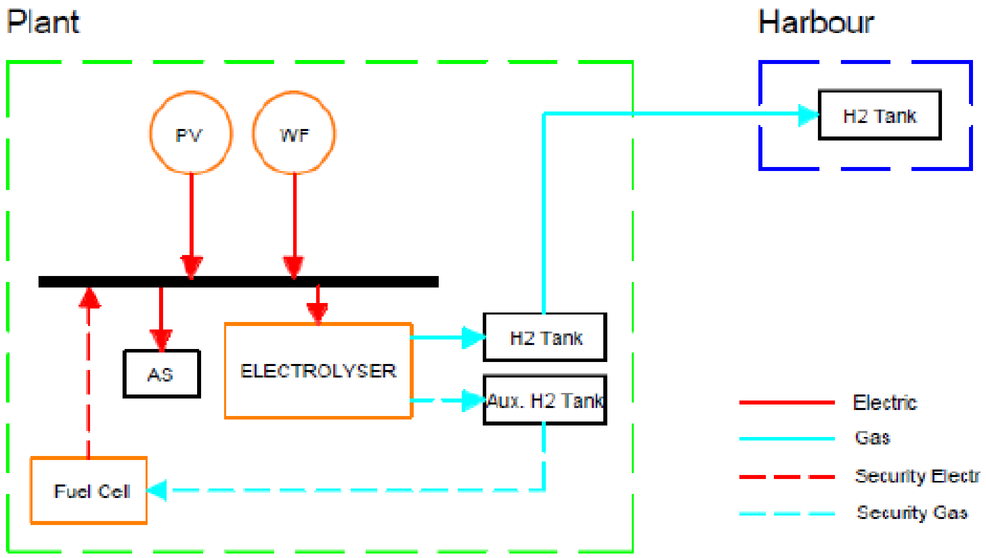


Figure 7-3 Case 3

7.2.1.4 Case 4: Hydrogen Production at Port with Grid Back-up

Power plant based on a wind farm, solar-PV farm, and a weak grid which would supply the ancillary services and the hydrogen production. The hydrogen production and consumption is located in the port/harbour, thus a power line to supply energy for the electrolyser would be needed.

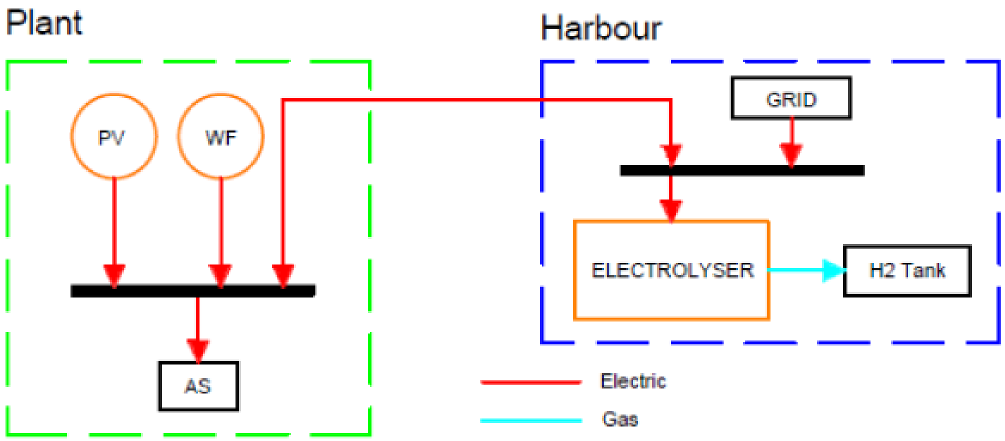


Figure 7-4 Case 4

7.3 Health, Safety and the Environment

It is commonly held that hydrogen possesses properties which render it a dangerous and difficult chemical to work with. This is epitomized by the notorious 1937 Hindenburg disaster, which saw a German passenger airship destroyed when its hydrogen lifting gas ignited.

Hydrogen does pose risks much like other fuels in certain circumstances. However, the unique properties of this chemical also afford it characteristics that make it safer than other substances. These risks, therefore, must be considered holistically relative to other fuels or energy carriers.

Some of the characteristics of hydrogen have been provided for in Table 7-1 below as evidence of the health and safety concerns surrounding hydrogen as a fuel:

Table 7-1 Hydrogen Characteristics

Characteristic	Risk
Low viscosity	Hydrogen gas has a very low viscosity and it is difficult to prevent hydrogen systems from developing leaks. The use of suitable sealing interfaces and appropriate components within a hydrogen system will significantly reduce the likelihood of this occurring. For high-pressure storage systems, hydrogen would leak nearly three times faster than natural gas and over five times faster than propane.
High diffusivity	Unlike heavier gaseous fuels, if a hydrogen leak occurs in an open or well-ventilated area its diffusivity and buoyancy will help to reduce the likelihood of a flammable mixture forming in the vicinity of the leak.
Buoyancy	The buoyancy of hydrogen can also be used to manage the risk normally associated with fuel handling by segregating the hydrogen from foreseeable sources of ignition using internal partitions and bulkheads and differential pressurisation. This can also be done by locating all potential sources of ignition well below the level of the equipment from which hydrogen may leak and accumulate and ensuring adequate ventilation and safe discharge of the exhaust.
Metal embrittlement	Hydrogen can cause embrittlement of high strength steels, titanium alloys and aluminium alloys with cracking and catastrophic failure of the metals at stress below the yield stress. The industry standard for components in hydrogen service is grade 316 stainless steel and cupro-nickel or coper for low-pressure applications.

Characteristic	Risk
Ignition energy	The energy necessary to initiate a hydrogen/air explosion is very small about 0.02 mJ. This is less than one tenth that of other fuels such as methane, LPG or petrol. Even small sparks, such as those produced by wearing certain types of clothing are capable of igniting hydrogen/air mixtures and causing an explosion. Clothing made of ordinary cotton, flame-retardant cotton or Nomex should be worn.

7.3.1 Regulatory Compliance

It has not been possible to fully address all of the health, safety and environmental aspects likely applicable to the SWIFTH$_2$ project within the resources of this feasibility study. It is desirable that future work will involve the full participation of a ship builder to allow for HSE to be investigated fully from the vessel perspective. These will include aspects such as:

- Whether the vessel will require additional structure to facilitate compartment segregation, resulting in increased weight.
- Will additional firefighting and detection systems been required.
- Compliance Maritime and Coastguard Agency and Health and Safety Executive requirements.

For onshore HSE aspects, the Control of Major Accident Hazards (COMAH) regulations 2015 will be applicable. The purpose of the COMAH regulations is to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any accidents which do occur.

The quantities of hydrogen (CAS number 1333-74-0) proposed for the SWIFTH$_2$ project would qualify for the upper tier requirements of the dangerous substances stipulated as part of the COMAH regulations.

The requirements of upper tier establishments includes the following:

- A safety report to show that arrangements are in place for the control of major accident hazards and to limit the consequences to people and the environment of any that do occur. This report will be prepared for the purposes of:
  - Demonstrating that a major accident prevention policy and a safety management system for implementing it have been put into effect;
  - Demonstrating that the major accident hazards and possible major accident scenarios in relation to the establishment have been identified and that the necessary measures have been taken to prevent such accidents and to limit their consequences for human health and the environment;

  - Demonstrating that adequate safety and reliability have been taken into account in the design, construction, operation and maintenance of any installation, storage facility, equipment and infrastructure connected with the establishment's operation which are linked to major accident hazards inside the establishment;
  - Demonstrating that an internal emergency plan has been prepared, which includes sufficient information to enable an external emergency plan to be prepared;
  - Providing sufficient information to the competent authority to enable decisions to be made regarding the siting of new activities or developments around establishments.
- The report should identify all major accident hazards and present a representative set of reasonably foreseeable major accident scenarios. Reference should be made to hazard identification and risk assessment techniques. A clear link between the various major accident scenarios identified and the measures proposed to defend against them should be made.
- The safety report should show how the necessary measures will prevent foreseeable failures which could lead to major accidents, and to limit the consequences of any that do occur.
- The physical integrity of plant and equipment must be considered at all stages from design through construction to operation and maintenance. This includes:
  - Justification of the design chosen e.g. whether inherent safety principles have been followed;
  - Evidence that the containment for dangerous substances has been designed to have structural integrity, that suitable materials have been selected for its construction, and that measures have been taken to protect against overpressure;
  - Justification of design standards and specifications used, with an explanation of how they provide a defence against the various potential failure modes identified;
  - Evidence that construction is to the required specification and the design intent has been delivered;
  - Evidence that the plant is operated within the design specification;
  - Justification and reasoning behind maintenance programmes, e.g. frequency, safe systems of work and whether preventive or reactive;
  - Arrangements for the periodic examination and assessment of safety-critical components;
  - Competence of maintenance staff.

7.4 Wind Farm Operation and Maintenance

Though SGRE have extensive service capability in the UK as a leading WTG supplier, currently, none of the island-side ferry route terminuses fall within an existing SGRE service hub territory (see Figure 7-5). This results in no ferry route possessing a distinct logistical advantage over the others in this regard.

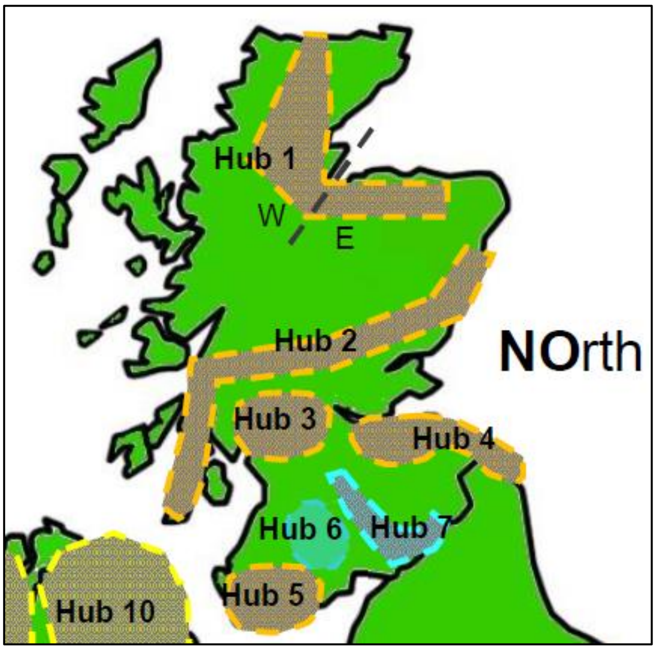


Figure 7-5 SGRE Onshore Hub Map

Any new wind farm will require its own dedicated team of service technicians. SGRE have stated that should a hydrogen vessel be commissioned in the Western Isles a service hub would be setup to provide operation and maintenance support to the wind farm regardless of the route(s) selected. As such, an assessment of the ferry routes based on proximity to the nearest available SGRE service hub becomes redundant.

SGRE would aim to create a local service presence close to the wind farm to provide the scheduled maintenance and may wish to employ local people and train them as service technicians for an on-island service hub. In areas of low population densities this may be harder. While SGRE would seek to recruit local people, this is not a firm commitment if suitable people cannot be found.

The service technicians would ideally be home-based and so travel distances to the wind farm would be minimal. They would be supported by an Operations Mobile Unit (OMU) or by available service technicians from the closest hub on the mainland when required.

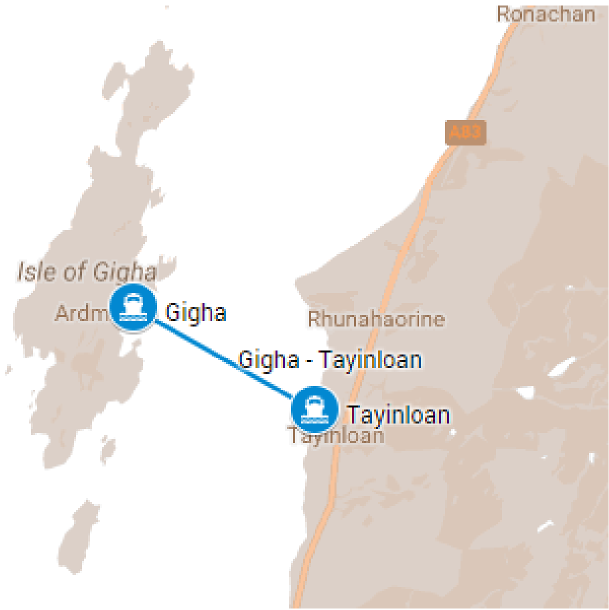
It may be necessary to service the turbines in a remote location through travelling technicians or from the nearby Inverness hub. Hence, travel times would be longer and consequently the warranted availability would be lower. The operation and maintenance (O&M) setup is therefore a key consideration warranting further investigation as part of the next phase of $SWIFTH_2$.

7.5 Other Improvements

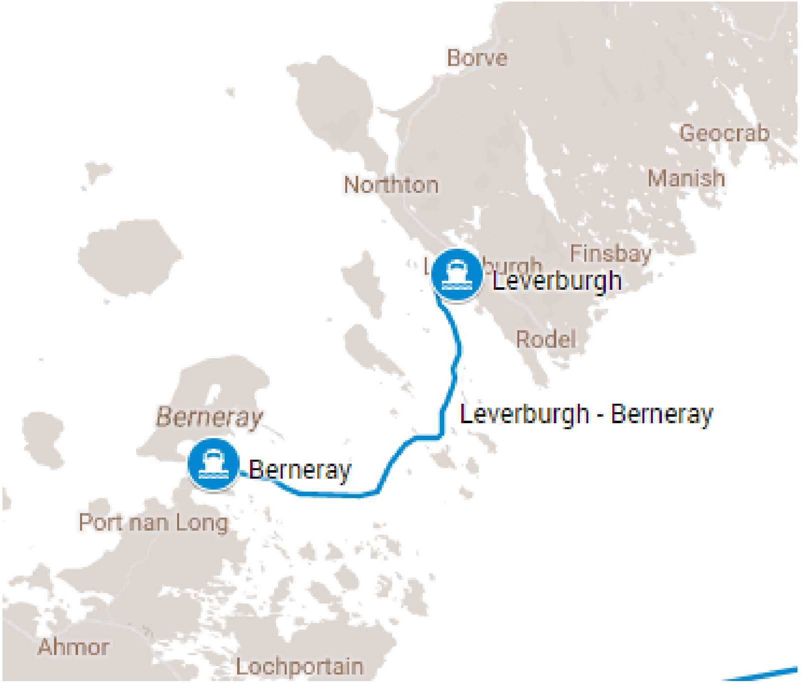
Depending on the scope and scale of the next phase of the $SWIFTH_2$ project, it is recommended that some or all of the following areas are addressed:

- It is recommended that the following refinements are made to the feasibility model in order to increase the sensitivity of the analysis undertaken:
    - Vessel energy demand: the model should be improved by incorporating the variation in energy demand both seasonally and throughout a route timetable (e.g. reduced service on a Sunday).
    - Dry dock ranges: accurate data from CMAL on distances from home ports to dry dock facilities should be utilised to improve accuracy. Performing the calculation based on energy consumption during journey rather than merely distances required to travel would also allow improve modelling accuracy.
    - Efficiency factors: greater understanding on how efficiencies for fuel cells, gas turbines and electrolysers vary in relation to other parameters will increase the accuracy of the energy demand and supply modelling. At present these variables are unresponsive to other inputs.
- A full HSE review should be undertaken in the next iteration.
- Assessment of the islands could be refined by using a variety of WTG models with more differing characteristics. For example, for planning purposes a lower WTG hub height could be used which maintains AEP but might stand a greater chance of gaining consent by the LPA.
- As travel times by operation and maintenance technicians would influence the warranted availability of a wind farm and hydrogen production plant, the O&M setup is therefore a key consideration warranting further investigation.
- It is important to note that although a fuel reserve factor is applied, no redundancy relating to security of supply is considered other than rounding up of the number of WTGs to the nearest whole as part of the wind farm sizing.

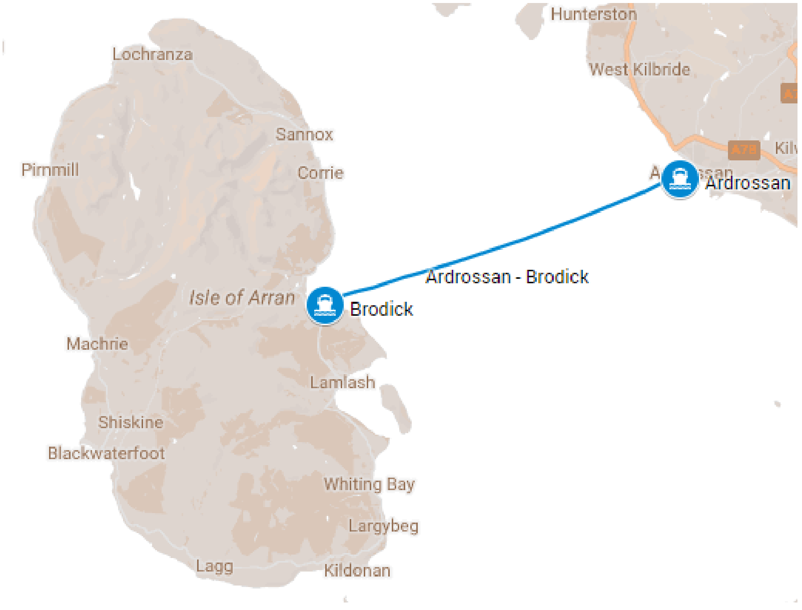
Appendix A Ferry Route Details

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Gigha - Tayinloan	MV Loch Ranza	200	Gigha	81	

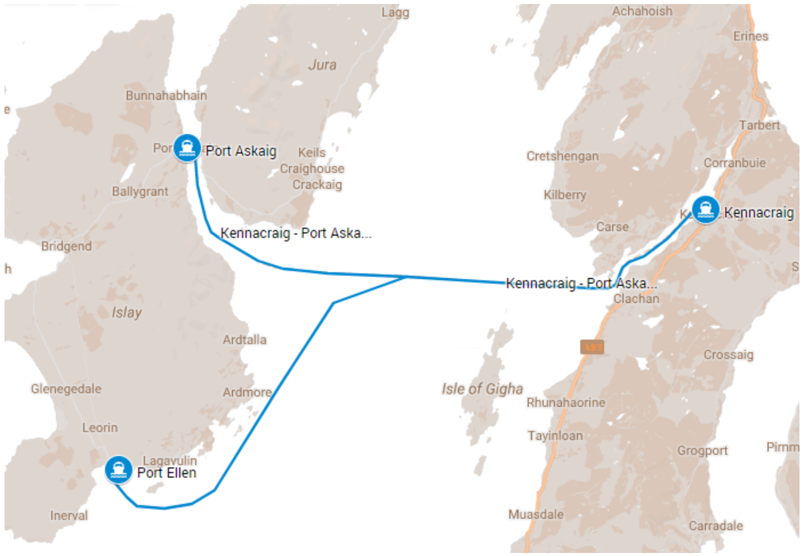
Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Barra – Eriskay	MV Loch Alainn	150	Barra	97	

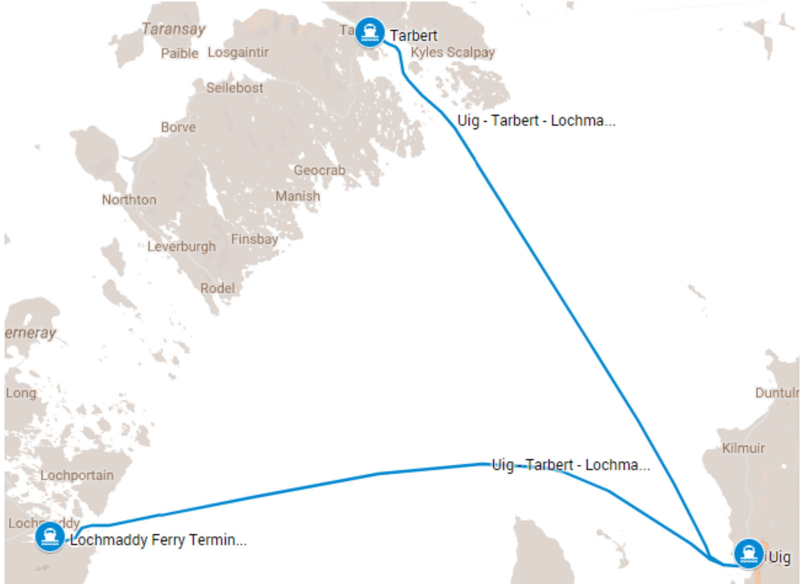
Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Leverburgh - Berneray	MV Loch Portain	195	Berneray	142	

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Craignure - Oban	MV Coruisk	250	Oban	161	
	MV Isle of Mull	968	Craignure		

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Ardrossan - Brodick	MV Caledonian Isles	1,000	Ardrossan	209	

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Mallaig - Lochboisdale - Armadale	MV Lord of the Isles	506	Lochboisdale	237	

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Kennacraig - Port Askaig / Port Ellen	MV Finlaggan	550	Kennacraig	237	

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Uig - Tarbert - Lochmaddy	MV Hebrides	612	Uig	349	
	802 (unnamed)	1,000			

Operational Route	Assigned Vessel(s)	Passenger Capacity [persons]	Home Port	Daily Distance Travelled [km]	Location Map
Stornoway - Ullapool	MV Loch Seaforth	700	Stornoway	541	

Appendix B Hydrogen Content Analysis

This analysis demonstrates various hybridisation modes and includes the range of bunkering frequencies agreed for analysis. Greater energy demand met by hydrogen results in a commensurate decrease in the energy demand met by traditional hydrocarbon fuel.

Methodology

The scenario is executed by changing two variables: the fraction of energy to be delivered by hydrogen, (P_h) and the bunkering frequency (period) factor, (T).

For Equation 2-1 and Equation 2-2 (P_h) is varied from 0 to 1 in increments of 0.05 to simulate energy to be delivered via hydrogen from 0% to 100% of demand. This is done for values of (T) to simulate daily (1), thrice weekly (2.3), twice weekly (3.5), weekly (7), and every 10 days (10) fuel requirement. A matrix of resulting internal fuel volumes is then plotted for (P_h) against (T). All other model variables are held static. Table 7-2 below itemises the key design inputs.

Table 7-2 Key Design Inputs and Assumptions

Parameter	Value / Setting
Fuels modelled	MGO, CGH2 (700 bar)
CGH2 power plant	Fuel cell
CGH2 power plant efficiency[19]	0.40
MGO power plant	Gas engine
MGO power plant efficiency	0.37
Fuel reserve factor (*R*)[20]	0.20
Bunkering frequency*	Various

*Vessel period energy demand assumes uniform demand every day of the year.

[19] Value recommended by ITM Power.

[20] Value recommended by CMAL.

Results

This scenario has been run for every route presented for analysis. The volumetric results are shown graphically and in tabular form for each vessel in Appendix B. For options not delivered by 100% hydrogen the total volume of space required is the summation of both fuel types. Note the change in chart axis scales between fuel types.

Key Findings

This analysis demonstrates the volumes of hydrogen required for the variables and assumptions outlined. Restricting the scenario variables further using a weekly refuelling profile and only 50% and 100% hydrogen energy delivery (P_h = 0.5, 1) gives the following results for this particular set of model inputs.

When viewed alongside figures provided from CMAL on internal MGO fuel volumes held for each vessel at 95% fill capacity, it is possible to see the difference in storage volumes between a traditionally powered vessel and a hydrogen equivalent in Table 7-3 below:

Table 7-3 Existing MGO and Equivalent Hydrogen Storage Sizing

Vessel	Existing MGO Storage [m³]*	Hydrogen Equivalent**			
		50% H_2 [m³]	Variance [%]	100% H_2 [m³]	Variance [%]
MV Loch Ranza	11.7	30.98	265	61.96	530
MV Loch Alainn	24.2	49.13	203	98.26	406
MV Loch Portain	24.6	105.58	429	211.15	858
MV Coruisk	63.7	153.25	241	306.5	481
MV Isle of Mull	126.4	251.50	199	503.01	398
MV Caledonian Isles	97.2	319.93	329	639.87	658
MV Lord of the Isles	107.9	406.08	376	812.16	753
802	144.2	571.49	396	1,142.98	793
MV Finlaggan	137.1	631.06	460	1,262.12	921
MV Hebrides	92.7	729.00	786	1,457.99	1,573
MV Loch Seaforth	308.9	879.08	285	1,758.17	569

*Aggregate total from figures supplied by CMAL. Bunkering profiles vary for each vessel. Does not include LNG volumes where applicable.

**Hydrogen stored at 700 bar and a weekly bunkering profile. Does not include hydrocarbon equivalent for 50% hydrogen energy delivery.

The volume required for a pure hydrogen powered vessel (employing a weekly bunkering profile at 700 bar compression) is over 400% of the volume of each vessels MGO storage in all but one instance of the above example. The chart below also details hydrogen volumes required for the same example.

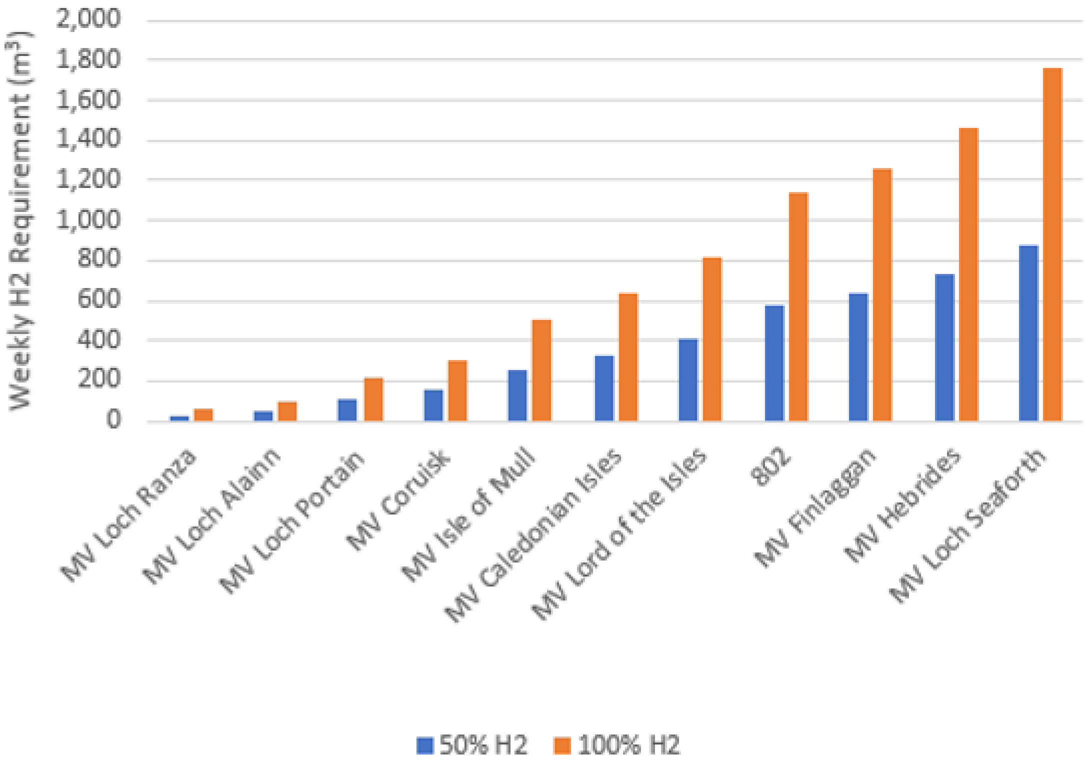


Figure 7-6 Pure and 50% Hybrid Hydrogen Volumes

As such, it can be demonstrated that in order to maintain as high a proportion of energy to be delivered via hydrogen, an increased frequency of bunkering should be considered in order to keep fuel volumes within an acceptable size.

Should an increase in bunkering frequency not prove technically viable, an alternative energy delivery system can be explored in the form of a hybrid design. This precedent has already been set with the purchasing of hybridised MGO and LNG vessels by CMAL constructed by Ferguson Marine (the MV Glen Sannox). A hybrid design option could offer greater reliability, redundancy, and fuel cost management which should be considered by the Consortium as an option to de-risk the project.

For the purposes of this Project, a pure 100% hydrogen delivery system will be explored as per guidance from the Consortium. The potential benefits for stakeholders of pure system are considered to be greater than said perceived benefits offered by a hybrid design.

Hydrogen Content Modelling Results

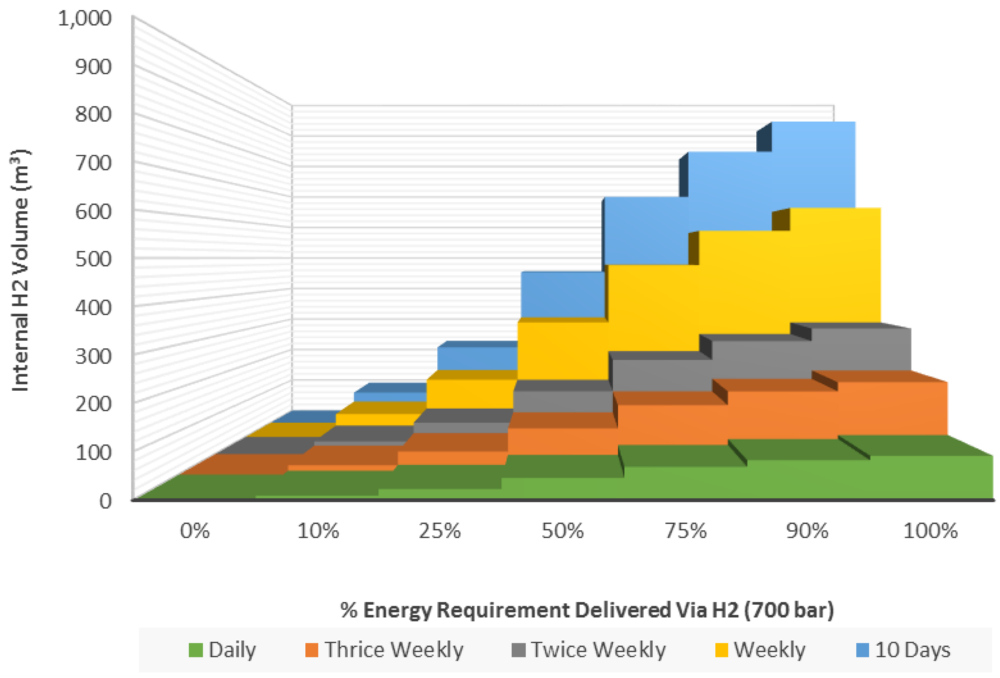


Figure 7-7 MV Caledonian Isles H_2 Volumes Required

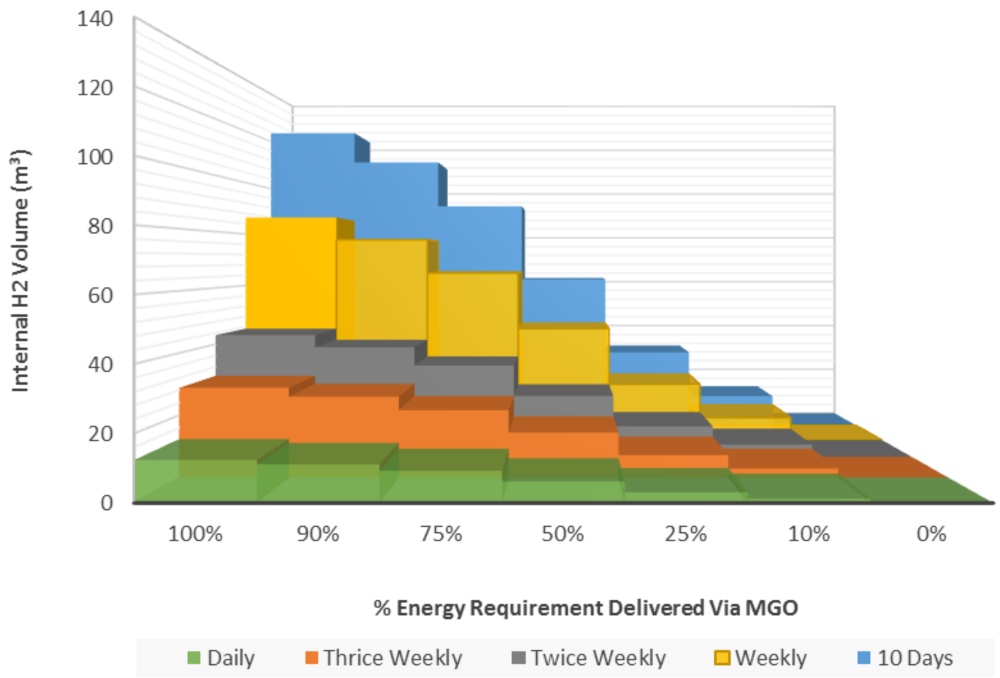


Figure 7-8 MV Caledonian Isles MGO Volumes Required

Table 7-4 MV Caledonian Isles Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	9.1	22.9	45.7	68.6	82.3	91.4
	Thrice Weekly	21.3	53.3	106.6	160.0	192.0	213.3
	Twice Weekly	32.0	80.0	160.0	240.0	287.9	319.9
	Weekly	64.0	160.0	319.9	479.9	575.9	639.9
	10 Days	91.4	228.5	457.1	685.6	822.7	914.1
MGO	Daily	11.1	9.3	6.1	3.1	1.2	0.00
	Thrice Weekly	25.9	21.6	14.4	7.2	2.9	0.00
	Twice Weekly	38.9	32.4	21.6	10.8	4.3	0.00
	Weekly	77.8	64.8	43.2	21.6	8.6	0.00
	10 Days	111.1	92.6	61.7	30.9	12.4	0.00
Total	Daily	20.3	32.1	51.9	71.6	83.5	91.4
	Thrice Weekly	47.3	74.9	121.1	167.2	194.8	213.3
	Twice Weekly	70.9	112.4	181.6	250.8	292.3	319.9
	Weekly	141.8	224.8	363.2	501.5	584.5	639.9
	10 Days	202.6	321.1	518.8	716.4	835.0	914.1

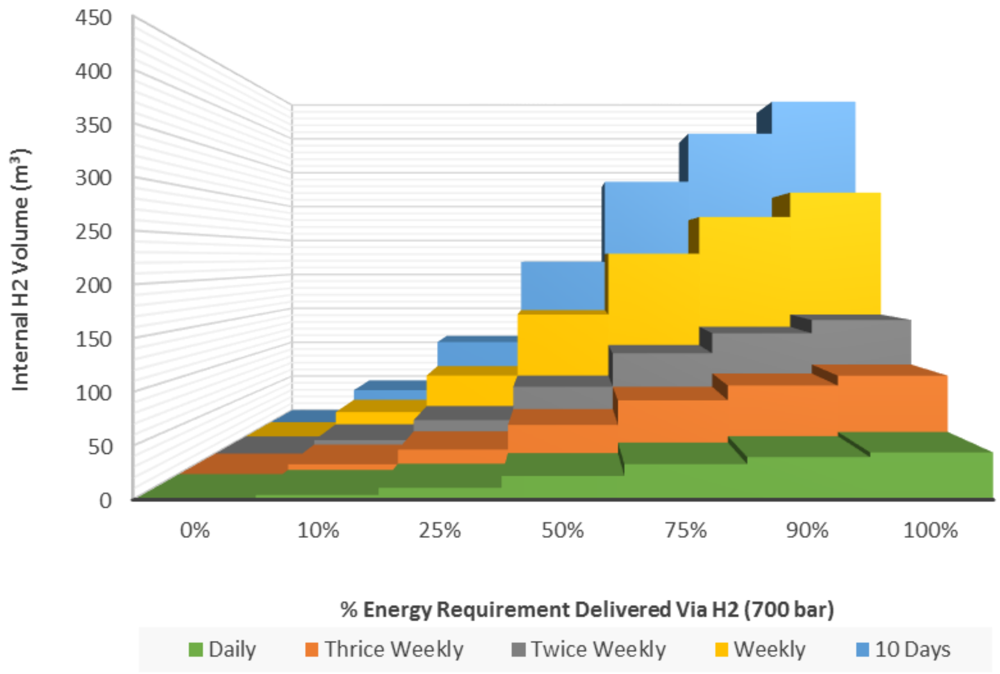


Figure 7-9 MV Coruisk H_2 Volumes Required

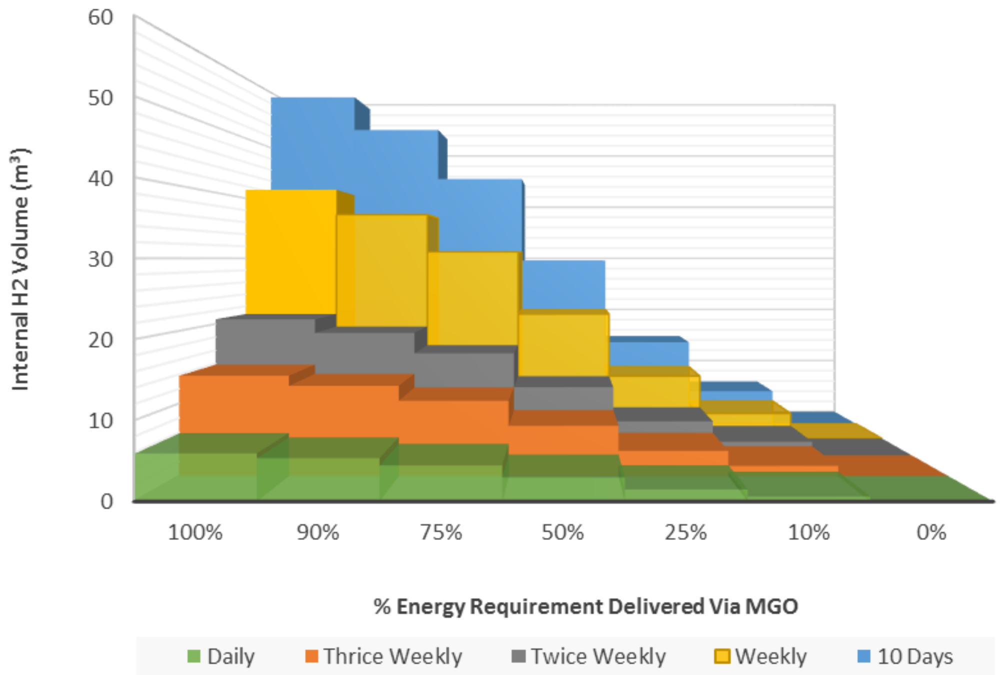


Figure 7-10MV Coruisk MGO Volumes Required

Table 7-5 MV Coruisk Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	4.4	10.9	21.9	32.8	39.4	43.8
	Thrice Weekly	10.2	25.5	51.1	76.6	91.9	102.2
	Twice Weekly	15.3	38.3	76.6	114.9	137.9	153.2
	Weekly	30.6	76.6	153.2	229.9	275.8	306.5
	10 Days	43.8	109.5	218.9	328.4	394.1	437.9
MGO	Daily	5.3	4.4	3.0	1.5	0.6	0.0
	Thrice Weekly	12.4	10.4	6.9	3.5	1.4	0.0
	Twice Weekly	18.6	15.5	10.4	5.2	2.1	0.0
	Weekly	37.3	31.1	20.7	10.4	4.1	0.0
	10 Days	53.2	44.4	29.6	14.8	5.9	0.0
Total	Daily	9.7	15.4	24.9	34.3	40.0	43.8
	Thrice Weekly	22.6	35.9	58.0	80.1	93.3	102.2
	Twice Weekly	34.0	53.8	87.0	120.1	140.0	153.2
	Weekly	67.9	107.7	174.0	240.2	280.0	306.5
	10 Days	97.0	153.8	248.5	343.2	400.0	437.9

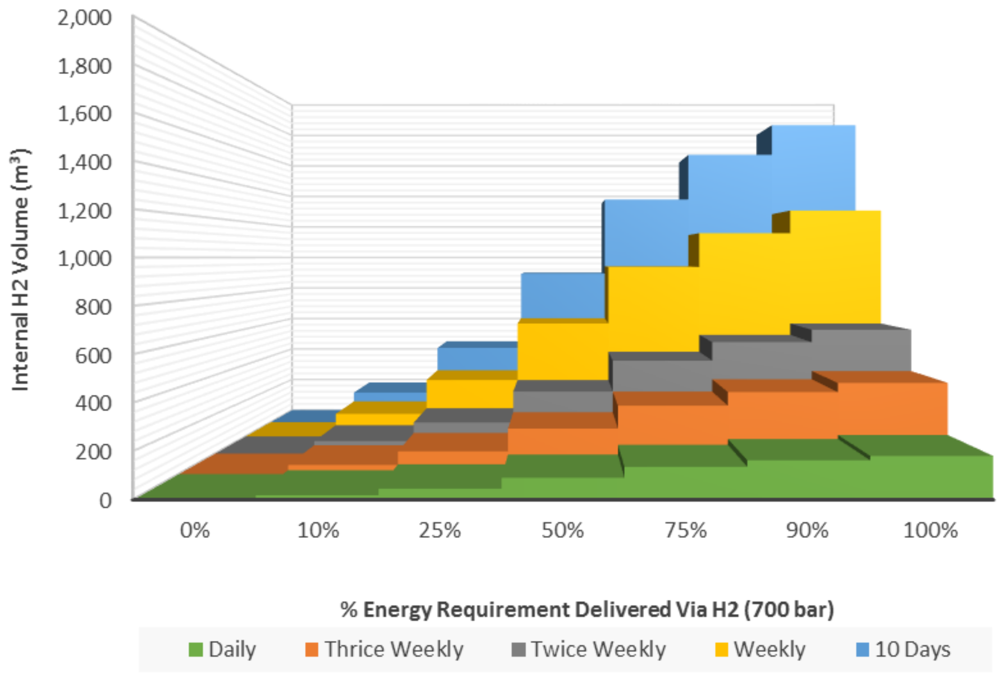


Figure 7-11 MV Finlaggan H_2 Volumes Required

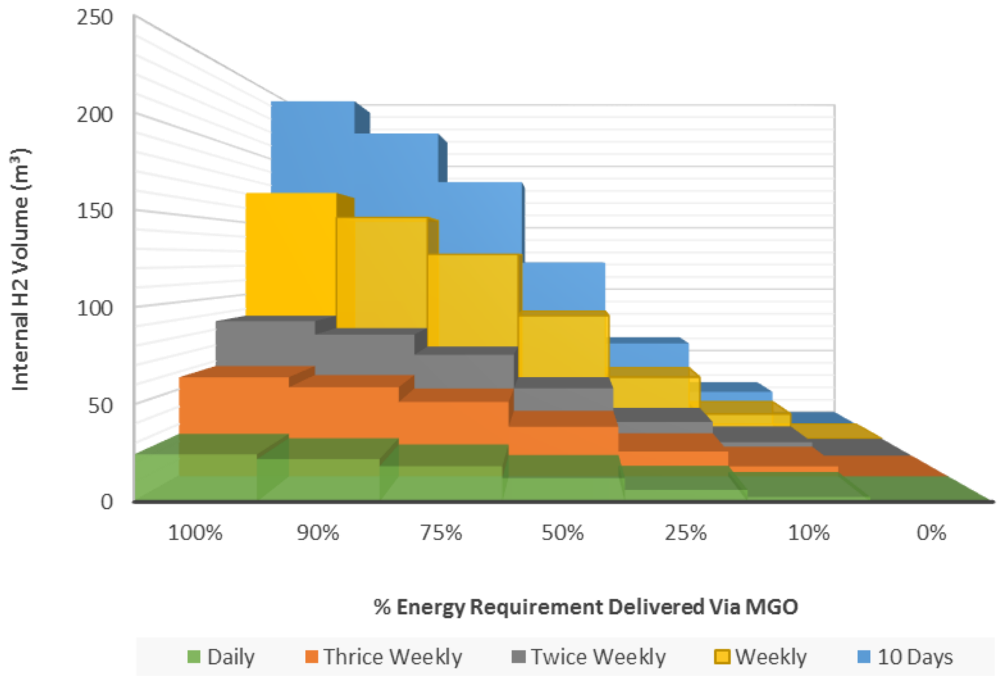


Figure 7-12 MV Finlaggan MGO Volumes Required

Table 7-6 MV Finlaggan Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	18.0	45.1	90.2	135.2	162.3	180.3
	Thrice Weekly	42.1	105.2	210.4	315.5	378.6	420.7
	Twice Weekly	63.1	157.8	315.5	473.3	568.0	631.1
	Weekly	126.2	315.5	631.1	946.6	1135.9	1262.1
	10 Days	180.3	450.8	901.5	1352.3	1622.7	1803.0
MGO	Daily	21.9	18.3	12.2	6.1	2.4	0.0
	Thrice Weekly	51.2	42.6	28.4	14.2	5.7	0.0
	Twice Weekly	76.7	63.9	42.6	21.3	8.5	0.0
	Weekly	153.5	127.9	85.3	42.6	17.1	0.0
	10 Days	219.2	182.7	121.8	60.9	24.4	0.0
Total	Daily	40.0	63.3	102.3	141.3	164.7	180.3
	Thrice Weekly	93.2	147.8	238.8	329.7	384.3	420.7
	Twice Weekly	139.8	221.7	358.2	494.6	576.5	631.1
	Weekly	279.7	443.4	716.3	989.2	1153.0	1262.1
	10 Days	399.5	633.4	1023.3	1413.2	1647.1	1803.0

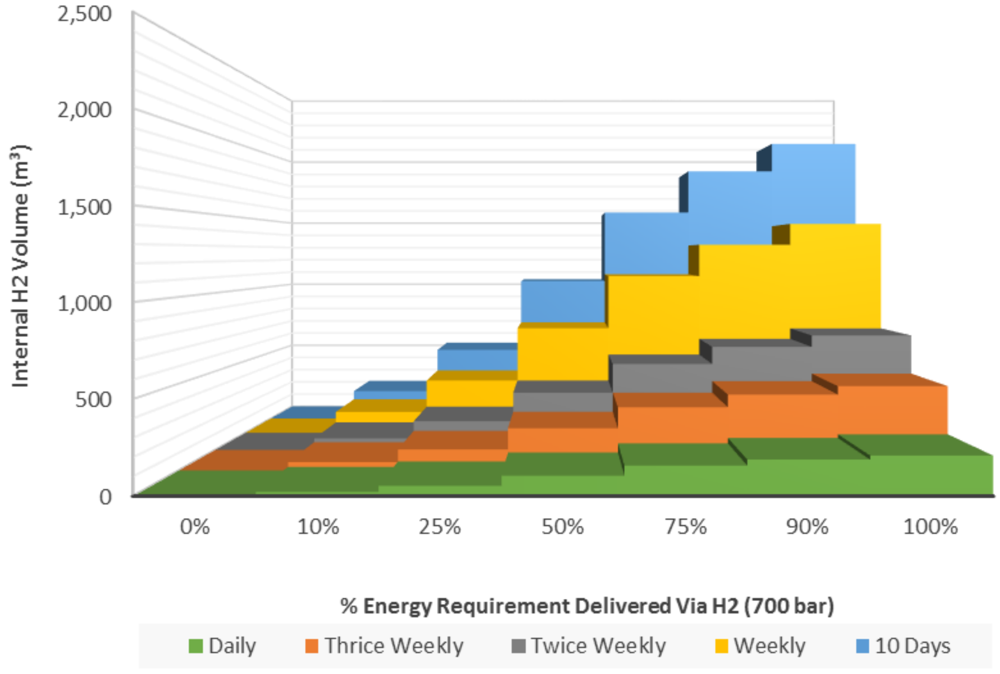


Figure 7-13 MV Hebrides H_2 Volumes Required

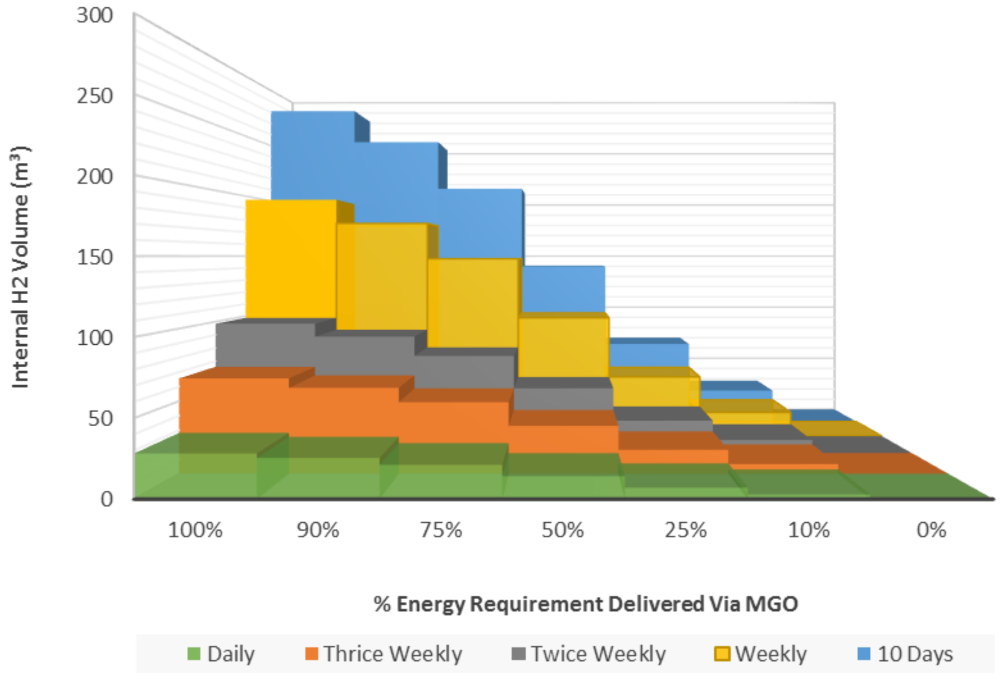


Figure 7-14 MV Hebrides MGO Volumes Required

Table 7-7 MV Hebrides Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	20.8	52.1	104.1	156.2	187.5	208.3
	Thrice Weekly	48.6	121.5	243.0	364.5	437.4	486.0
	Twice Weekly	72.9	182.2	364.5	546.7	656.1	729.0
	Weekly	145.8	364.5	729.0	1093.5	1312.2	1458.0
	10 Days	208.3	520.7	1041.4	1562.1	1874.6	2082.8
MGO	Daily	25.3	21.1	14.1	7.0	2.8	0.0
	Thrice Weekly	59.1	49.2	32.8	16.4	6.6	0.0
	Twice Weekly	88.6	73.9	49.2	24.6	9.8	0.0
	Weekly	177.3	147.7	98.5	49.2	19.7	0.0
	10 Days	253.2	211.0	140.7	70.3	28.1	0.0
Total	Daily	46.2	73.2	118.2	163.2	190.3	208.3
	Thrice Weekly	107.7	170.7	275.8	380.9	444.0	486.0
	Twice Weekly	161.5	256.1	413.7	571.4	665.9	729.0
	Weekly	323.1	512.2	827.5	1142.7	1331.9	1458.0
	10 Days	461.5	731.7	1182.1	1632.5	1902.7	2082.8

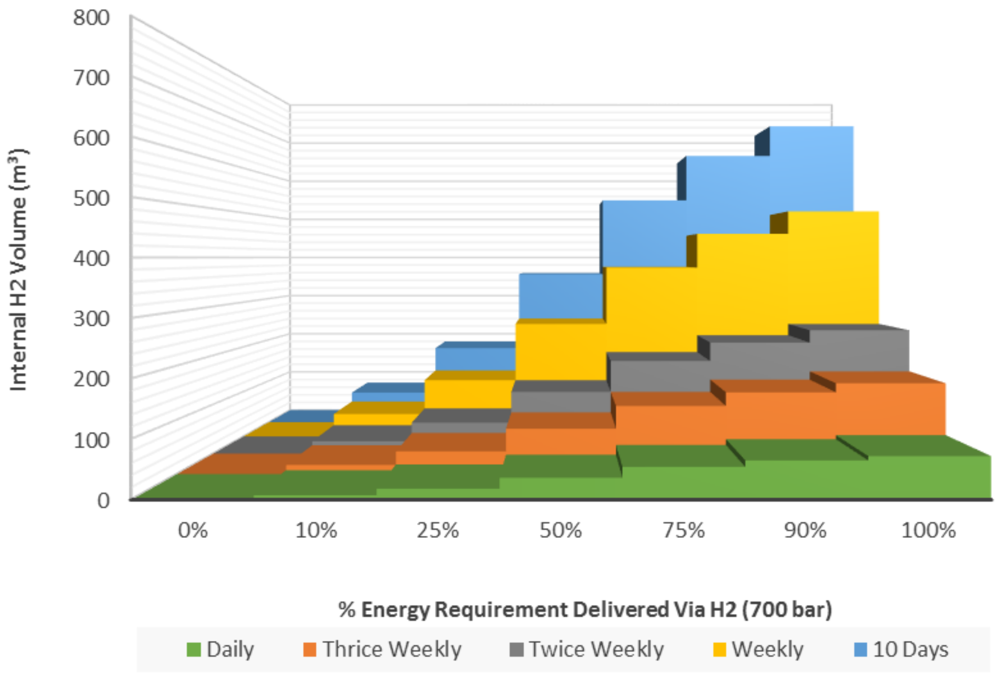


Figure 7-15 MV Isle of Mull H_2 Volumes Required

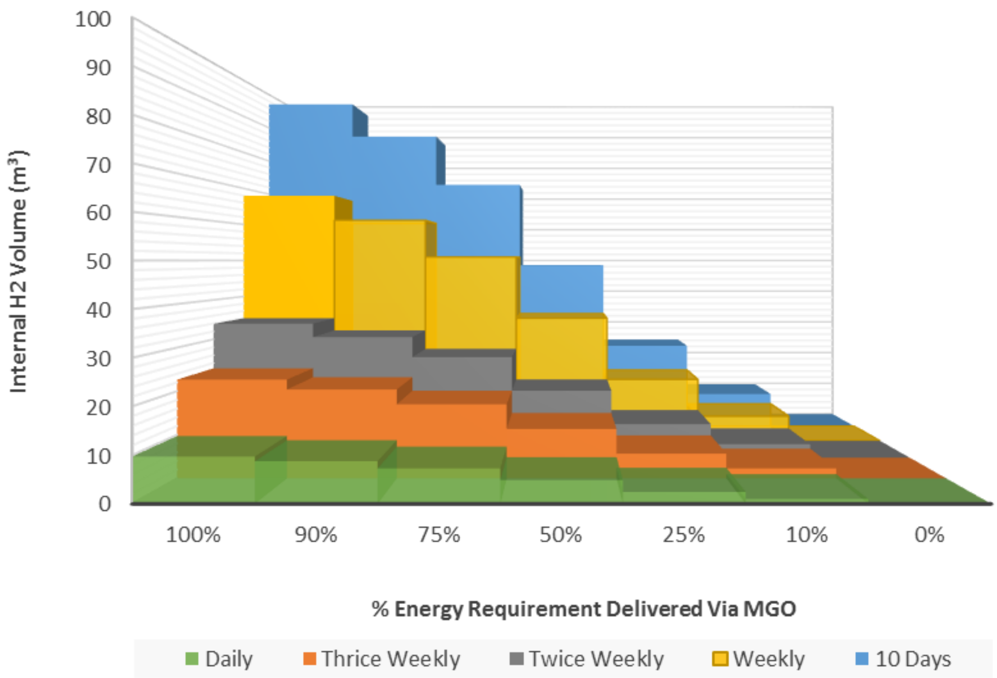


Figure 7-16 MV Isle of Mull MGO Volumes Required

Table 7-8 MV Isle of Mull Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	7.2	18.0	35.9	53.9	64.7	71.9
	Thrice Weekly	16.8	41.9	83.8	125.8	150.9	167.7
	Twice Weekly	25.2	62.9	125.8	188.6	226.4	251.5
	Weekly	50.3	125.8	251.5	377.3	452.7	503.0
	10 Days	71.9	179.6	359.3	538.9	646.7	718.6
MGO	Daily	8.7	7.3	4.9	2.4	1.0	0.0
	Thrice Weekly	20.4	17.0	11.3	5.7	2.3	0.0
	Twice Weekly	30.6	25.5	17.0	8.5	3.4	0.0
	Weekly	61.2	51.0	34.0	17.0	6.8	0.0
	10 Days	87.4	72.8	48.5	24.3	9.7	0.0
Total	Daily	15.9	25.2	40.8	56.3	65.6	71.9
	Thrice Weekly	37.2	58.9	95.2	131.4	153.2	167.7
	Twice Weekly	55.7	88.4	142.7	197.1	229.7	251.5
	Weekly	111.5	176.7	285.5	394.2	459.5	503.0
	10 Days	159.2	252.5	407.8	563.2	656.4	718.6

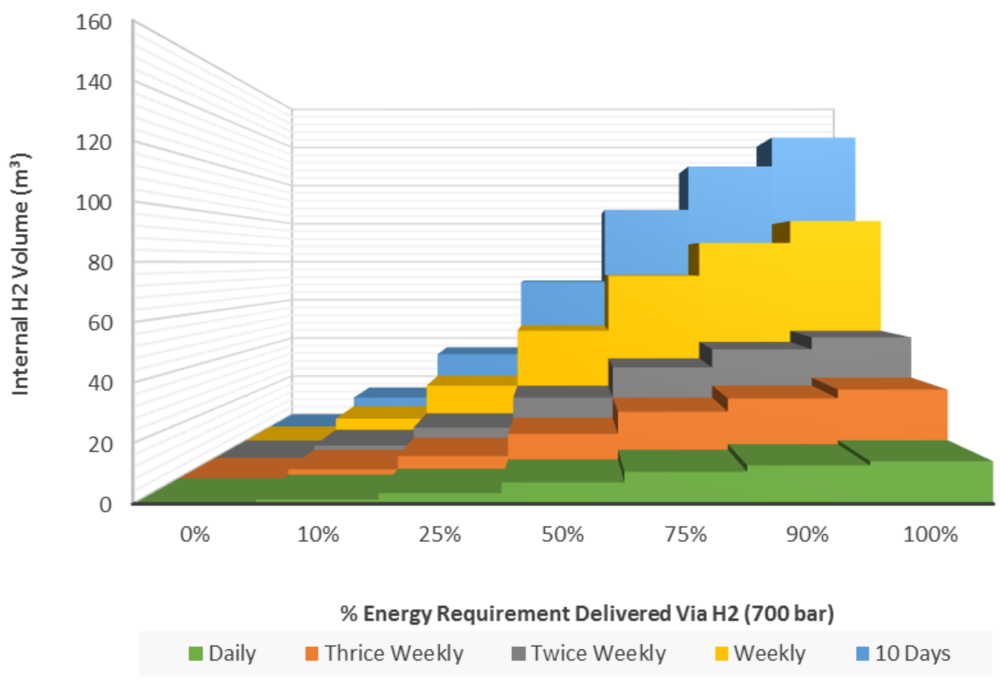


Figure 7-17 MV Loch Alainn H_2 Volumes Required

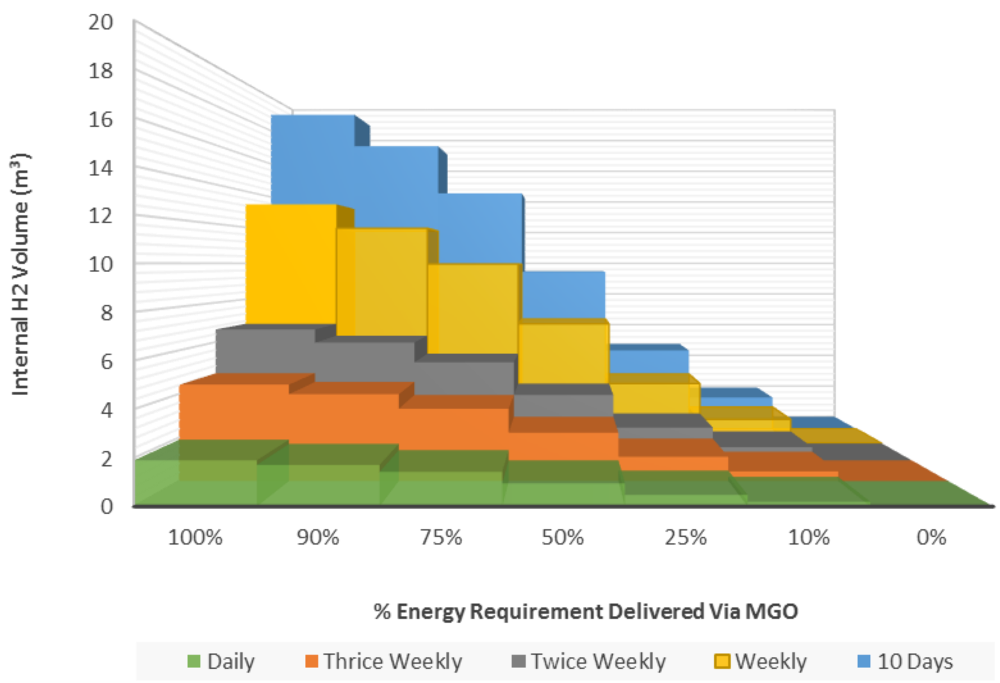


Figure 7-18 MV Loch Alainn MGO Volumes Required

Table 7-9 MV Loch Alainn Fuel Volumes Required [m³]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	1.4	3.5	7.0	10.5	12.6	14.0
	Thrice Weekly	3.3	8.2	16.4	24.6	29.5	32.8
	Twice Weekly	4.9	12.3	24.6	36.8	44.2	49.1
	Weekly	9.8	24.6	49.1	73.7	88.4	98.3
	10 Days	14.0	35.1	70.2	105.3	126.3	140.4
MGO	Daily	1.7	1.4	0.9	0.5	0.2	0.0
	Thrice Weekly	4.0	3.3	2.2	1.1	0.4	0.0
	Twice Weekly	6.0	5.0	3.3	1.7	0.7	0.0
	Weekly	11.9	10.0	6.6	3.3	1.3	0.0
	10 Days	17.1	14.2	9.5	4.7	1.9	0.0
Total	Daily	3.1	4.9	8.0	11.0	12.8	14.0
	Thrice Weekly	7.3	11.5	18.6	25.7	29.9	32.8
	Twice Weekly	10.9	17.3	27.9	38.5	44.9	49.1
	Weekly	21.8	34.5	55.8	77.0	89.8	98.3
	10 Days	31.1	49.3	79.7	110.0	128.2	140.4

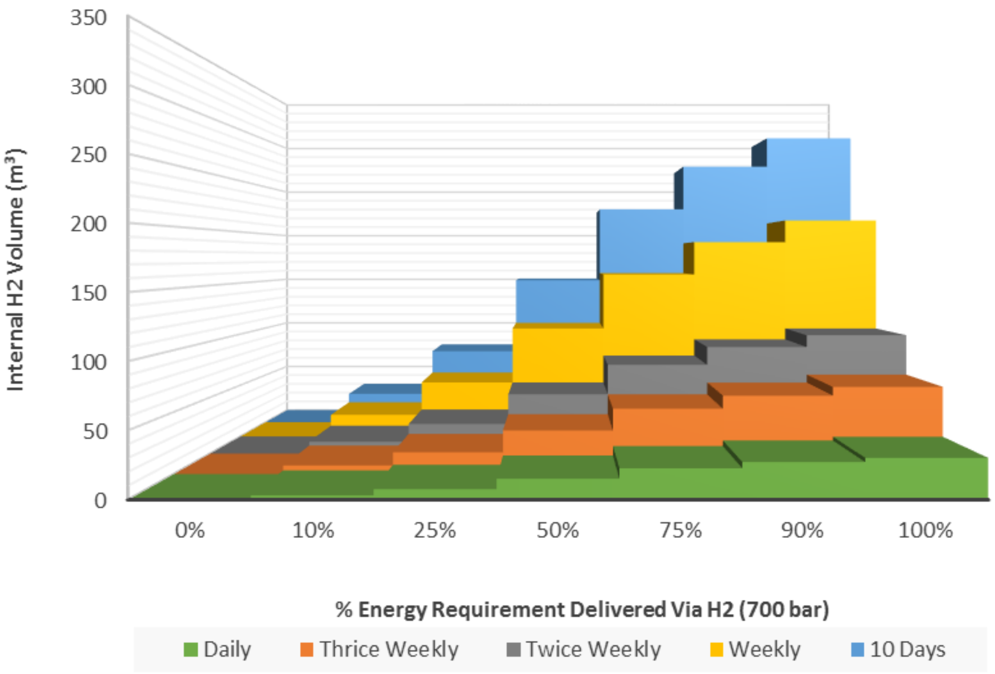


Figure 7-19 MV Loch Portain H_2 Volumes Required

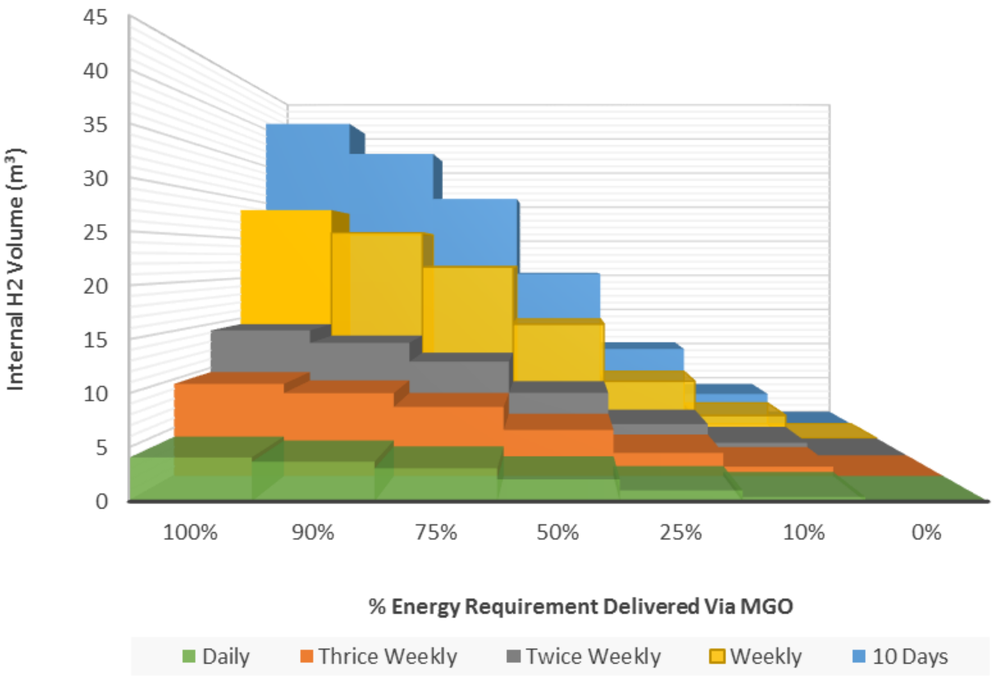


Figure 7-20 MV Loch Portain MGO Volumes Required

Table 7-10 MV Loch Portain Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	3.0	7.5	15.1	22.6	27.1	30.2
	Thrice Weekly	7.0	17.6	35.2	52.8	63.3	70.4
	Twice Weekly	10.6	26.4	52.8	79.2	95.0	105.6
	Weekly	21.1	52.8	105.6	158.4	190.0	211.2
	10 Days	30.2	75.4	150.8	226.2	271.5	301.6
MGO	Daily	3.7	3.1	2.0	1.0	0.4	0.0
	Thrice Weekly	8.6	7.1	4.8	2.4	1.0	0.0
	Twice Weekly	12.8	10.7	7.1	3.6	1.4	0.0
	Weekly	25.7	21.4	14.3	7.1	2.9	0.0
	10 Days	36.7	30.6	20.4	10.2	4.1	0.0
Total	Daily	6.7	10.6	17.1	23.6	27.6	30.2
	Thrice Weekly	15.6	24.7	39.9	55.2	64.3	70.4
	Twice Weekly	23.4	37.1	59.9	82.7	96.4	105.6
	Weekly	46.8	74.2	119.8	165.5	192.9	211.2
	10 Days	66.8	106.0	171.2	236.4	275.6	301.6

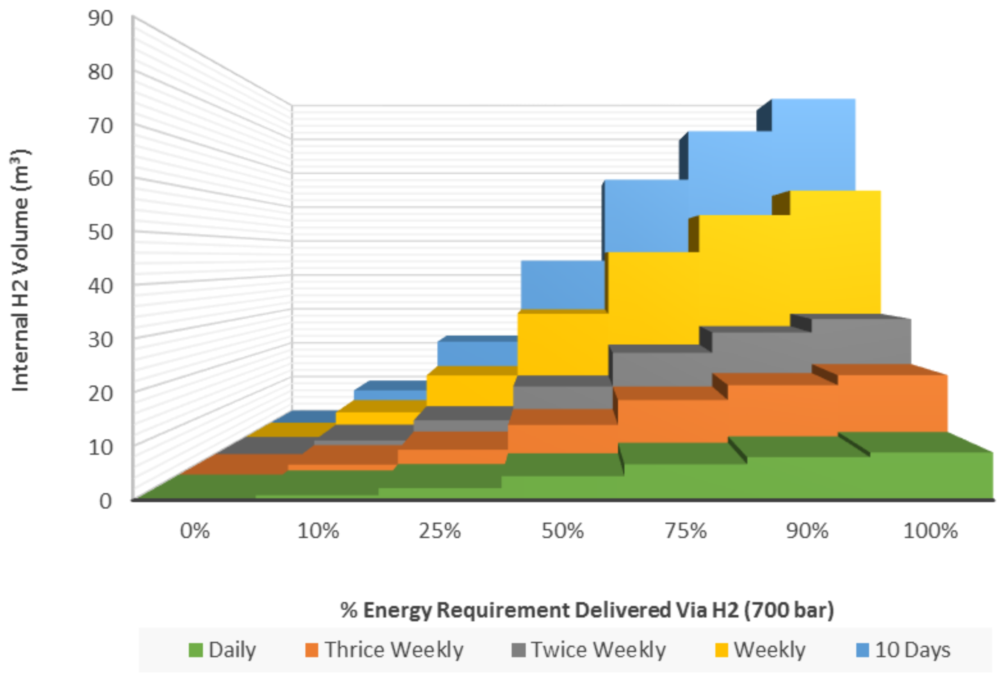


Figure 7-21 MV Loch Ranza H_2 Volumes Required

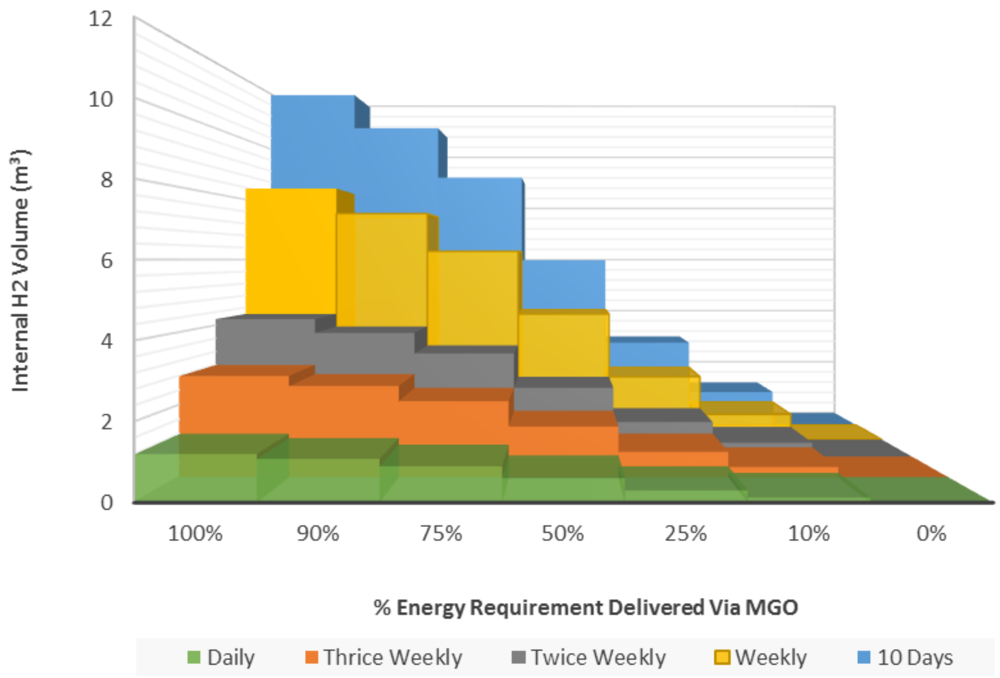


Figure 7-22 MV Loch Ranza MGO Volumes Required

Table 7-11 MV Loch Ranza Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	0.9	2.2	4.4	6.6	8.0	8.9
	Thrice Weekly	2.1	5.2	10.3	15.5	18.6	20.7
	Twice Weekly	3.1	7.7	15.5	23.2	27.9	31.0
	Weekly	6.2	15.5	31.0	46.5	55.8	62.0
	10 Days	8.9	22.1	44.3	66.4	79.7	88.5
MGO	Daily	1.1	0.9	0.6	0.3	0.1	0.0
	Thrice Weekly	2.5	2.1	1.4	0.7	0.3	0.0
	Twice Weekly	3.8	3.1	2.1	1.0	0.4	0.0
	Weekly	7.5	6.3	4.2	2.1	0.8	0.0
	10 Days	10.8	9.0	6.0	3.0	1.2	0.0
Total	Daily	2.0	3.1	5.0	6.9	8.1	8.9
	Thrice Weekly	4.6	7.3	11.7	16.2	18.9	20.7
	Twice Weekly	6.9	10.9	17.6	24.3	28.3	31.0
	Weekly	13.7	21.8	35.2	48.6	56.6	62.0
	10 Days	19.6	31.1	50.2	69.4	80.9	88.5

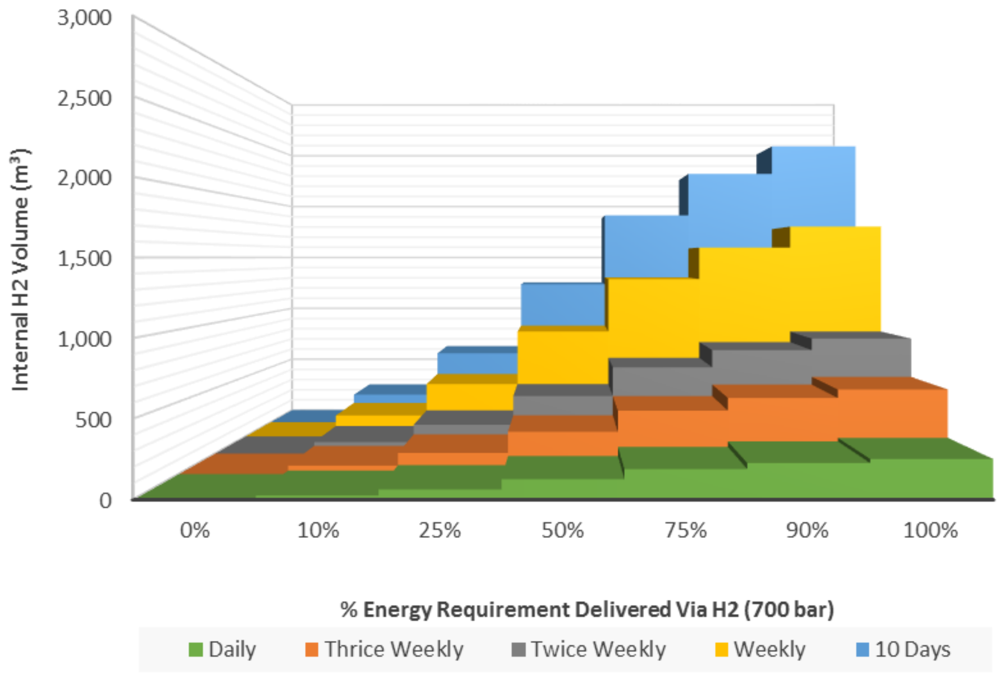


Figure 7-23 MV Loch Seaforth H_2 Volumes Required

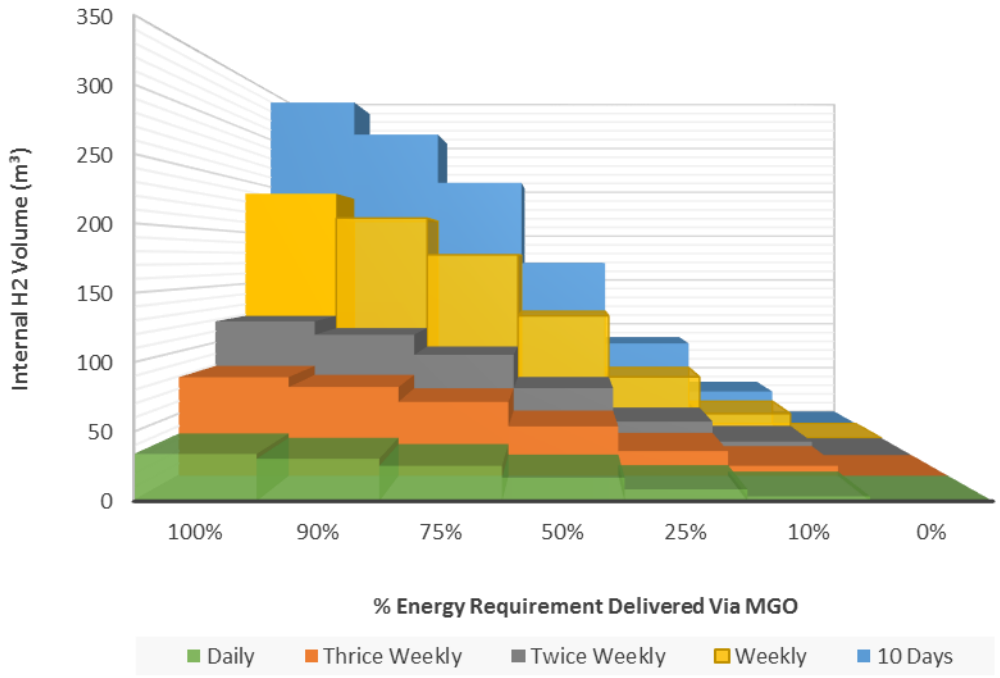


Figure 7-24 MV Loch Seaforth MGO Volumes Required

Table 7-12 MV Loch Seaforth Fuel Volumes Required [m³]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	25.1	62.8	125.6	188.4	226.1	251.2
	Thrice Weekly	58.6	146.5	293.0	439.5	527.5	586.1
	Twice Weekly	87.9	219.8	439.5	659.3	791.2	879.1
	Weekly	175.8	439.5	879.1	1318.6	1582.4	1758.2
	10 Days	251.2	627.9	1255.8	1883.8	2260.5	2511.7
MGO	Daily	30.5	25.4	17.0	8.5	3.4	0.0
	Thrice Weekly	71.3	59.4	39.6	19.8	7.9	0.0
	Twice Weekly	106.9	89.1	59.4	29.7	11.9	0.0
	Weekly	213.8	178.1	118.8	59.4	23.8	0.0
	10 Days	305.4	254.5	169.7	84.8	33.9	0.0
Total	Daily	55.7	88.2	142.5	196.9	229.4	251.2
	Thrice Weekly	129.9	205.9	332.6	459.3	535.4	586.1
	Twice Weekly	194.8	308.8	498.9	689.0	803.1	879.1
	Weekly	389.6	617.7	997.8	1378.0	1606.1	1758.2
	10 Days	556.5	882.4	1425.5	1968.6	2294.4	2511.7

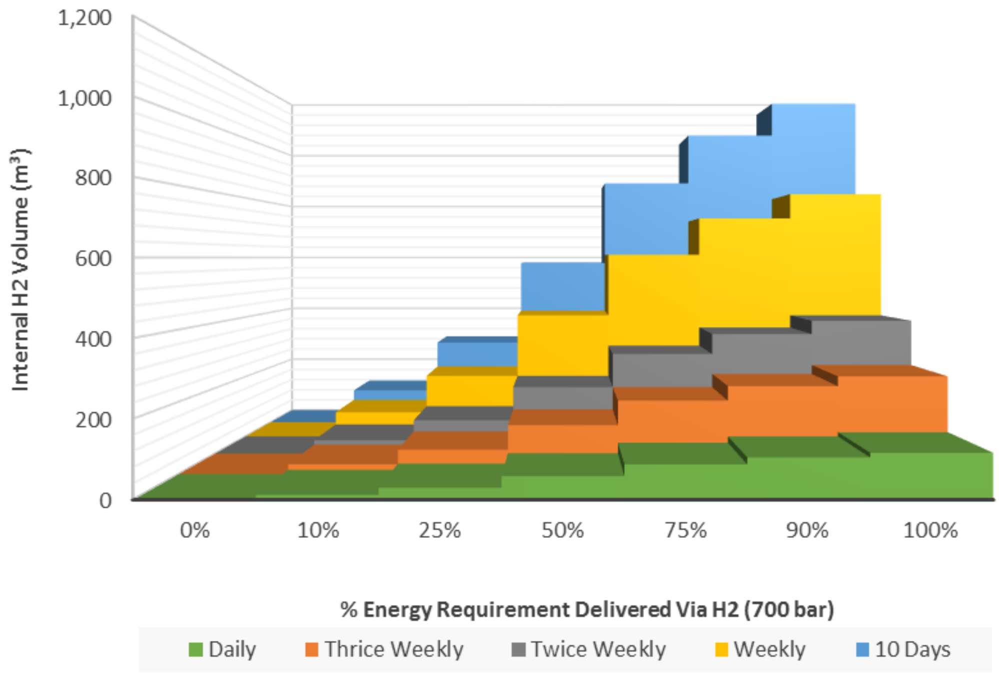


Figure 7-25 MV Lord of the Isles H_2 Volumes Required

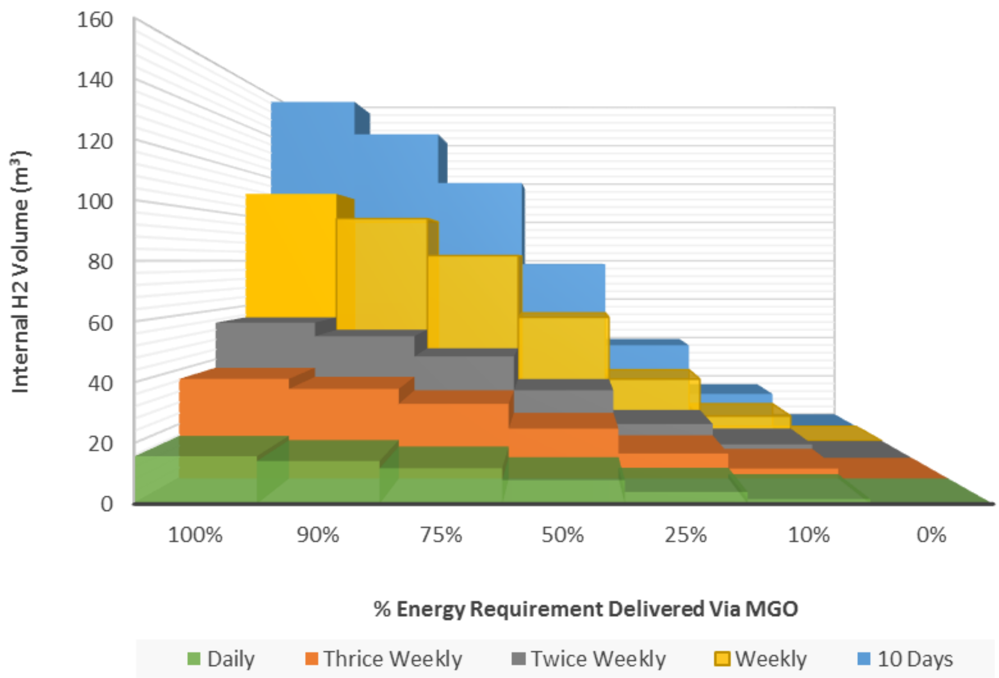


Figure 7-26 MV Lord of the Isles MGO Volumes Required

Table 7-13 MV Lord of the Isles Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	11.6	29.0	58.0	87.0	104.4	116.0
	Thrice Weekly	27.1	67.7	135.4	203.0	243.6	270.7
	Twice Weekly	40.6	101.5	203.0	304.6	365.5	406.1
	Weekly	81.2	203.0	406.1	609.1	730.9	812.2
	10 Days	116.0	290.1	580.1	870.2	1044.2	1160.2
MGO	Daily	14.1	11.8	7.8	3.9	1.6	0.0
	Thrice Weekly	32.9	27.4	18.3	9.1	3.7	0.0
	Twice Weekly	49.4	41.1	27.4	13.7	5.5	0.0
	Weekly	98.7	82.3	54.9	27.4	11.0	0.0
	10 Days	141.1	117.6	78.4	39.2	15.7	0.0
Total	Daily	25.7	40.8	65.8	90.9	106.0	116.0
	Thrice Weekly	60.0	95.1	153.6	212.2	247.3	270.7
	Twice Weekly	90.0	142.7	230.5	318.3	371.0	406.1
	Weekly	180.0	285.3	460.9	636.5	741.9	812.2
	10 Days	257.1	407.6	658.5	909.4	1059.9	1160.2

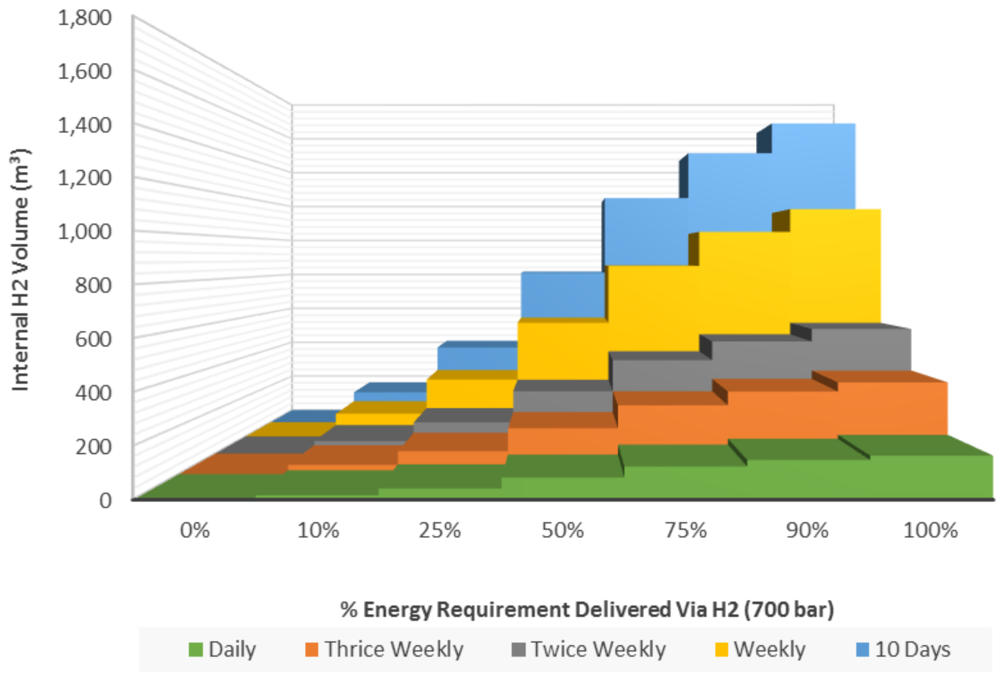


Figure 7-27 802 H_2 Volumes Required

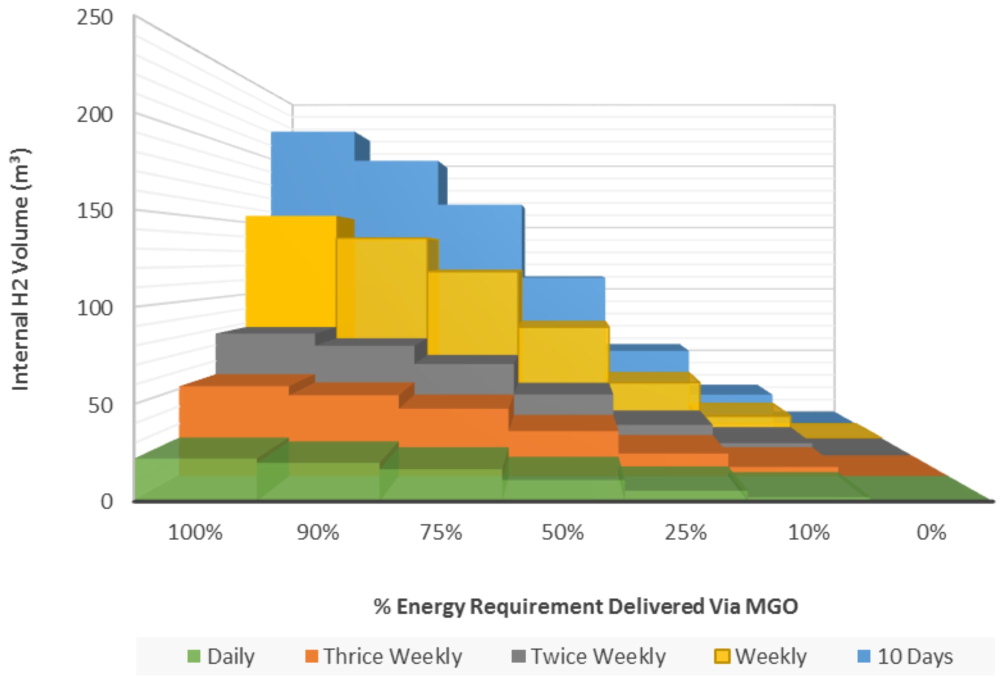


Figure 7-28 802 MGO Volumes Required

Table 7-14 802 Fuel Volumes Required [m^3]

Fuel	Bunkering Frequency	Energy Requirement Delivered by H_2					
		10%	25%	50%	75%	90%	100%
H_2	Daily	16.3	40.8	81.6	122.5	147.0	163.3
	Thrice Weekly	38.1	95.2	190.5	285.7	342.9	381.0
	Twice Weekly	57.1	142.9	285.7	428.6	514.3	571.5
	Weekly	114.3	285.7	571.5	857.2	1028.7	1143.0
	10 Days	163.3	408.2	816.4	1224.6	1469.6	1632.8
MGO	Daily	19.9	16.5	11.0	5.5	2.2	0.0
	Thrice Weekly	46.3	38.6	25.7	12.9	5.1	0.0
	Twice Weekly	69.5	57.9	38.6	19.3	7.7	0.0
	Weekly	139.0	115.8	77.2	38.6	15.4	0.0
	10 Days	198.5	165.4	110.3	55.1	22.1	0.0
Total	Daily	36.2	57.4	92.7	128.0	149.2	163.3
	Thrice Weekly	84.4	133.9	216.2	298.6	348.0	381.0
	Twice Weekly	126.6	200.8	324.3	447.9	522.1	571.5
	Weekly	253.3	401.6	648.7	895.8	1044.1	1143.0
	10 Days	361.8	573.6	926.7	1279.8	1491.6	1632.8

Appendix C List of Model Values and Standard Variables

Table 7-15 Feasibility Model Input Values

Values	
Hydrogen Higher Heating Value (HHV)	141.86 MJ/kg
Hydrogen Lower Heating value (LHV)	119.93 MJ/kg
Hydrogen Density (LH2)	70.90 kg/m^3
Hydrogen Density (700 bar)	39.69 kg/m^3
Hydrogen Density (350 bar)	23.65 kg/m^3
Hydrogen Energy Density, u_h (LH2)	8.50 MJ/L
Hydrogen Energy Density, u_h (700 bar)	4.76 MJ/L
Hydrogen Energy Density, u_h (350 bar)	2.84 MJ/L
LNG Higher Heating Value (HHV)	55.20 MJ/kg
LNG Lower Heating Value (LHV)	48.60 MJ/kg
LNG Density	457 kg/m^3
LNG Energy Density, u_f	22.20 MJ/L
MGO Higher Heating Value (HHV)	45.90 MJ/kg
MGO Lower Heating Value (LHV)	42.80 MJ/kg
MGO Density	890 kg/m^3
MGO Energy Density, u_f	38.09 MJ/L

Table 7-16 Feasibility Model Input Variables

Variables	
Efficiency, fuel cell, η_h	0.40
Efficiency, gas engine (hydrogen), η_h	0.37
Efficiency, gas engine (hydrocarbon), η_f	0.37
Electrolyser water supply	9.00 kg_w / kg_{h2}
WTG model	SWT-DD-130, 4.30 MW
WTG average wind speed at hub height	9.00 m/s
WTG AEP Probability	P75

Table 7-17 Feasibility Model Resultants

Resultants	
Efficiency, electrolyser, η_e	0.5552
WTG average annual electricity (gross @ 9.0 m/s)	20,000 MWh
WTG average annual electricity (net of losses @ 9.0 m/s)	15,000 MWh
WTG average daily electricity	41.07 MWh
WTG maximum daily electricity	103.20 MWh
WTG capacity factor, C_p	0.40

Appendix D Fuel Compression Analysis Results

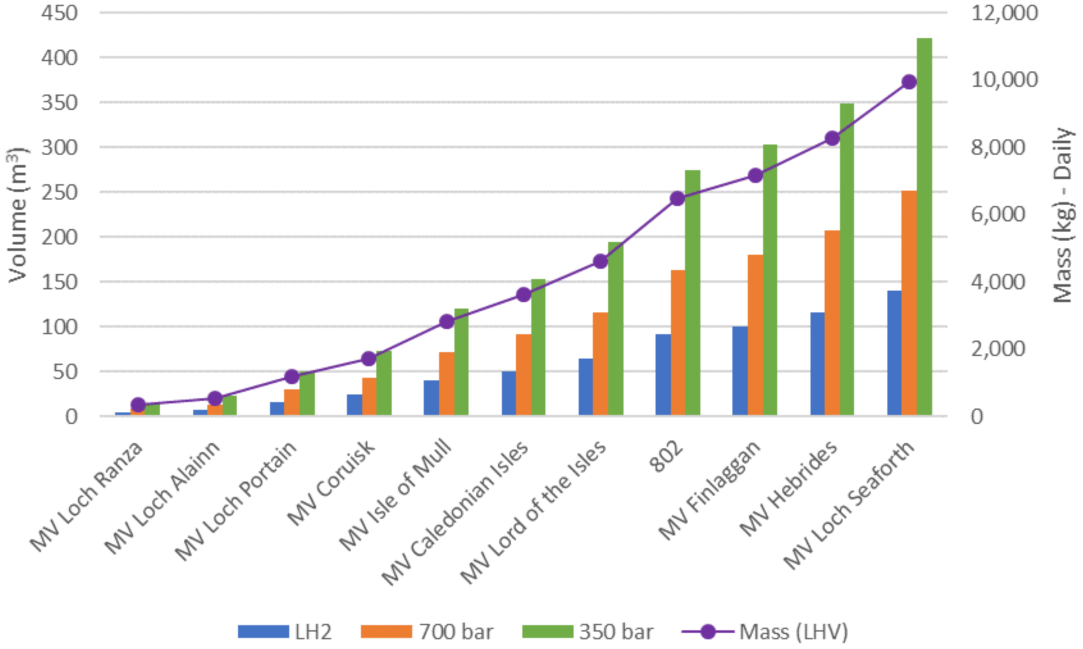


Figure 7-29 Daily Bunkering Frequency

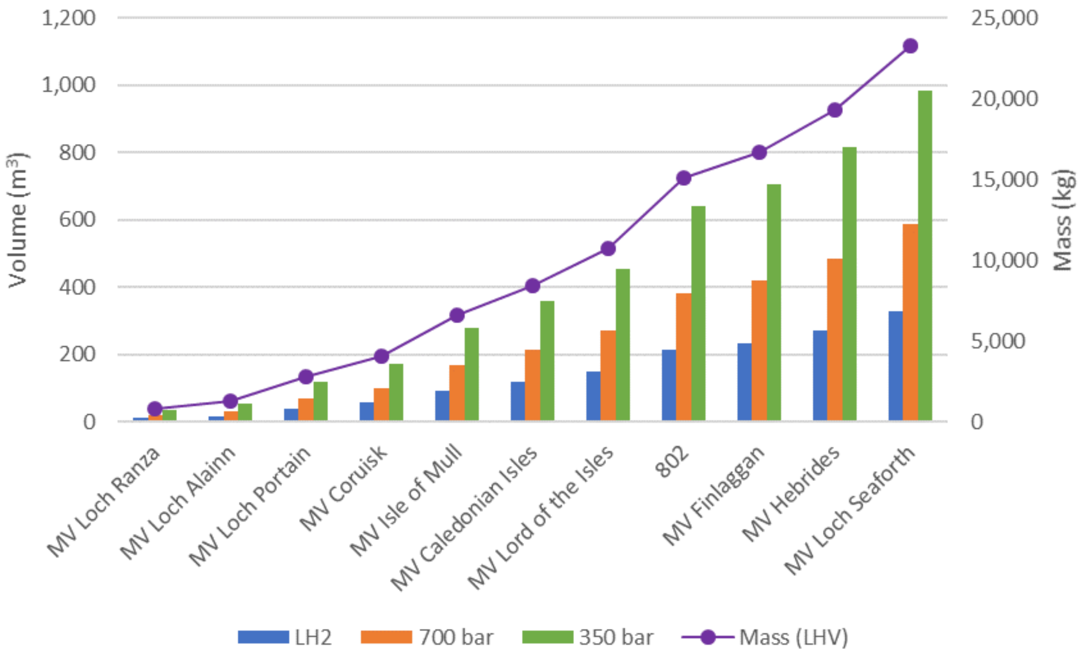


Figure 7-30 Thrice Weekly Bunkering Frequency

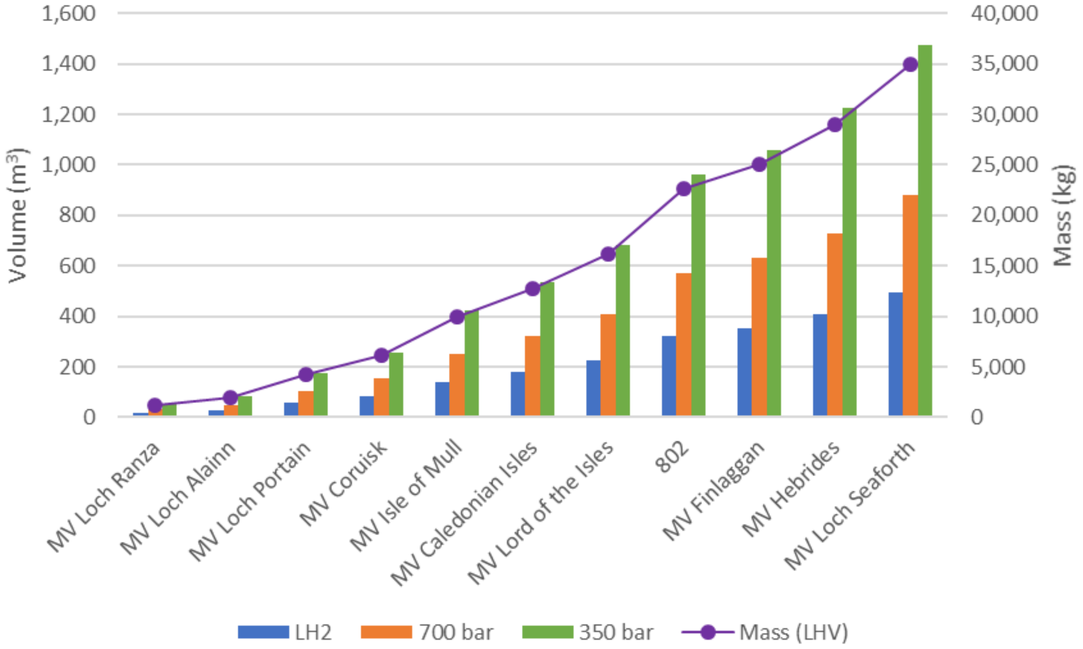


Figure 7-31 Twice Weekly Bunkering Frequency

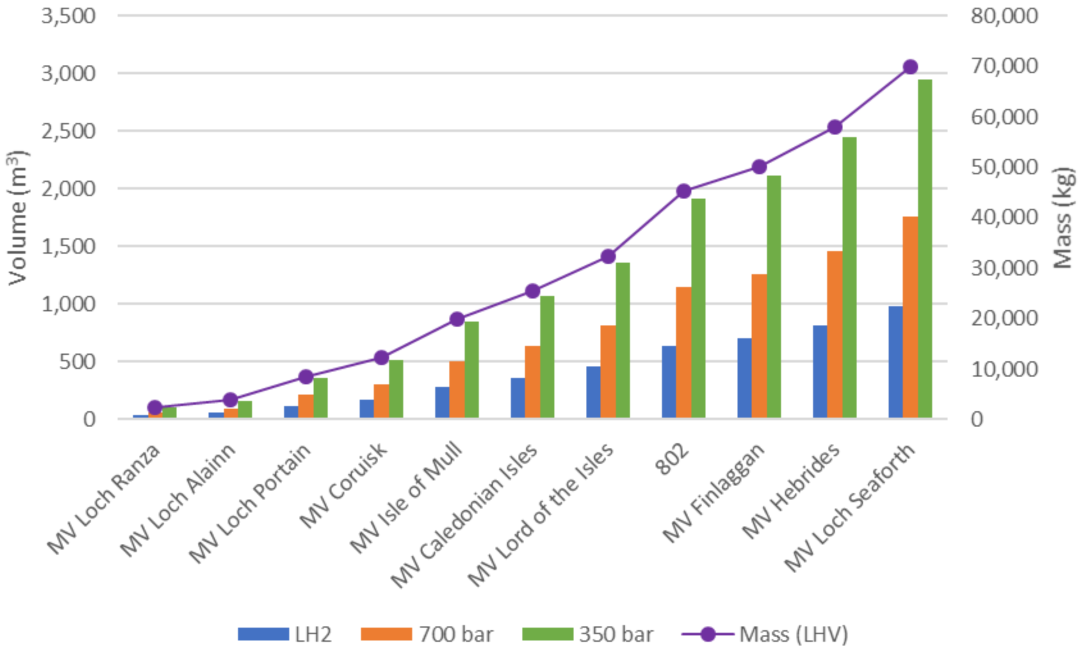


Figure 7-32 Weekly Bunkering Frequency

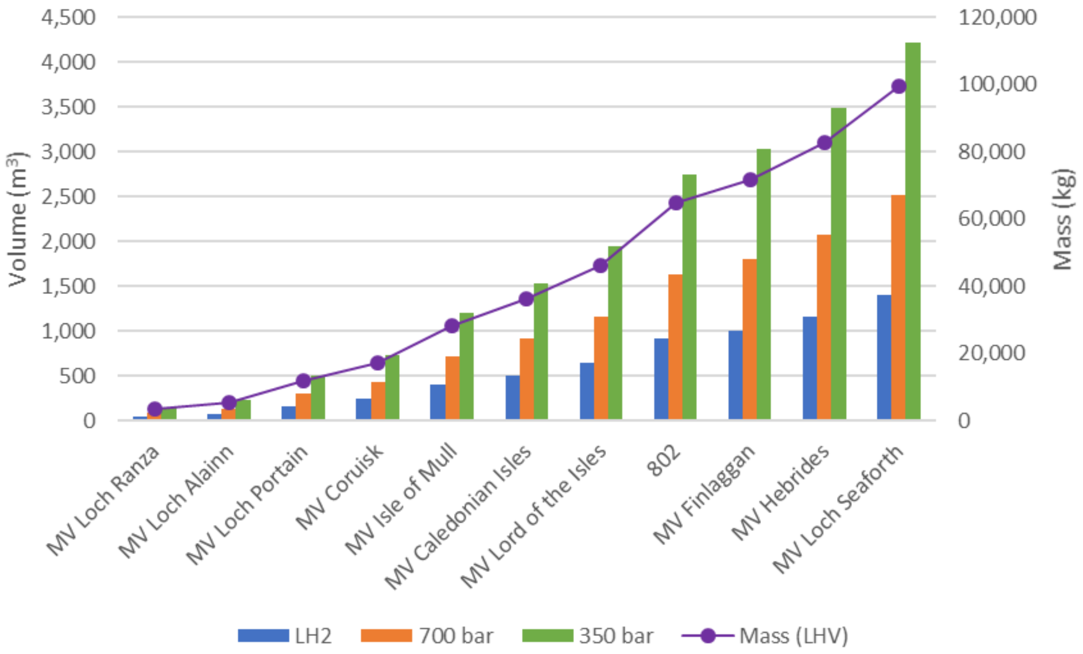


Figure 7-33 10 Day Bunkering Frequency

Appendix E WTG Specifications: SWT-DD-130

Rotor
Type .... 3-bladed, horizontal axis
Position .... Upwind
Diameter .... 130 m
Swept area .... 13,300 m²
Nominal speed .... 12.5 rpm
Operational speed range. 5.0 – 15.25 rpm
Power regulation .... Pitch regulation with variable speed
Rotor tilt .... 7.5 degrees

Blade
Type .... Self-supporting
Blade length .... 63 m
Maximum chord .... 4.2 m
Aerodynamic profile .... Siemens Gamesa Renewable Energy proprietary airfoils, DU-xx-W-xxx
Material .... GRE
Surface gloss .... Semi-gloss, < 30 / ISO2813
Surface color .... Light grey, RAL 7035 or White, RAL 9010

Aerodynamic Brake
Type .... Full span pitching
Activation .... Active, hydraulic

Load-Supporting Parts
Hub .... Nodular cast iron
Main shaft .... Nodular cast iron
Nacelle bed frame .... Nodular cast iron

Mechanical Brake
Type .... Hydraulic disc brake
Position .... Generator rear end

Canopy
Type .... Totally enclosed
Surface gloss .... Semi-gloss, 20-40 / ISO2813
Color .... Light grey, RAL 7035 or White, RAL 9010

Generator
Type .... Synchronous, PMG
Nominal power .... 4.5 MW

Grid Terminals (LV)
Nominal power .... 4.3 MW
Voltage .... 690 V
Frequency .... 50 Hz or 60 Hz

Yaw System
Type .... Active
Yaw bearing .... Externally geared
Yaw drive .... 12 electric gear motors
Yaw brake .... Passive friction brake

Controller
Type .... Siemens Integrated Control System (SICS)
SCADA system .... WPS

Tower
Type .... Tubular steel
Hub height .... 85–155 m, site-specific
Hybrid steel/concrete: 165m
Corrosion protection .... Painted
Surface gloss .... Semi-gloss, 20-40 / ISO2813
Color .... Light grey, RAL 7035 or White, RAL 9010

Operational Data
Cut-in wind speed .... 3 m/s
Nominal power at .... 13 m/s
Cut-out wind speed .... 28 m/s
Re-cut-in wind speed .... 23 m/s

Weights (approximately)
Blade .... 17 Metric tons
Rotor .... 96 Metric tons
Nacelle (split -) .... 33 Metric tons
Nacelle .... 103 Metric tons
Nacelle transport .... 106 Metric tons
Hub .... 45 Metric tons

Appendix F Wind Farm Sizing Analysis Results

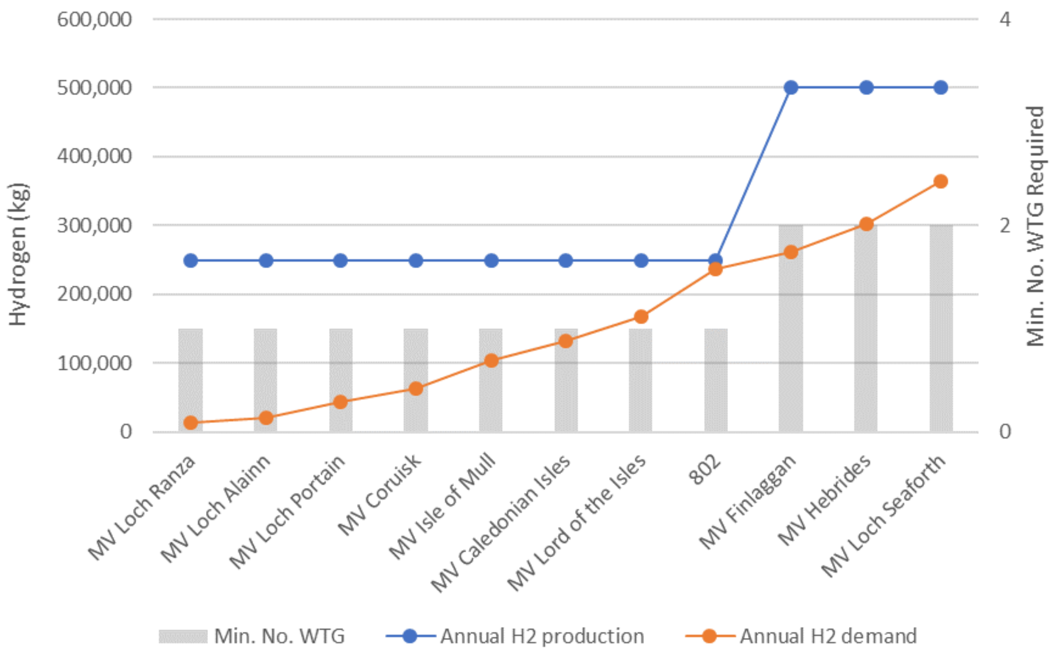


Figure 7-34 10% Hydrogen Delivery

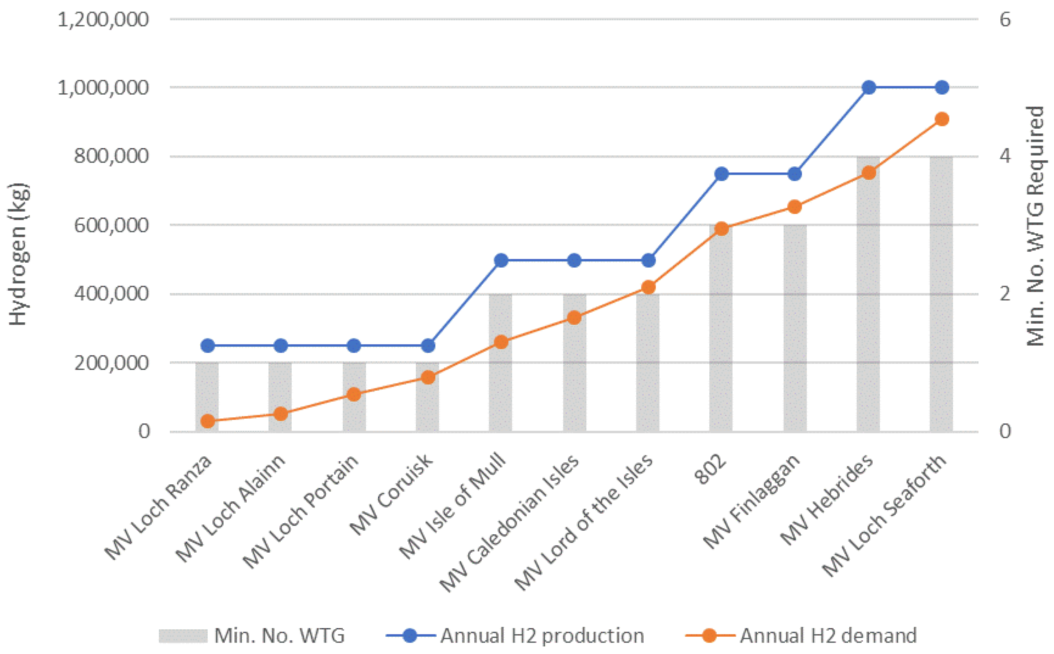


Figure 7-35 25% Hydrogen Delivery

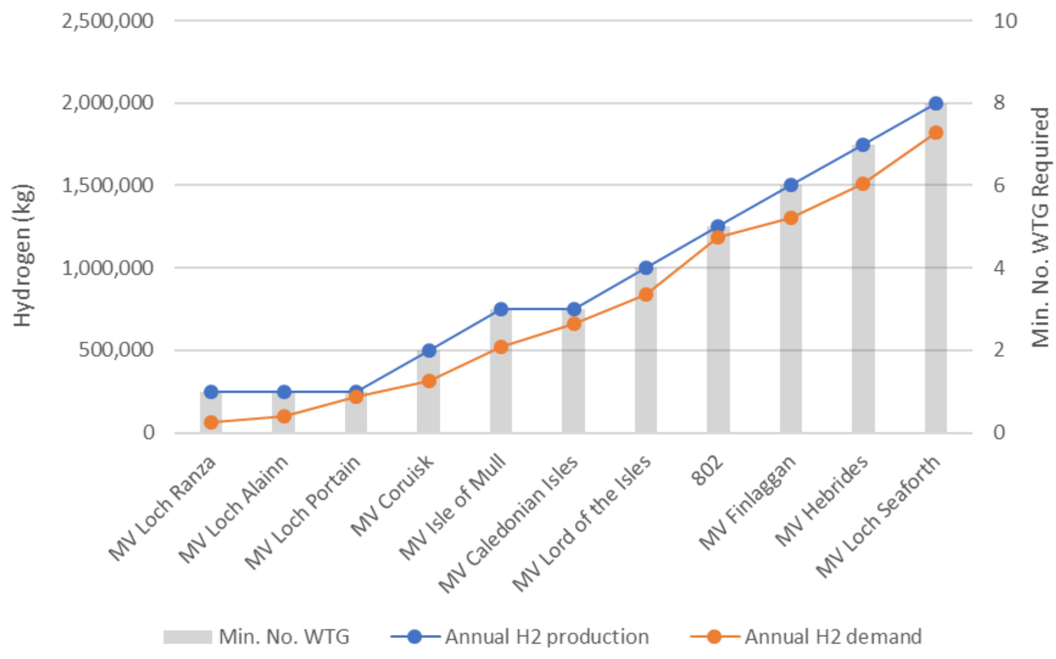


Figure 7-36 50% Hydrogen Delivery

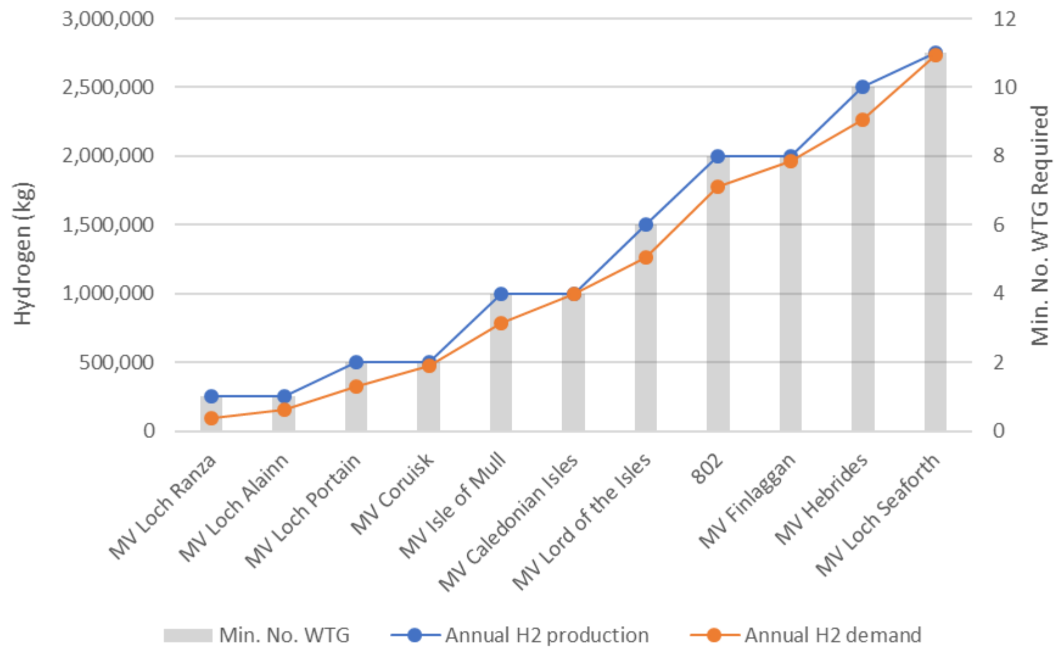


Figure 7-37 75% Hydrogen Delivery

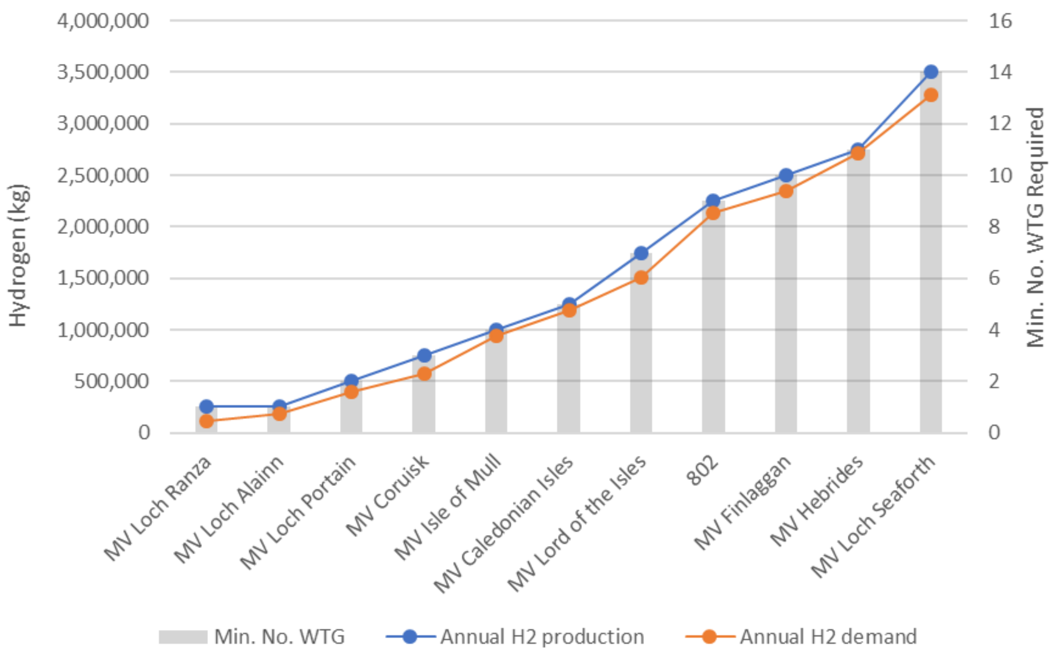


Figure 7-38 90% Hydrogen Delivery

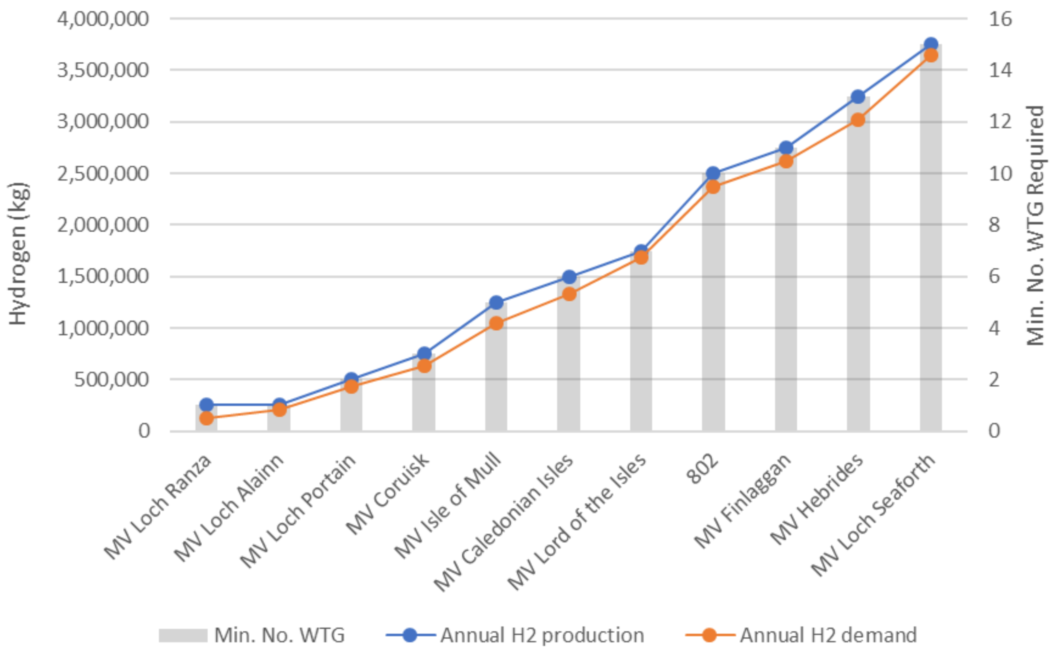


Figure 7-39 100% Hydrogen Delivery

Appendix G Barra Wind Farm Financial Assumptions

Parameter	Assumption	Source
Dates		
Financial Close	31 Mar 2020	Per Wood email 3/10/18
Operations Commence	01 Jan 2021	Wood Email 09/10/18 8-month construction period. Modelled 9 months to achieve consistency with period ends between options.
Operations Duration (yrs.)	25	P&S meeting 02/10/18
Operations End	31 Dec 2045	Model Output
Wind Generation		
Installed Capacity (MW)	4.30	Wood SWIFTH Inputs Tracker [v7]
Capacity Factor	46.90%	Wood SWIFTH Inputs Tracker [v7]
Annual Output P50 (MWh)	17,666	Wood SWIFTH Inputs Tracker [v7]
Hydrogen Production		
Daily H2 Demand (kg)	599	Wood SWIFTH Inputs Tracker [v7]
Electrolyser Efficiency	0.5552	Wood 'Hydrogen production calculator'
Lower Heating Value	119.93	Wood 'Hydrogen production calculator'
Conversion Factor (MJ to MWH)	3,600	Wood 'Hydrogen production calculator'
Exchange Rate		
£/€ Rate	1.134	Working Assumption
Escalation		
Rate	2.50%	Standard Assumption
Base Date	01 Apr 2018	Wood email 03/10/18 assume base date of April 18

Parameter	Assumption	Source
Uplift Periodicity (MThs)	12	Standard assumption
Debtors Terms		
Electrolyser Revenue (days)	30	Working Assumption
VAT Bridge Facility		
All-In Rate	3.50%	Based on observed terms in the market.
Arrangement Fee	1.50%	Based on observed terms in the market.
Commitment Fee	1.25%	Based on observed terms in the market.
Senior Debt		
Construction Period All-In	4.50%	Based on observed terms in the market.
Arrangement Fee	1.50%	Based on observed terms in the market.
Commitment Fee	1.25%	Based on observed terms in the market.
Target Gearing	80%	Based on P&S Beinn Ghrideag
Operations Period All-In	4.20%	Based on observed terms in the market.
DSCR Min Target	1.30	Based on observed terms in the market.
DSCR Avg Target	1.30	Based on observed terms in the market.
LLCR Min Target	1.30	Based on observed terms in the market.
LLCR Avg Target	1.30	Based on observed terms in the market.
Hedging	100%	Working Assumption
Repayment Period (yrs.)	15	Based on observed terms in the market.
Fixed DSRA	£150k	Based on debt repayment profile
Decommissioning Facility	Yes	Working Assumption

Parameter	Assumption	Source
Subordinated Debt		
All-in rate	8%	Based on P&S Beinn Ghrideag
Repayment Period	15 yrs.	Working Assumption
Accounting/Tax		
Tax Rate post April 2020	17%	Enacted rate
VAT	No VAT modelled on ops income and costs	Standard assumption on Projects of this nature.
Capital Allowances General Pool Rate	18%	Enacted rate
Interest Rate on Positive Cash Balances	0%	Working Assumption
Interest Rate on Overdraft Position	2.5%	Working Assumption
Operating Costs (Real £/Annum)		
WTG O&M	58,000	SWIFTH Inputs Tracker [v7]' - Lower £58k per WTG (1)
BOP O&M	1,800	SWIFTH Inputs Tracker [v7]' - Lower £1.8k per WTG (1)
Statutory Inspection	1,500	SWIFTH Inputs Tracker Lower [v7]' provided by Wood - £1.5k per WTG (1)
Asset Management	13,000	SWIFTH Inputs Tracker [v7]' provided by Wood-Lower £13k per WTG (1)
Electricity Consumed on site	1,400	SWIFTH Inputs Tracker [v7]' provided by Wood- Lower £1.4k per WTG (1)

Parameter	Assumption	Source
Meter Service Charge	1,500	SWIFTH Inputs Tracker [v7]' provided by Wood- Lower £1.5k per site (1)
Telecommunication Service Charge	1,500	SWIFTH Inputs Tracker [v7]' provided by Wood- Lower £1.5k per site (1)
Insurance	14,263	Per CMCD 11/10/18 prorate based on Beinn Ghrideag. £29,852*(4.3MW/9MW)
Land Rental	10,294	Per CMCD 11/10/18 prorate based on Beinn Ghrideag. £21,545*(4.3MW/9MW)
Accountancy	5,000	Based on P&S Beinn Ghrideag..
Legal Advisers	5,000	Based on P&S.Beinn Ghrideag.
Rates	-	Based on a rateable value of £95,385 and assuming this is a Community Project then 100% relief could be obtained. We have assumed that the electricity generation is for "distribution for sale to consumers" - assuming electrolyser is consumer.
Environmental Monitoring Survey Cost	5,000	SWIFTH Inputs Tracker [v7]' provided by Wood- £5k per site (1) per year for the first three years.
Contingency	2,316	3% of WTG O&M, BOP O&M, Stat Inspection, Asset Management, Electricity Consumed on Site, Meter Service Charge
Land Rental	2.5% of Gross Income	Per P&S – assume same as Point and Sandwick Wind farm.
Seasonality		
January	9.95%	Wood SWIFTH Inputs Tracker [v7]
February	8.88%	Wood SWIFTH Inputs Tracker [v7]

Parameter	Assumption	Source
March	9.21%	Wood SWIFTH Inputs Tracker [v7]
April	7.87%	Wood SWIFTH Inputs Tracker [v7]
May	7.32%	Wood SWIFTH Inputs Tracker [v7]
June	6.72%	Wood SWIFTH Inputs Tracker [v7]
July	6.36%	Wood SWIFTH Inputs Tracker [v7]
August	7.09%	Wood SWIFTH Inputs Tracker [v7]
September	8.19%	Wood SWIFTH Inputs Tracker [v7]
October	9.32%	Wood SWIFTH Inputs Tracker [v7]
November	9.29%	Wood SWIFTH Inputs Tracker [v7]
December	9.80%	Wood SWIFTH Inputs Tracker [v7]
Construction Costs		
Turbine Cost (£)	2,317,931	SWIFTH Inputs Tracker [v7] - £2.318m Per WTG (1)
BOP (civil and electrical) (£)	1,255,977	SWIFTH Inputs Tracker [v7] - £1.256m Per WTG (1)
Owner engineering cost (£)	101,250	SWIFTH Inputs Tracker [v7] - Lower £2,500 Per Week per WTG (1)
WF Connection to electrolyser (£)	527,000	SWIFTH Inputs Tracker [v7] - £227,000 + (£100,000 *3KM) = £527,000
Construction Management (£)	21,011	SWIFTH Inputs Tracker [v7] - 0.5% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £4.20m * 0.5%

Parameter	Assumption	Source
Other Capex (£)	420,216	SWIFTH Inputs Tracker [v7] - Lower 10% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £4.20m * 10%
Contingency (£)	210,108	SWIFTH Inputs Tracker [v7] - 5% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £4.20m * 5%
Bank Monitoring Fee	5,000	JC Assumption

Appendix H Stornoway Wind Farm Financial Assumptions

Parameter	Assumption	Source
Dates		
Financial Close	31 Mar 2020	Per Wood email 3/10/18
Operations Commence	01 Jan 2022	Wood Email 09/10/18' 15-20 months Construction period. Modelled 21 months to achieve consistency with period ends between scenarios.
Operations Duration (yr.)	25	P&S meeting 02/10/18
Operations End	31 Dec 2046	Model Output
Wind Generation		
Installed Capacity (MW)	64.5	Wood SWIFTH Inputs Tracker [v7]
Capacity Factor	42.50%	Wood SWIFTH Inputs Tracker [v7]
Annual Output P50 (MWh)	240,134	Wood SWIFTH Inputs Tracker [v7]
Hydrogen Production		
Daily H2 Demand (kg)	10,063	Wood SWIFTH Inputs Tracker [v7]
Electrolyser Efficiency %	0.5552	'Hydrogen production calculator' provided by Wood
Lower Heating Value	119.93	'Hydrogen production calculator' provided by Wood
Conversion Factor (MJ to MWH)	3,600	'Hydrogen production calculator' provided by Wood
Exchange Rate		
£/€ Rate	1.134	Working Assumption
Escalation		
Rate	2.50%	Standard Assumption

Parameter	Assumption	Source
Base Date	01 Apr 2018	Wood email 03/10/18
Uplift Periodicity (MThs)	12	Working Assumption
Debtors Terms		
electrolyser Revenue (days)	30	Working Assumption
VAT Bridge Facility		
All-In Rate	3.50%	Based on observed terms in the market.
Arrangement Fee	1.50%	Based on observed terms in the market.
Commitment Fee	1.25%	Based on observed terms in the market.
Senior Debt		
Construction Period All-In	4.50%	Based on observed terms in the market.
Arrangement Fee	1.50%	Based on observed terms in the market.
Commitment Fee	1.25%	Based on observed terms in the market.
Target Gearing	80%	Based on P&S Beinn Ghrideag
Operations Period All-In	4.20%	Based on Observed Rates in Market
DSCR Min Target	1.30	Based on observed terms in the market.
DSCR Avg Target	1.30	Based on observed terms in the market.
LLCR Min Target	1.30	Based on observed terms in the market.

Parameter	Assumption	Source
LLCR Avg Target	1.30	Based on observed terms in the market.
Repayment Period	15 yrs.	Based on observed terms in the market.
Fixed DSRA	£2.5m	Working Assumption based on debt repayment profile
Decommissioning Facility	Yes	Working Assumption
Subordinated Debt		
All-in rate	8%	Based on P&S Beinn Ghrideag
Repayment Period	15 yrs.	Working Assumption
Accounting/Tax		
Tax Rate post April 2020	17%	Enacted rate
VAT	No VAT modelled on ops income and costs	Standard assumption on Projects of this nature.
Capital Allowances General Pool Rate	18%	Enacted rate
Interest Rate on Positive Cash Balances	0%	Prudent Assumption
Interest Rate on Overdraft Position	2.5%	Prudent Assumption
Operating Costs (Real £/Annum)		
WTG O&M	870,000	SWIFTH Inputs Tracker [v7]' - £58k per WTG (15)
BOP O&M	27,000	SWIFTH Inputs Tracker [v7]' - Lower £1.8k per WTG (15)

Parameter	Assumption	Source
Statutory Inspection	22,500	SWIFTH Inputs Tracker [v7]' - Lower £1.5k per WTG (15)
Asset Management	195,000	SWIFTH Inputs Tracker [v7]' - Lower £13k per WTG (15)
Electricity Consumed on site	21,000	SWIFTH Inputs Tracker [v7]' - Lower £1.4k per WTG (15)
Meter Service Charge	1,500	SWIFTH Inputs Tracker [v7]' - Lower £1.5k per site (1)
Telecommunication Service Charge	1,500	SWIFTH Inputs Tracker [v7]' - Lower £1.5k per site (1)
Insurance	213,939	Per CMCD 11/10/18 prorate based on Beinn Ghrideag £29,852*(64.5MW/9MW)
Land Rental	154,406	Per CMCD 11/10/18 prorate based on Beinn Ghrideag £21,545*(64.5MW/9MW)
Accountancy	5,000	Based on P&S Beinn Ghrideag
Legal Advisers	5,000	Based on P&S Beinn Ghrideag
Rates	469,295	Based on a rateable value of £1,086,332 a poundage rate of .48 and 10% relief based on it being a renewable project. We have assumed that the electricity generation is for "distribution for sale to consumers" - assuming Electrolyser is consumer.
Environmental Monitoring Survey Cost	5,000	SWIFTH Inputs Tracker [v4]' - £5k per site (1) per year for the first three years.

Parameter	Assumption	Source
Contingency	34,110	3% of WTG O&M, BOP O&M, Stat Inspection, Asset Management, Electricity Consumed on Site, Meter Service Charge
Land Rental	2.5% of Gross Income	Per Beinn Ghrideag – assume same as Point and Sandwick Wind farm.
Seasonality		
January	9.12%	Wood SWIFTH Inputs Tracker [v7]
February	8.20%	Wood SWIFTH Inputs Tracker [v7]
March	8.79%	Wood SWIFTH Inputs Tracker [v7]
April	8.09%	Wood SWIFTH Inputs Tracker [v7]
May	7.99%	Wood SWIFTH Inputs Tracker [v7]
June	7.62%	Wood SWIFTH Inputs Tracker [v7]
July	7.64%	Wood SWIFTH Inputs Tracker [v7]
August	7.92%	Wood SWIFTH Inputs Tracker [v7]
September	8.14%	Wood SWIFTH Inputs Tracker [v7]
October	8.80%	Wood SWIFTH Inputs Tracker [v7]
November	8.63%	Wood SWIFTH Inputs Tracker [v7]
December	9.04%	Wood SWIFTH Inputs Tracker [v7]
Construction Costs		
Turbine Cost (£)	34,768,965	SWIFTH Inputs Tracker [v7] - £2.318m Per WTG (15)
BOP (civil and electrical) (£)	18,839,655	SWIFTH Inputs Tracker [v7] - £1.256m Per WTG (15)

Parameter	Assumption	Source
Owner engineering cost (£)	3,543,750	SWIFTH Inputs Tracker [v7] - Lower £2,500 Per Week Per WTG (15)
WF Connection to electrolyser (£)	1,227,000	SWIFTH Inputs Tracker [v7] - £227,000 + (£100,000 *10KM(lower)) = £1,227,000
Construction Management (£)	291,897	SWIFTH Inputs Tracker [v7] - 0.5% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £58.4m * 0.5%
Other Capex (£)	5,837,937	SWIFTH Inputs Tracker [v7] - Lower 10% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £58.4m * 10%
Contingency (£)	2,918,969	SWIFTH Inputs Tracker [v7] - 5% of Capex (Assuming Turbine Cost, BOP, Owner Engineering and WF Connection to Electrolyser) exc Contingency = £58.4m * 5%
Bank Monitoring Fee (£)	10,000	Working Assumption - £5K per annum paid in advance

Appendix I Barra Electrolyser Financial Assumptions

Parameter	Assumption	Source
Dates		
Financial Close	31 Mar 2020	Per Wood email 3/10/18
Operations Commence	01 Jan 2021	ITM email 09/10/18 indicated '12 months from order to delivery and a further 2 months for installation, commissioning and integration'. For modelling purposes condensed to 9 months to mirror timing for Wind farm construction and in theory the electrolyser could be ordered before FC. For this modelling exercise we just need to ensure that all construction costs are included within the Model. The timing of these payments will have minimal impact at this feasibility stage.
Operations Duration (yrs.')	25	P&S meeting 02/10/18
Operations End	31 Dec 2045	Model Output
Hydrogen Production		
Daily H2 Demand (kg)	599	Wood SWIFTH Inputs Tracker [v7]
Electrolyser Efficiency	0.5552	'Hydrogen production calculator' provided by Wood
Lower Heating Value	119.93	'Hydrogen production calculator' provided by Wood
Conversion Factor (MJ to MWH)	3,600	'Hydrogen production calculator' provided by Wood
Marine Gas Oil (MGO)		
Existing Cost per kWh	50p	CalMac email 24/10/18

Parameter	Assumption	Source
Primary Energy Supply - MGO (kWh per day)	25,393	Wood email 1/12/18
Primary Energy Supply - H2 (kWh per day)	19,955	Wood email 1/12/18
Existing Energy Usage (MGO) per Day (KWh)	6,186	CalMac email 24/10/18
Energy Usage (Hydrogen) per Day (kWh)	7,984	Wood email 25/10/18
electrolyser efficiency for conversion	40%	Wood email 25/10/18
Litres of MGO used per Hour	100	Calmac email 24/10/18
Exchange Rate		
£/€ Rate	1.134	Working Assumption
Escalation		
Base Date	01 Apr 2018	Wood email 03/10/18 assume base date of April 18
Uplift Periodicity (MThs)	12	Working Assumption
Debtors Terms		
electrolyser Revenue (days)	30	Working Assumption
VAT Bridge Facility		
All-In Rate	3.5%	Prudent working assumption in absence of comparable Projects
Arrangement Fee	1.50%	Prudent working assumption in absence of comparable Projects

Parameter	Assumption	Source
Commitment Fee	1.25%	Prudent working assumption in absence of comparable Projects
Senior Debt		
Construction Period All-In	5%	Prudent working assumption in absence of comparable Projects
Arrangement Fee	1.50%	Prudent working assumption in absence of comparable Projects
Commitment Fee	1.25%	Prudent working assumption in absence of comparable Projects
Target Gearing	80%	Prudent working assumption in absence of comparable Projects
Operations Period All-In	4.70%	Prudent working assumption in absence of comparable Projects
DSCR Min Target	1.40	Prudent working assumption in absence of comparable Projects
DSCR Avg Target	1.40	Prudent working assumption in absence of comparable Projects
LLCR Min Target	1.40	Prudent working assumption in absence of comparable Projects
LLCR Avg Target	1.40	Prudent working assumption in absence of comparable Projects
Repayment Period	15 yrs.	Prudent working assumption in absence of comparable Projects
Hedging	100%	Prudent working assumption in absence of comparable Projects
Fixed DSRA	£220k	Working Assumption
Decommissioning Facility	Yes	Working Assumption

Parameter	Assumption	Source
Subordinated Debt		
All-in rate	N/A	Working Assumption that pure equity injected.
Repayment Period	N/A	Working Assumption that pure equity injected.
Accounting/Tax		
Tax Rate post April 2020	17%	Enacted rate
VAT	No VAT modelled on ops income and costs	Standard assumption on Projects of this nature as
Capital Allowances General Pool Rate	18%	Enacted rate
Capital Allowances Special Rate Pool	8%	Enacted rate
Interest Rate on Positive Cash Balances	0%	Prudent Assumption
Interest Rate on Overdraft Position	2.5%	Prudent Assumption
Operating Costs (Real £/Annum)		
electrolyser Annual Maintenance	32,945	SWIFTH Inputs Tracker [v7]' provided by Wood– Lower 2% of electrolyser Capital Cost
Compressor C1 Annual Maintenance	5,291	SWIFTH Inputs Tracker [v7]' provided by Wood - 1% of C1 Capital Cost
Compressor C2 Annual Maintenance	14,109	SWIFTH Inputs Tracker [v7]' - 1% of C2 Capital Costs

Parameter	Assumption	Source
Telecommunication Service Charge	2,500	SWIFTH Inputs Tracker [v7]' provided by Wood- £2,500 for Wind farm site. Modelled same for electrolyser
Insurance.	20,000	No cost provided. We have no comparator information available thus have included a working assumption of £20k.
Accountancy	5,000	Working Assumption based on P&S Beinn Ghrideag
Legal Advisers	5,000	Working Assumption based on P&S Beinn Ghrideag
Rates	50,000	Assessor unable to provide indicative cost. We have modelled £50k for Barra.
Water Standing Charge	1,000	Wood provided estimate at £142.91 per year (14/10/18). We have rounded to nearest £1k for prudence.
Contingency (5% of all costs)		
Assumed 5% of Costs given lack of detail on some costs.	6,792	Assumed 5% of Costs given lack of detail on some costs.
Water	£0.06/kg H2	Wood provided range of £0.8042 to £2.1442 £/M3 (14/10/18). ITM confirmed 28 litres of water for every kg of H2 produced (11/10/18). 0.028 m3 per kg Produced. Therefore, cost per kg is (£2.1442/1000 *28)

Parameter	Assumption	Source
Land Rental	3.5% of Gross Income	No input provided. Working Assumption based on P&S Beinn Ghrideag (2.5%) plus 1% for prudence.
Construction Costs		
Electrolyser (£)	1,647,250	Wood SWIFTH Inputs Tracker [v7]
20 Bar Buffer Storage (euros)	5,000	Wood SWIFTH Inputs Tracker [v7]
200 Bar Pier Storage (euros)	300,000	Wood SWIFTH Inputs Tracker [v7]
Dispenser (euros)	250,000	Wood SWIFTH Inputs Tracker [v7]
Compressor C1 (euros)	600,000	SWIFTH Inputs Tracker [v7] lower - provided by Wood
Compressor C2 (euros)	1,600,000	SWIFTH Inputs Tracker [v7] lower- provided by Wood
Shore Side Integration Costs (£)	611,505	SWIFTH Inputs Tracker [v7] Lower – provided by Wood. Sum of electrolyser,20 Bar Storage, 200 Bar Storage, Dispenser(s), C1 and C2 all multiplied by 0.15
electrolyser Connection to Dispenser (£)	9,400	Per ITM Power email 09/10/19 £3,100 for non-civils. Per Wood email 10/10/18 £7,500 for Civils. Wood indicated that ITM's cost includes £1,200 of costs that have been included within Wood's civils estimate thus ITM (£3,100-£1,200=£1,900) + Wood (£7,500) is £9,400
Contingency (£)	150,413	Included 3% Contingency on all costs to mirror contingency on Wind Model

Parameter	Assumption	Source
Bank Monitoring Fee (£)	5,000	Working Assumption - £5000 paid in advance per annum
RTFO – For RTFO Scenario		
Fuel not subject to obligation (L)	450,000	RTFO - guidance - part - 1 - process - guidance - year 11'
Conversion factor for L to kg	4.58	RTFO - guidance - part - 1 - process - guidance - year 11'
Fuel not subject to Obligation	98,253	450,000 litres/4.58
First Obligation Period	01 Jan 2022	First Ops Period
End of Obligation Period	31 Dec 2032	RTFO - guidance - part - 1 - process - guidance - year 11' - last year of outlined obligation periods. Assumed ends thereafter for prudency.
Renewable Transport Fuel Certificates per kg	9.16	RTFO - guidance - part - 1 - process - guidance - year 11' - Clause 1.14. 9.16 RTFC's per kg from Hydrogen made from renewable energy.
£ per RTFC	£0.40	50% of Buy-Out Price per 'RTFO Guidance Part 1 – Year 11'
RTFC Inflation Profile	Nil	Prudent Position
RTFC Debtor Days	90	Prudent Position

Parameter	Assumption	Source
Percentage of RTFC's sold	Profile	50% of the obligation Per Table 2 on Page 22 of the 'RTFO Guidance Part 1 – Year 11'. This is on the basis that the RFNBO would count double towards the target consequently the electrolyser company would need to redeem half of the amount of RTFC's shown in Table 2 to meet its own obligation.

Appendix J Stornoway Electrolyser Financial Assumptions

Parameter	Assumption	Source
Dates		
Financial Close	31 Mar 2020	Per Wood email 3/10/18
Operations Commence	01 Jan 2022	ITM email 09/10/18 indicated '12 months from order to delivery and a further 2 months for installation, commissioning and integration'. The construction period modelled here is longer than this in order that we can mirror the dates per the Wind farm. For this modelling exercise we just need to ensure that all construction costs are included within the Model. The timing of these payments will have minimal impact at this feasibility stage.
Operations Duration (yrs.)	25	P&S meeting 02/10/18
Operations End	31 Dec 2046	Model Output
Hydrogen Production		
Daily H2 Demand (kg)	10,063	Wood SWIFTH Inputs Tracker [v7]
electrolyser Efficiency (%)	0.5552	Hydrogen production calculator provided by Wood
Lower Heating Value	119.93	Hydrogen production calculator provided by Wood

Parameter	Assumption	Source
Conversion Factor (MJ to MWH)	3,600	Hydrogen production calculator provided by Wood
Marine Gas Oil (MGO)		
Existing Cost per KWh	50p	CalMac email 24/10/18
Primary Energy Supply – MGO (kWh/day)	364,395	Wood email 1/12/18
Primary Energy Supply – H2 (kWh/day)	335,238	Wood email 1/12/18
Existing Energy Usage (MGO) per Day (KWh)	110,700	CalMac email 25/10/18
Energy Usage (Hydrogen) per Day (KWh)	134,100	Wood email 25/10/18
electrolyser efficiency for conversion	40%	Wood email 25/10/18
Litres of MGO used per Hour	1,435	CalMac email 24/10/18
Exchange Rate		
£/€ Rate	1.134	Working Assumption
Escalation		
Rate	2.50%	Standard
Base Date	01 Apr 2018	Wood email 03/10/18 assume base date of April 18
Uplift Periodicity (MThs)	12	Working Assumption

Parameter	Assumption	Source
Debtors Terms		
electrolyser Revenue (days)	30	Working Assumption
VAT Bridge Facility		
All-In Rate	3.5%	Observed Rates in Market
Arrangement Fee	1.50%	Observed Rates in Market
Commitment Fee	1.25%	Observed Rates in Market
Senior Debt		
Construction Period All-In	5%	Prudent working assumption in absence of comparable Projects
Arrangement Fee	1.50%	Prudent working assumption in absence of comparable Projects
Commitment Fee	1.25%	Prudent working assumption in absence of comparable Projects
Target Gearing	80%	Prudent working assumption in absence of comparable Projects
Operations Period All-In	4.70%	Prudent working assumption in absence of comparable Projects
DSCR Min Target	1.40	Prudent working assumption in absence of comparable Projects
DSCR Avg Target	1.40	Prudent working assumption in absence of comparable Projects

Parameter	Assumption	Source
LLCR Min Target	1.40	Prudent working assumption in absence of comparable Projects
LLCR Avg Target	1.40	Prudent working assumption in absence of comparable Projects
Repayment Period	15 yrs.	Prudent working assumption in absence of comparable Projects
Fixed DSRA	£1.8m	Working Assumption based on Debt Capacity
Hedging	100%	Working Assumption
Decommissioning Facility	Yes	Working Assumption
Accounting/Tax		
Tax Rate post April 2020	17%	Enacted rate
VAT	No VAT modelled on ops income and costs	Standard assumption on Projects of this nature.
Capital Allowances General Pool Rate	18%	Enacted rate
Interest Rate on Positive Cash Balances	0%	Prudent Assumption
Interest Rate on Overdraft Position	2.5%	Prudent Assumption
Operating Costs (Real £/Annum)		
electrolyser Annual Maintenance	352,205	SWIFTH Inputs Tracker [v7]' – Lower 2% of electrolyser Capital Cost

Parameter	Assumption	Source
Compressor C1 Annual Maintenance	31,111	SWIFTH Inputs Tracker [v7]' - 1% of C1 Capital Cost
Compressor C2 Annual Maintenance	106,667	SWIFTH Inputs Tracker [v7]' - 1% of C2 Capital Costs
Telecommunication Service Charge	2,500	SWIFTH Inputs Tracker [v7]' - £2,500 for Wind farm site. Modelled same for electrolyser
Insurance	40,000	No cost provided. We have assumed £20k for Barra. Owing to the additional storage requirements for the bigger Project we have doubled the modelled Barra Costs (2*£20k).
Accountancy	5,000	Working Assumption based on P&S
Legal Advisers	5,000	Working Assumption based on P&S
Rates	100,000	Assessor unable to provide indicative cost. We have modelled £50k for Barra. Owing to the additional storage requirements we would expect this cost to be higher. We have doubled the rates cost modelled for Barra (£50k x2) as a prudent position.

Parameter	Assumption	Source
Water Standing Charge	1,000	Wood provided estimate at £142.91 per year (14/10/18). We have rounded to nearest £1k for prudence).
Contingency (5% of all costs)	32,174	Assumed 5% of Costs given lack of detail on some costs.
Water	£0.06/kg H2	Wood provided range of £0.8042 to £2.1442 £/M3 (14/10/18). ITM confirmed 28 litres of water for every kg of H2 produced (11/10/18). 0.028 m3 per kg Produced. Therefore, cost per kg is (£2.1442/1000 *28)
Land Rental	3.5% of Gross Income	No input provided. Working Assumption based on P&S (2.5%) plus 1% for prudence.
Construction Costs		
Electrolyser (£)	17,610,250	Wood SWIFTH Inputs Tracker [v7]
20 Bar Buffer Storage (euros)	80,000	Wood SWIFTH Inputs Tracker [v7]
200 Bar Pier Storage (euros)	5,000,000	Wood SWIFTH Inputs Tracker [v7]
Dispenser (euros)	900,000	Wood SWIFTH Inputs Tracker [v7]

Parameter	Assumption	Source
Compressor C1 (euros)	3,500,000	SWIFTH Inputs Tracker [v7] lower -provided by Wood
Compressor C2 (euros)	12,000,000	SWIFTH Inputs Tracker [v7] lower-provided by Wood
Shore Side Integration Costs (£)	5,505,538	SWIFTH Inputs Tracker [v7] Lower – provided by Wood. Sum of electrolyser,20 Bar Storage, 200 Bar Storage, Dispenser(s), C1 and C2 all multiplied by 0.15
Electrolyser Connection to Dispenser (£)	9,400	Per ITM Power email 09/10/19 £3,100 for non-civils. Per Wood email 10/10/18 £7,500 for Civils. Wood indicated that ITM's cost includes £1,200 of costs that have been included within Wood's civils estimate thus ITM (£3,100-£1,200=£1,900) + Wood (£7,500) is £9,400
Contingency (£)	1,266,556	Included 3% Contingency on all costs to mirror contingency on Wind Model
Bank Monitoring Fee (£)	10,000	Working Assumption - £5000 paid in advance per annum. X2 in construction period.

Parameter	Assumption	Source
RTFO – For RTFO Scenario		
Fuel not subject to obligation (L)	450,000	RTFO - guidance - part - 1 - process - guidance - year 11'
Conversion factor for L to kg	4.58	RTFO - guidance - part - 1 - process - guidance - year 11'
Fuel not subject to Obligation	98,253	450,000 litres/4.58
First Obligation Period	01 Jan 2022	First Ops Period
End of Obligation Period	31 Dec 2032	RTFO - guidance - part - 1 - process - guidance - year 11' - last year of outlined obligation periods. Assumed ends thereafter for prudency.
Renewable Transport Fuel Certificates per kg	9.16	RTFO - guidance - part - 1 - process - guidance - year 11' - Clause 1.14. 9.16 RTFC's per kg from hydrogen made from renewable energy.
£ per RTFC	£0.40	50% of Buy-Out Price per 'RTFO Guidance Part 1 – Year 11'
RTFC Inflation Profile	Nil	Prudent Position
RTFC Debtor Days	90	Prudent Position

Parameter	Assumption	Source
Percentage of RTFC's sold	Profile	50% of the obligation Per Table 2 on Page 22 of the 'RTFO Guidance Part 1 – Year 11'. This is on basis that the RFNBO would count double towards the target consequently the electrolyser company would need to redeem half of the amount of RTFC's shown in Table 2 to meet its own obligation.

Appendix K Land-use and Planning Constraints Maps

The following LPA spatial guidance for WTG development maps contain OS data © Crown copyright and database right (2018).

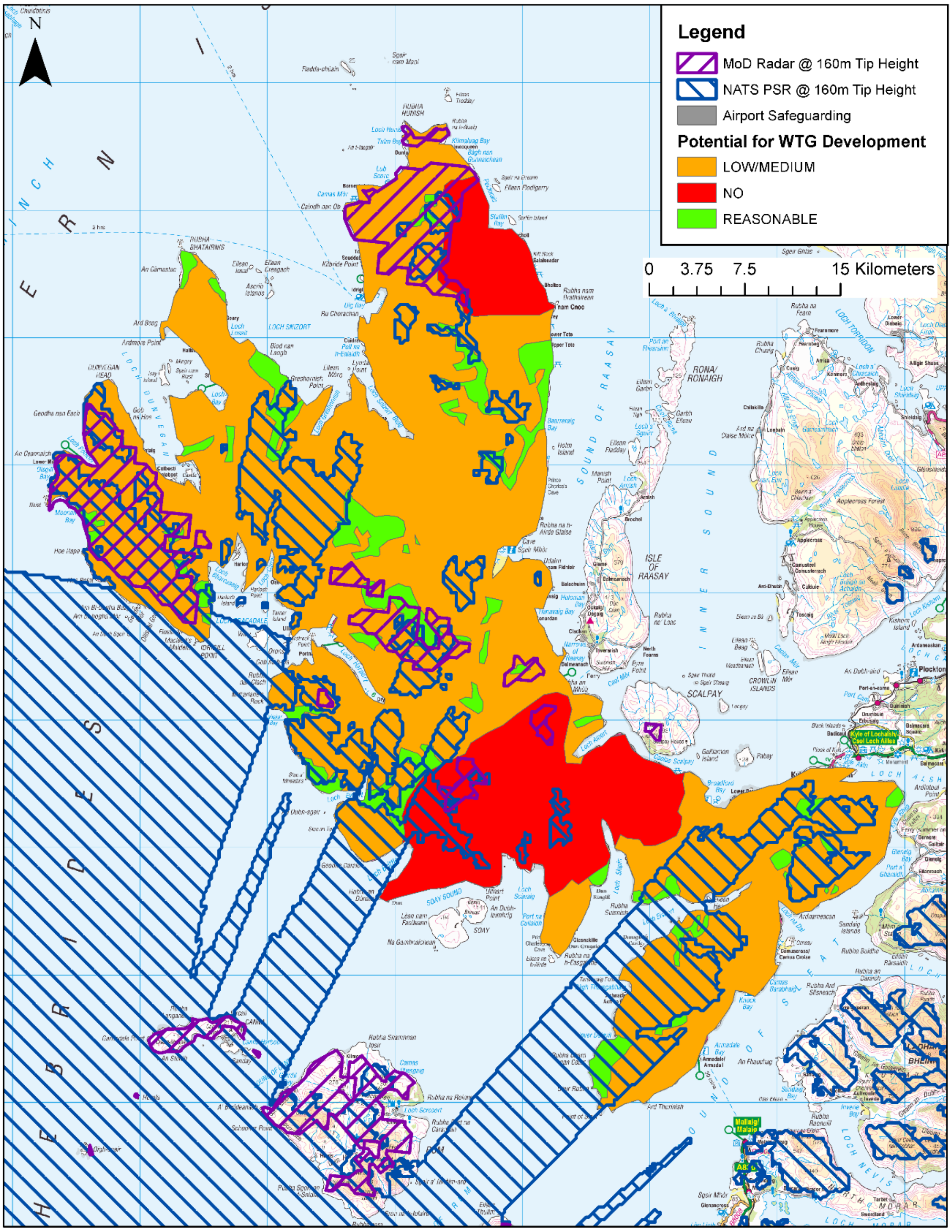


Figure 7-40 Aviation Constraints (Skye)

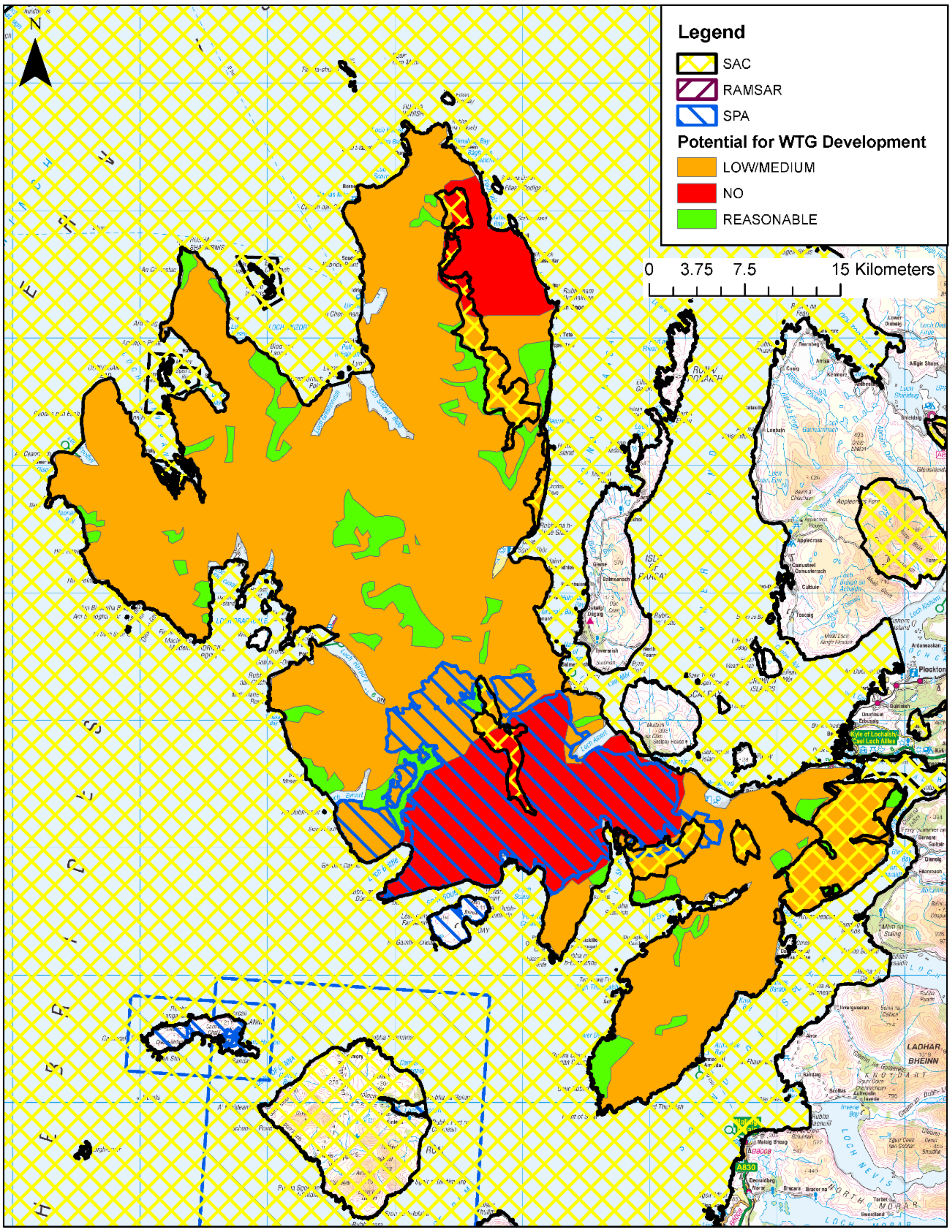


Figure 7-41 Environmental Designations (Skye)

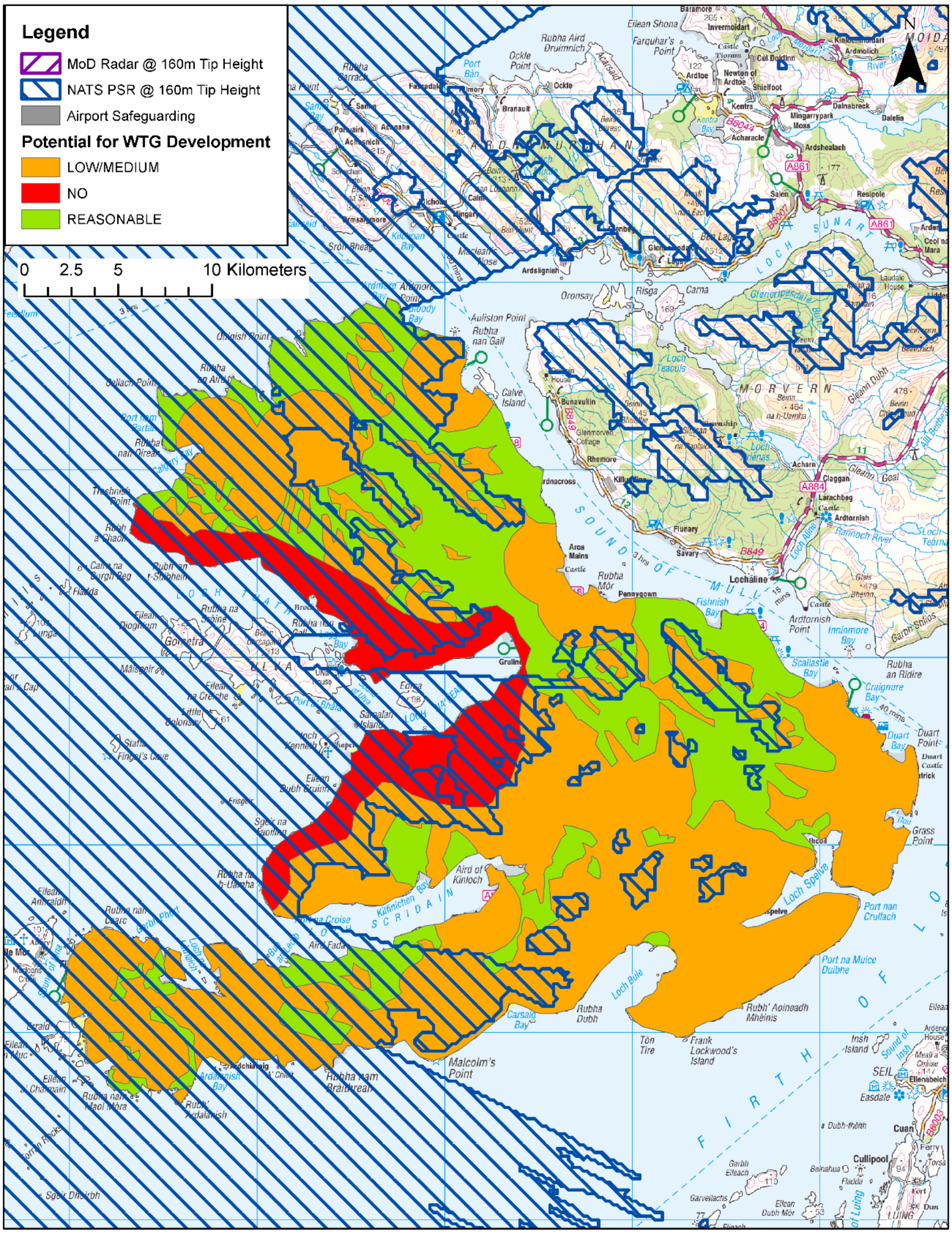


Figure 7-42 Aviation Constraints (Mull)

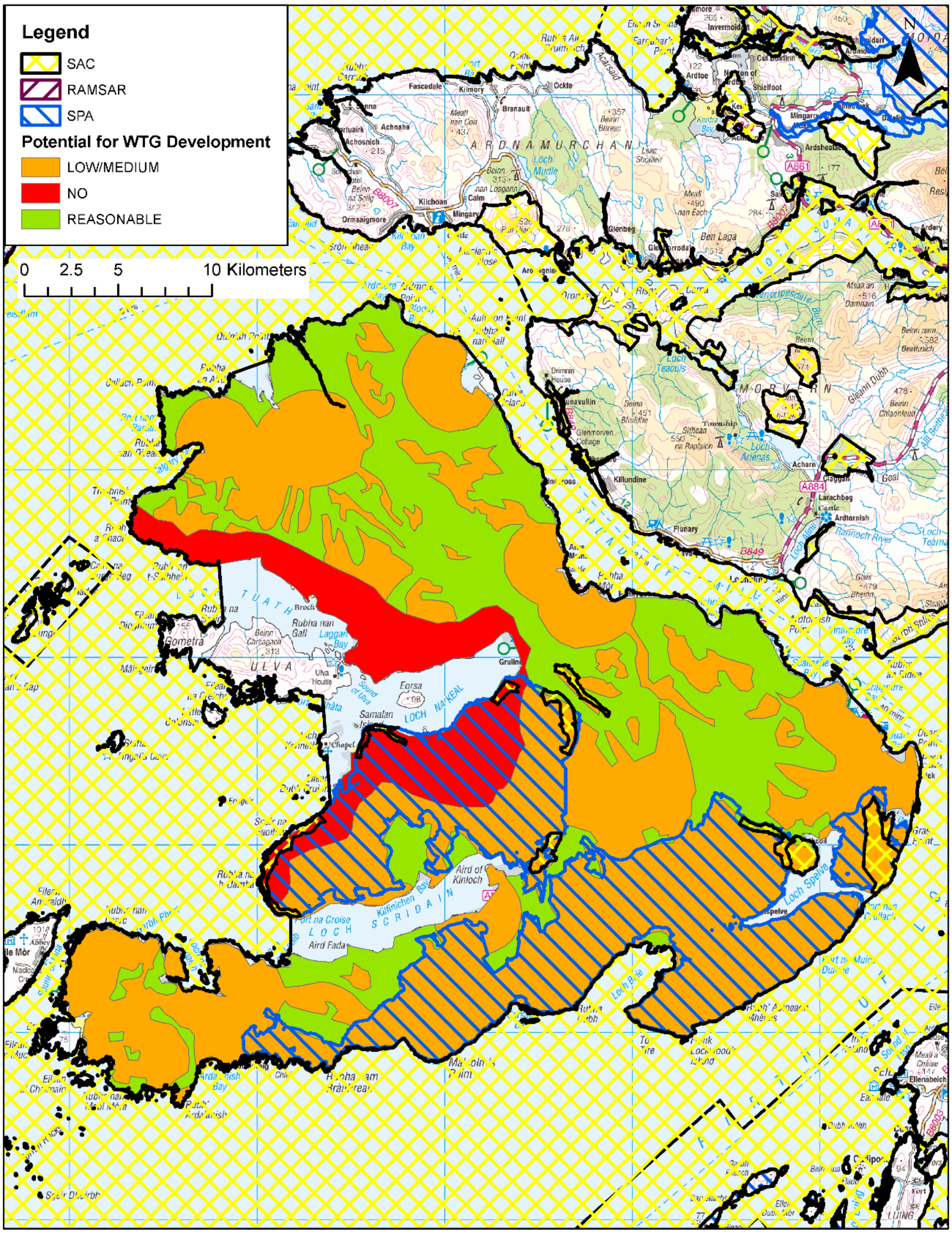


Figure 7-43 Environmental Designations (Mull)

Figure 7-44 Aviation Constraints (Gigha)

Figure 7-45 Environmental Designations (Gigha)

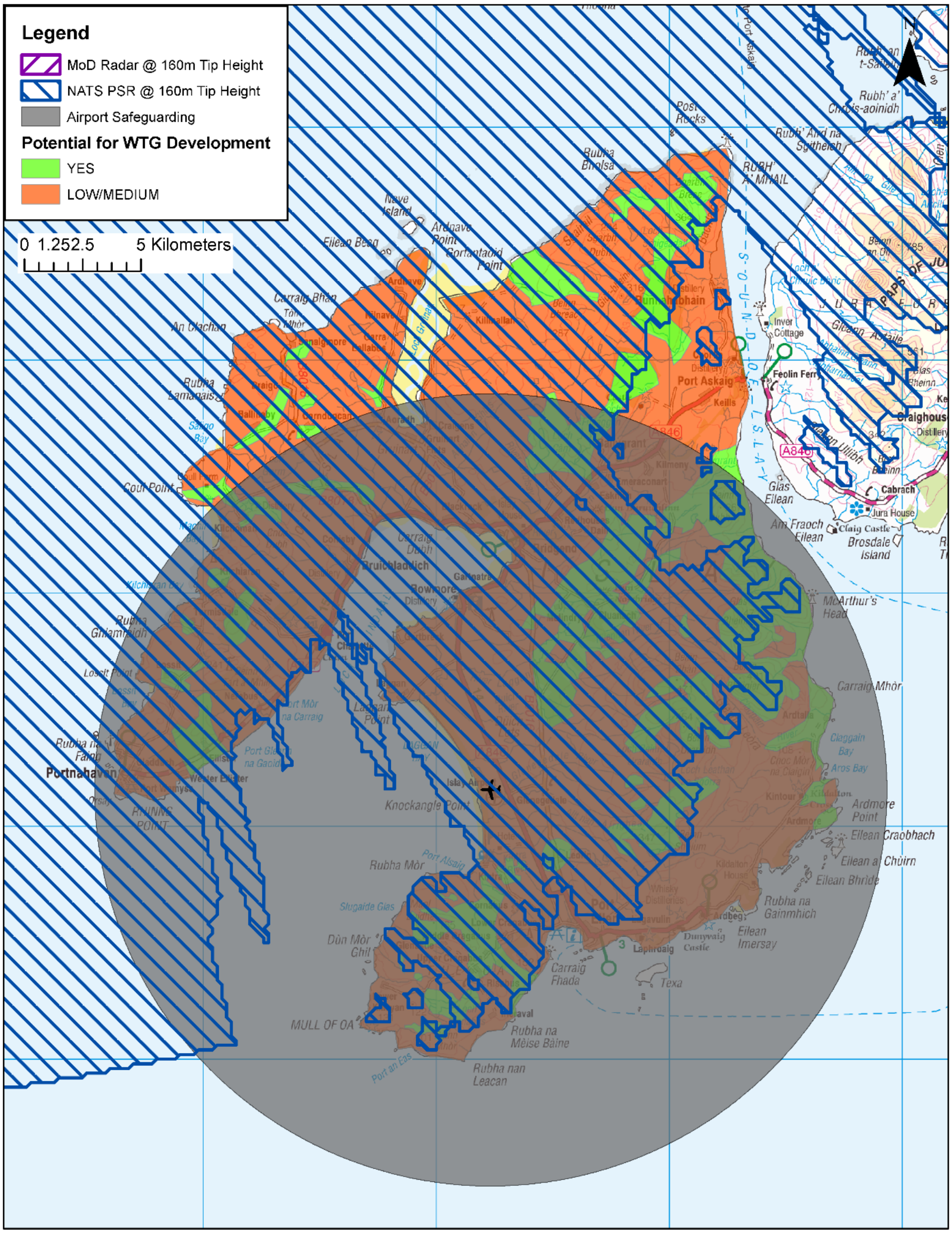


Figure 7-46 Aviation Constraints (Islay)

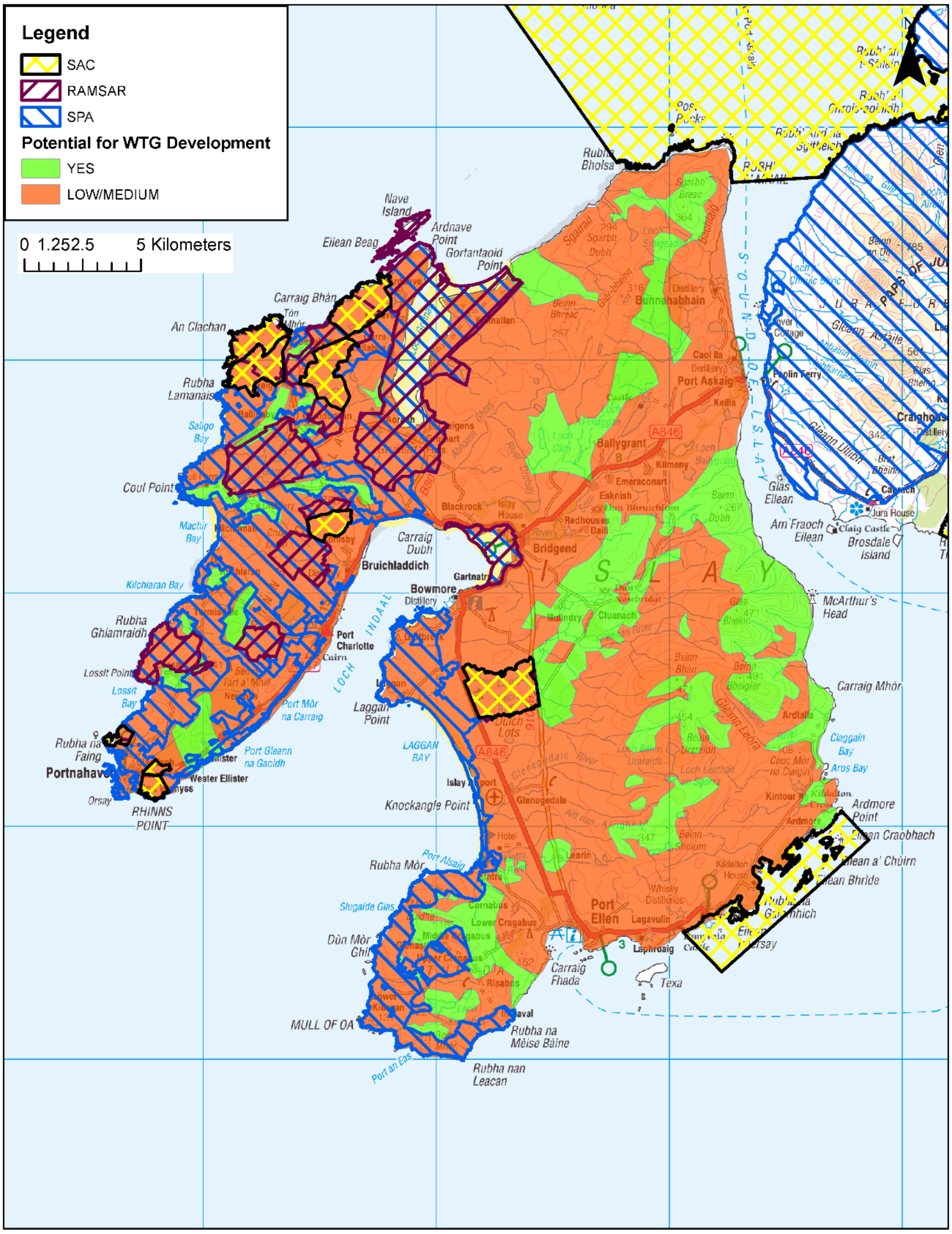


Figure 7-47 Environmental Designations (Islay)

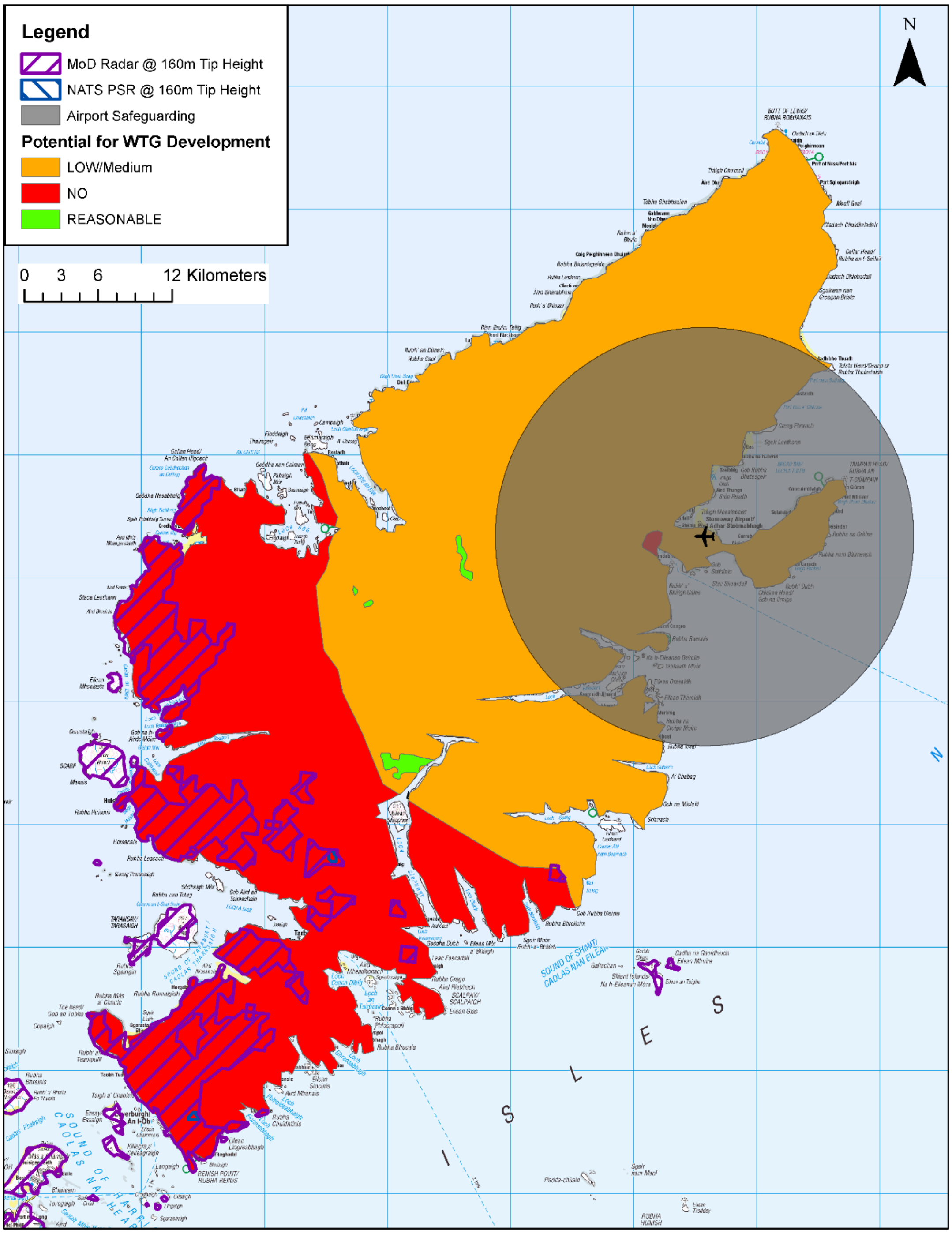


Figure 7-48 Aviation Constraints (Lewis & Harris)

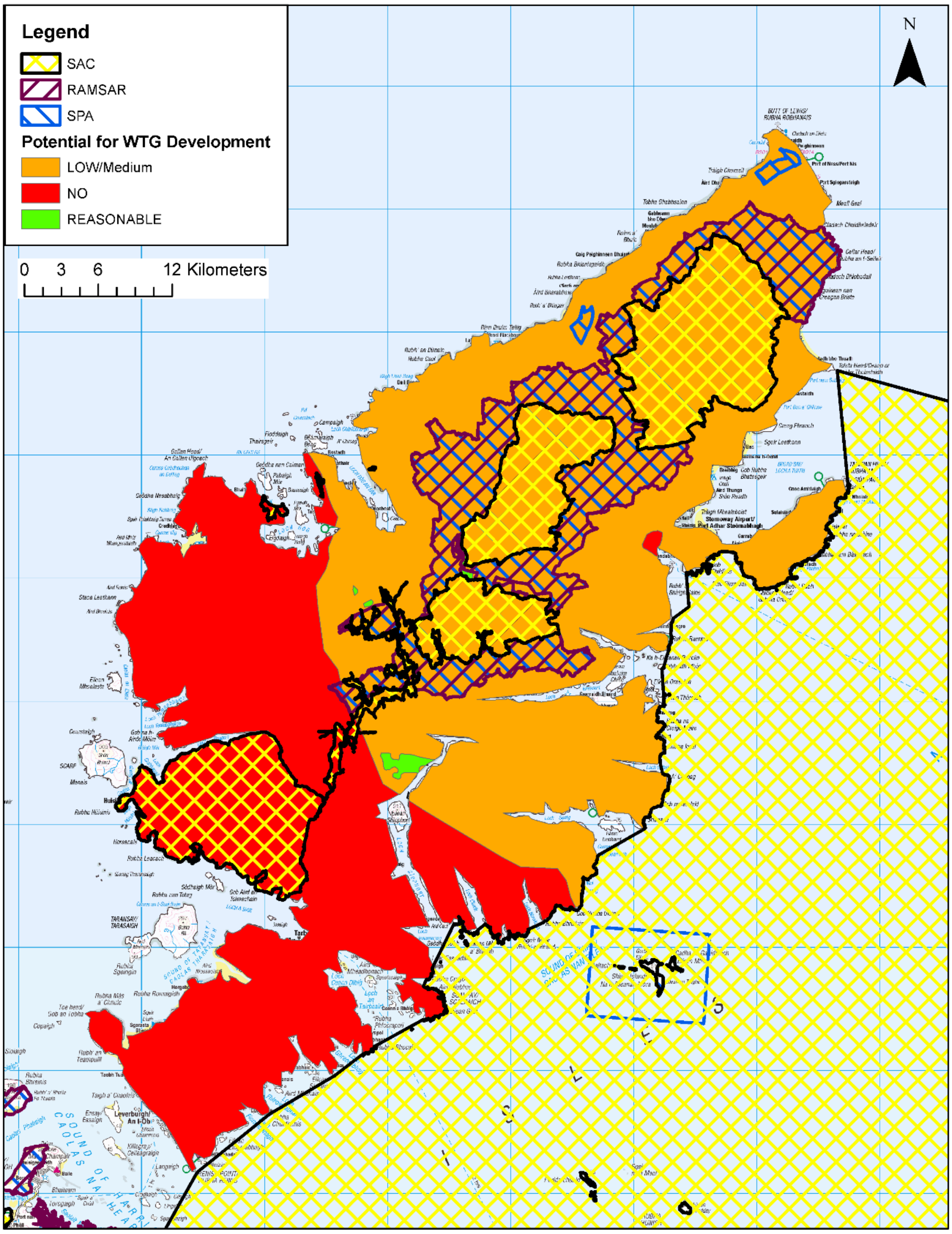


Figure 7-49 Environmental Designations (Lewis & Harris)

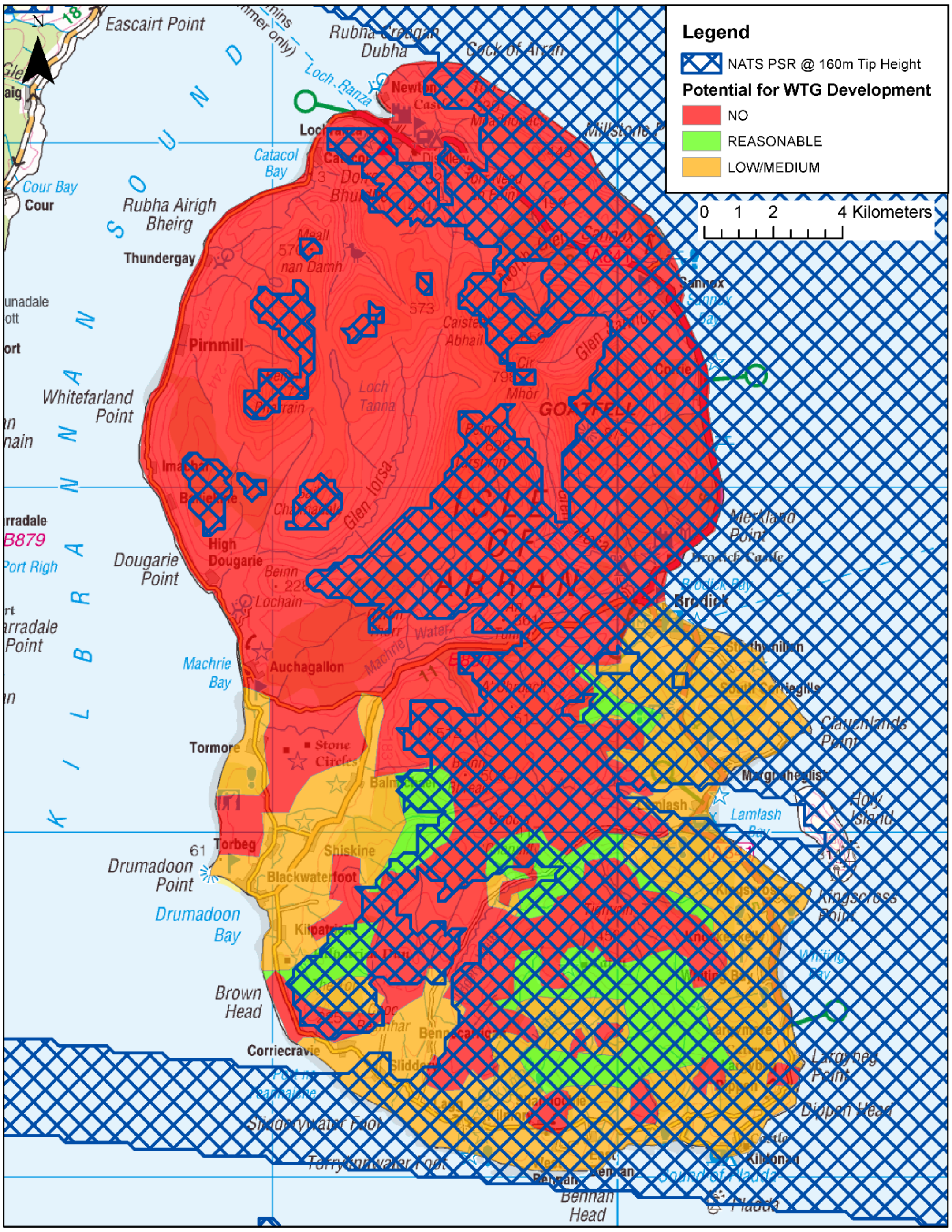


Figure 7-50 Aviation Constraints (Arran)

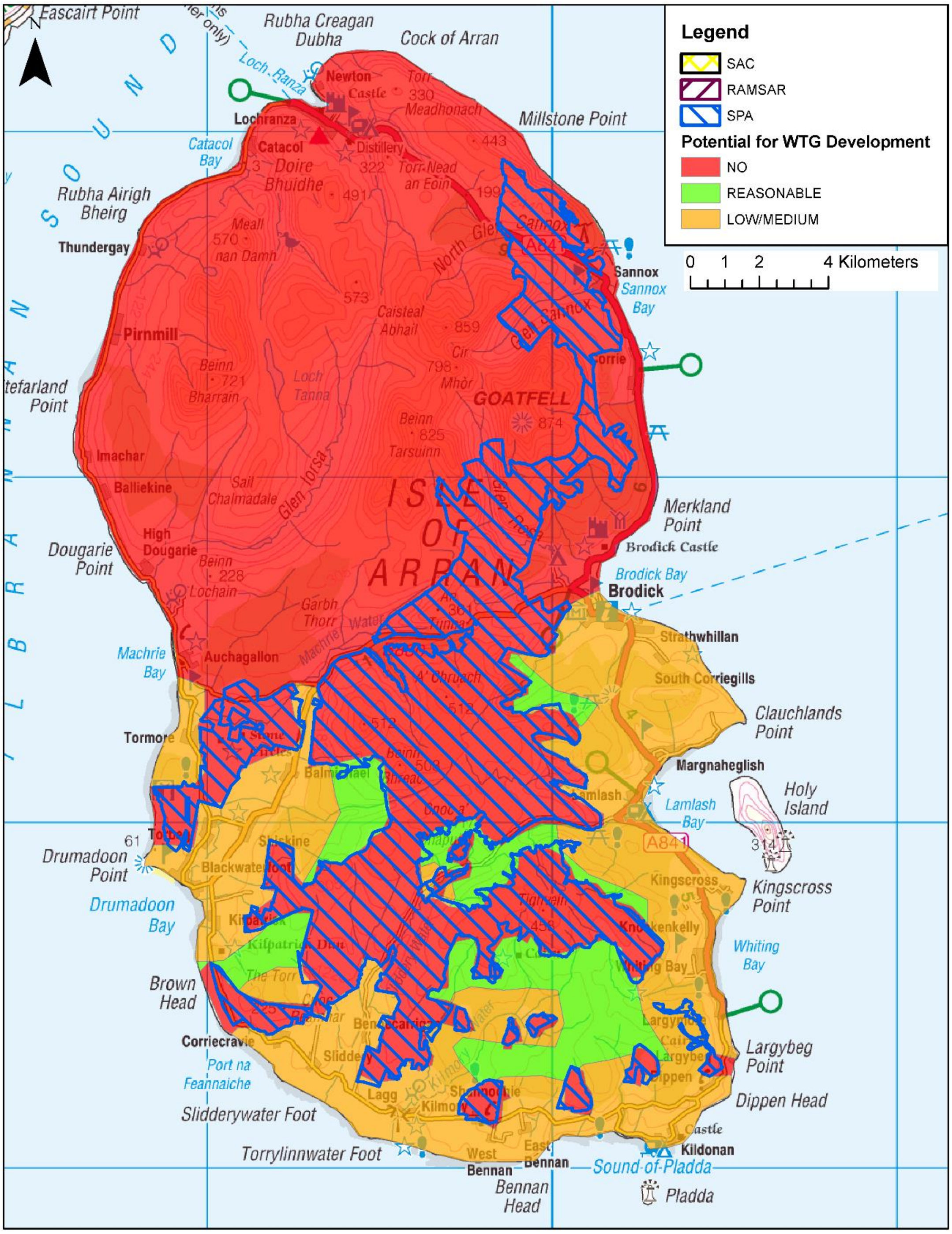


Figure 7-51 Environmental Designations (Arran)

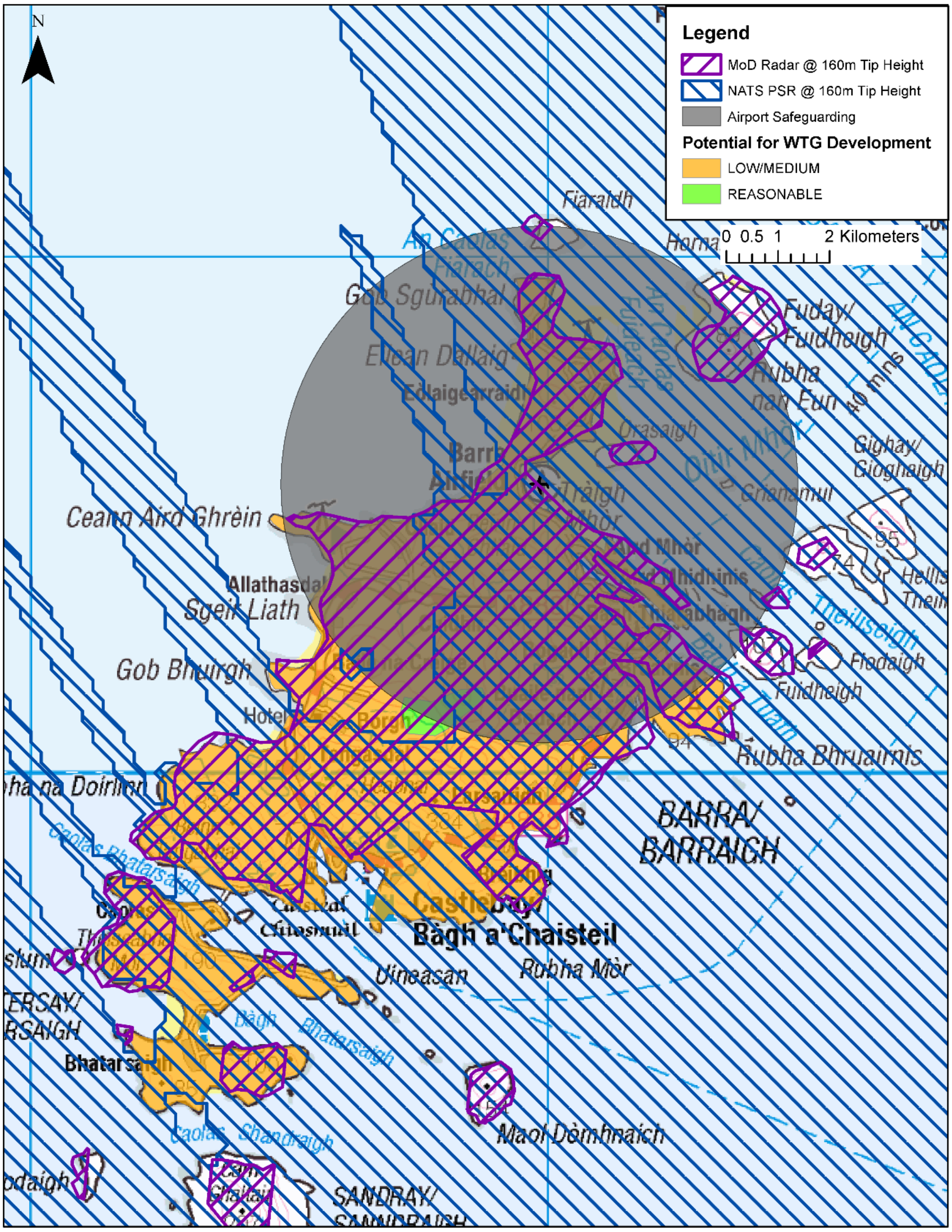


Figure 7-52 Aviation Constraints (Barra)

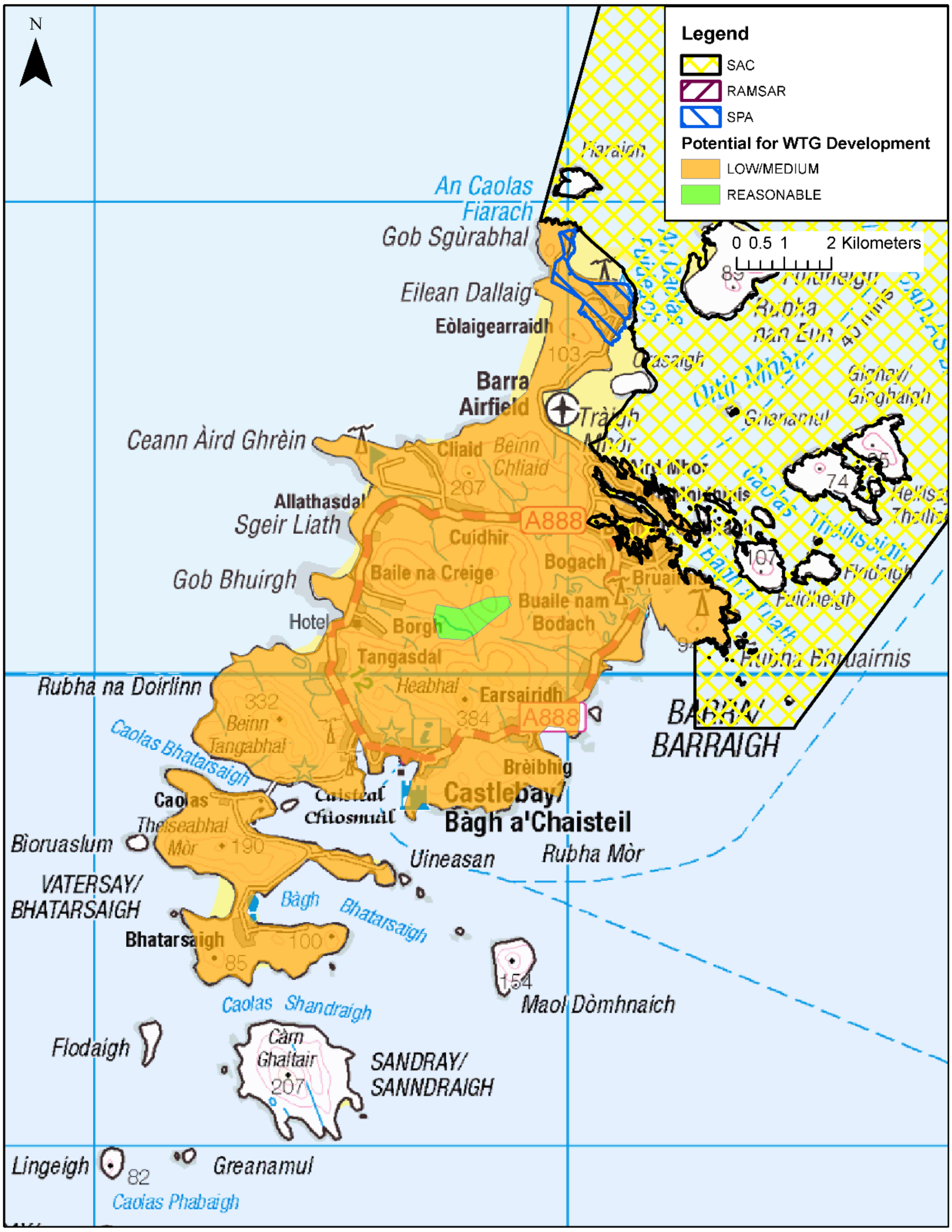


Figure 7-53 Environmental Designations (Barra)

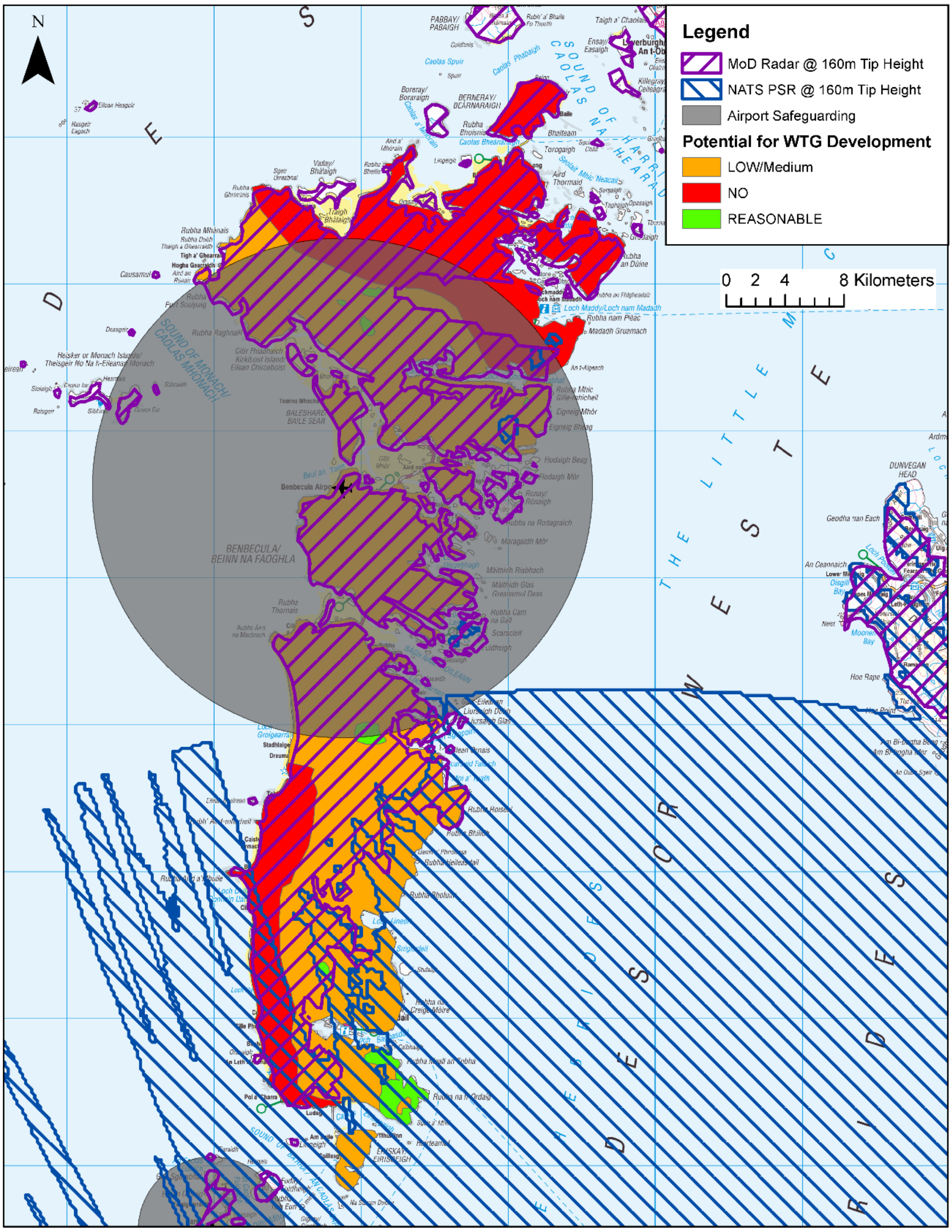


Figure 7-54 Aviation Constraints (Berneray / Uist / Eriskay)

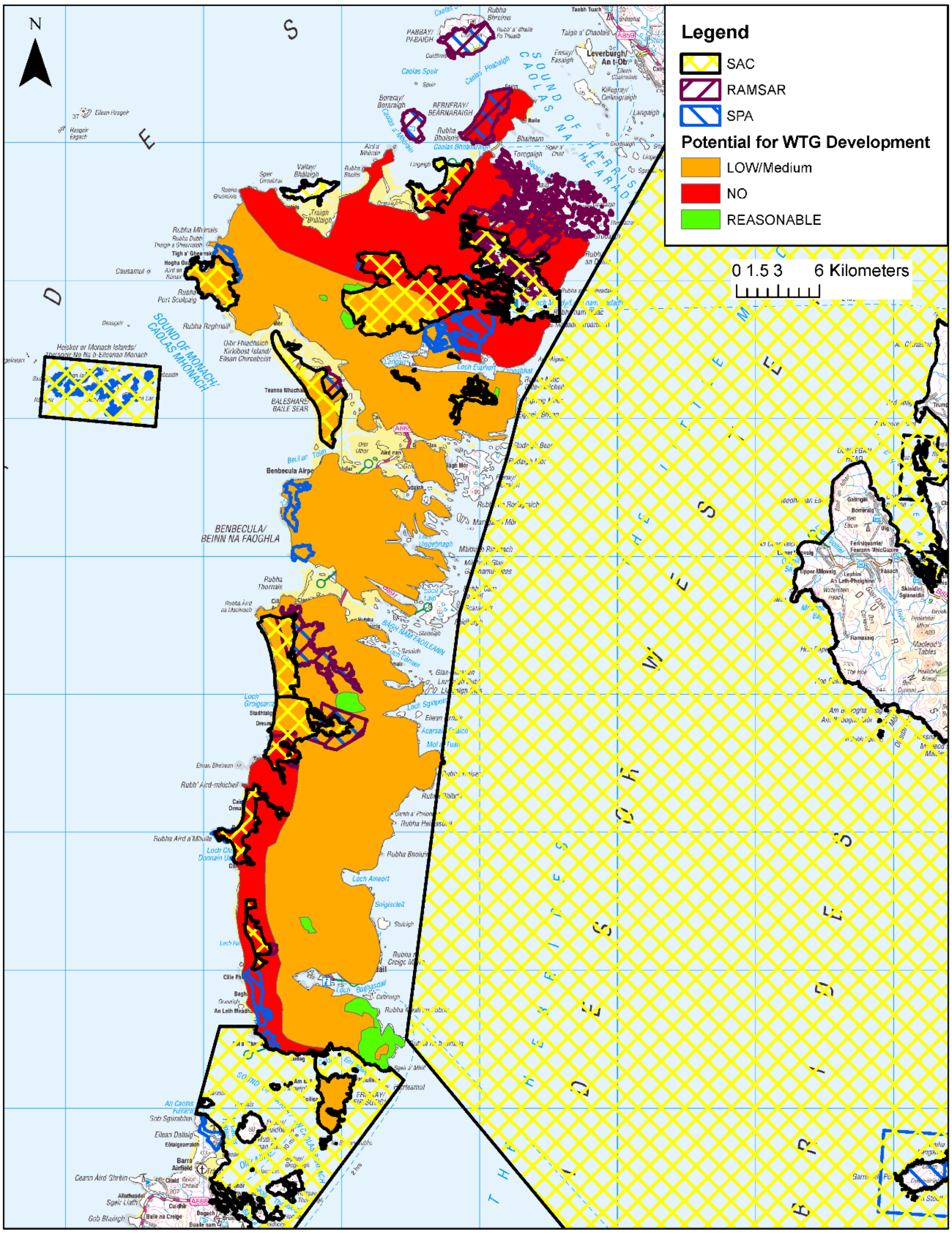


Figure 7-55 Environmental Designations (Berneray / Uist / Eriskay)

Appendix L Access Study Port Information

Port	Details
Aird Mhor Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries. • Ferguson Marine offloaded a LTM1220 5.2 (220 tonne) crane weighing 60 tonnes with an axle load of 12 tonnes per axle during for the construction of an Enercon E-44 WTG on the Aird Mhor slip.
Ardminish Ferry Terminal	• Exclusively used by small roll on roll off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Armadale Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components.
Arnish Point	• Deep water fabrication yard used for offshore construction vessels and WTG deliveries. • Deep water fabrication yard used for offshore construction vessels and used previously for WTG delivery vessels.
Berneray Ferry Terminal:	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No Quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Bowmore Harbour	• Small marina and quay currently used to moor pleasure craft. • Quayside is too narrow for crane or laydown operations. • Water depth may be too shallow for ship deliveries.

Port	Details
Brodick Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed & used for ferry traffic with no quayside area or facilities for offloading WTG components.
Bruichladdich Pier	• Exclusively used as a tanker refuelling station. • Exclusively designed and used as a tanker refuelling station no quayside area or facilities for offloading WTG components**.**
Castle Bay Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed & used for ferry traffic with no quayside area or facilities for offloading WTG components. • Water depth possibly too shallow for ship deliveries.
Craignure Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Eriskay Ferry Terminal:	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No Quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Fionnphort Beach Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Fishnish Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.

Port	Details
Kallin Harbour Central Uist:	• Small marina and quay currently used to moor fishing vessels. • Port quayside is too narrow for crane or laydown operations. • Water depth may be too shallow for ship deliveries.
Leverburgh Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components. • Water depth possibly too shallow for ship deliveries.
Lochboisdale South Uist Ferry Terminal:	• Exclusively used by large passenger / car / freight ferry. • Although mainly used for ferry traffic the 10m wide quayside area could possibly facilitate the offloading of components. • Quayside would have to be checked for max weight capacity. • Water depth may be too shallow for ship deliveries so towed barges would have be used.
Lochmaddy North Uist Ferry Terminal:	• Exclusively used by large passenger / car / freight ferry. • Although mainly used for ferry traffic the 10m wide quayside area could possibly facilitate the offloading of components. • Quayside would have to be checked for max weight capacity. • Water depth may be too shallow for ship deliveries so towed barges would have be used.
Lochranza Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Only an access ramp for ferry traffic. • Quayside too small for crane or laydown operations. • Water depth too shallow for ship deliveries.
Otternish North Uist Ferry Terminal:	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No Quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.

Port	Details
Port Askaig Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components. • Water depth possibly too shallow for ship deliveries.
Port Ellen Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port is exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components. • Water depth possibly too shallow for ship deliveries.
Portree Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components.
Sconser Ferry Terminal	• Exclusively used by small roll on-roll/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.
Stornoway Port	• Used by large passenger / car / freight ferry plus oil and gas support vessels. • East quay used exclusively for ferry traffic. • West quay used as a service base for survey vessels exploring the waters west of the Hebrides and could support WTG delivery vessels.
Tarbert Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Quayside is too narrow for crane or laydown operations. • Water depth may be too shallow for ship deliveries.
Tobermory Ferry Terminal	• Exclusively used by small roll-on/roll-off car ferry. • Port has only an access ramp for ferry traffic. • No quayside for crane or laydown operations. • Water depth too shallow for ship deliveries.

Port	Details
Uig Ferry Terminal	• Exclusively used by large passenger / car / freight ferry. • Port exclusively designed and used for ferry traffic with no quayside area or facilities for offloading WTG components.

Appendix M Risk Register

The following risks have been identified as pertaining to this phase of the SWIFTH$_2$ project:

Table 7-18 Risk Register

Risk Description	Consequences	Category	Mitigation
Lack of hydrogen safety competence of local emergency services.	Local emergency services unable to adequately respond to a callout.		Development of project safety case and health & safety file. Training of emergency service personnel in hydrogen related HSE incidents and hazards.
Hydrogen infrastructure is underused.	A longer than forecast repayment term is required.		• Size wind and hydrogen infrastructure commensurately to the quantities of hydrogen required. • Explore additional customers and/or other shipping routes. • Share project costs with additional partners.

Risk Description	Consequences	Category	Mitigation
Codes and standards applicable to hydrogen technologies not fully developed or understood. Additional work required to acquire complete understanding.	Delay to project.		• Review of all applicable codes and standards to be undertaken as part of the design phase. • Consult with participants from other similar projects.
Public acceptance: Many people perceive hydrogen as a dangerous substance which may impede consenting.	Delay and/or failure of project to obtain planning consent.		Public awareness campaign to inform stakeholders.
Higher demand for hydrogen required than designed for.	Potential loss of new revenue.		Design system for optional future expansion based on likely scenario for wider hydrogen adoption in the area.

Risk Description	Consequences	Category	Mitigation
Batteries become more technically and commercially viable for ships than hydrogen.	Hydrogen infrastructure becomes a stranded asset.		Build in suitable commercial arrangements to guarantee ferry route is serviced by a hydrogen ferry for the lifetime of the hydrogen generating plant.
CO_2-neutral synthetic methane becomes the dominant marine fuel.	Hydrogen infrastructure becomes a stranded asset.		Build in suitable commercial arrangements to guarantee ferry route is serviced by a hydrogen ferry for the lifetime of the hydrogen generating plant.