HydroGlen Renewable Hydrogen Powered Farm

A Non-Technical Summary of the HydroGlen Project Feasibility Study, March 2021

This project received funding support from the Scottish Government's Community and Renewable Energy Scheme (CARES).

Project Partners

The James Hutton Institute[1] (HydroGlen Project Lead) is a globally recognised research organisation delivering fundamental and applied science to drive the sustainable use of land and natural resources. The Institute's research farms have long been at the forefront of innovation in land and agricultural practices; trialling and testing new farming methods, livestock and crops; and demonstrating transformative ways of managing our land.

Water to Water[2] is a Scottish renewable energy project development specialist with a background in major infrastructure commercial project development, construction, operation and innovation in the energy sector. They are the HydroGlen project originators and project technical experts. Water to Water supports customers through full project lifecycles, from concept through to project-managing delivery.

Technical Feasibility Report Authors

RINA[3] were commissioned through a tendering process in December 2020 to deliver a Technical Feasibility Report, utilising their energy system modelling software to develop configuration options for HydroGlen, including safety, electrical and environmental elements.

This report includes RINA's key findings - the full Technical Feasibility Report is available on request from alison.hester@hutton.ac.uk.

[1] https://www.hutton.ac.uk/
[2] https://watertowater.co.uk/
[3] https://www.rina.org/en

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Summary

HydroGlen is a proposed renewable (green) hydrogen powered farming community project in north-east Scotland, located at the James Hutton Institute's research farm and residential community at Glensaugh. Green hydrogen is emerging as a key component of Scotland's decarbonisation plans and there is a need to demonstrate how farming communities can contribute to the energy transition through green hydrogen production and use, representing a significant step for this sector in helping to address Scotland's net-zero greenhouse gas (GHG) emission goals.

This report gives a non-technical summary of the findings of the HydroGlen technical feasibility study carried out in January-March 2021.

- HydroGlen demonstrates the feasibility of enabling farming and other rural communities to become self-reliant, low-carbon energy producers and exporters, generating 100%+ of their energy requirements (electricity, heating and transport) utilising a combination of renewable electricity, on-site hydrogen production, compression, and storage.
- Three different system configurations were analysed to help frame the design of the system and components, optimising size, capacity, and location of the required technologies within the current community footprint. Modularity was considered highly desirable in order to allow for future scaling as required.
- The off-grid scenario (BASE CASE) demonstrated feasibility, but also the requirement for additional hydrogen storage to cover the (infrequent) periods when energy demand exceeded on-site renewable energy production. The grid-connected scenarios limited energy draw-down from the national grid to less than 10% of energy requirements; even at this low level, the modelled reduction in energy storage required dropped by *c.* 30% compared to the off-grid scenario.
- Our two grid-connected scenarios compare a 50:50 mix of hydrogen and electric vehicles (CASE 2) with 100% hydrogen vehicles (CASE 3). CASE 3 requires a 40% increase in hydrogen production compared to CASE 2 but requires less storage because the hydrogen vehicles also effectively provide hydrogen storage capacity.
- CASE 3 offers a substantial increase in available hydrogen for a minor Levelised Cost of Energy (LCoE) impact due to additional electrolysers and an increase in primary electricity generation, represented by an additional 100 kW of solar PV.
- For HydroGlen, a system retaining a grid connection with import/export capacity is considered the best option - it simplifies system design, reduces the need for system redundancy to cope with periods of low or zero renewable energy production, and facilitates additional revenue generation through grid export.
- At present we consider it important to design a system that can support both hydrogen and electric vehicle technologies with straightforward scaling up or down of different components - technological advancements are happening fast with both types of vehicle and, for high-power-output farm vehicles in particular, it is challenging to predict the likely future availability and specifications of hydrogen-fuelled versus battery electric vehicles.

1. Introduction

HydroGlen is a proposed renewable (green) hydrogen powered farming community project in north-east Scotland, located at the James Hutton Institute's research farm and residential community at Glensaugh. HydroGlen seeks to demonstrate the feasibility of enabling farming and other rural communities to become self-reliant, low-carbon energy producers and exporters, generating 100%+ of their energy requirements (electricity, heating, and transport) utilising a combination of renewable electricity, on-site hydrogen production, compression and storage.

The Scottish Government is committed to becoming a net-zero greenhouse gas (GHG) emitter by 2045, requiring massive reductions in energy, heat, transport, industry, agriculture and land use sector emissions. Agriculture was reported to be the third-highest emitter of greenhouse gases in Scotland in 2018 and has a vital role to play in meeting Scotland's net-zero targets. Green hydrogen is emerging as a key component of Scotland's decarbonisation plans[4], and our HydroGlen project will play an important role in demonstrating how farming communities can contribute to the energy transition through green hydrogen production and use, representing a significant step for this sector in addressing Scotland's net-zero goals.

Renewably generated electricity (e.g. using wind, wave, tidal, solar energy) is now the cheapest form of electricity production[5] and has a dominant role to play in decarbonisation. However, these energy sources are intrinsically 'intermittent' and energy generation does not always coincide with demand; energy storage is therefore critical to unlock the full potential of low carbon electricity. Green hydrogen as a key component in energy production and storage systems offers an exciting solution and a transformative model for contributing to Scotland's net-zero ambitions, as well as creating new, previously unrealised, potential revenue streams. For rural communities in particular, this offers energy-independence and a promising alternative to an all-electric approach to decarbonisation.

2. Overview

The HydroGlen feasibility study was commissioned in December 2020 with support from the Scottish Government's Community and Renewable Energy Scheme (CARES), prior to commencing detailed design for planning, consenting, and construction. The study reviewed several renewable energy generation and storage scenarios in order to understand how best to satisfy the electricity, heating and transport fuel requirements at Glensaugh. This analysis helped to frame the design of the system and its components, optimising the size, capacity, and location of the required technologies within the current community footprint. Underpinning the design was the requirement for a modular and scalable solution to accommodate future growth in energy demand. The study also examined safety and risk, potential environmental impacts and the existing grid connection.

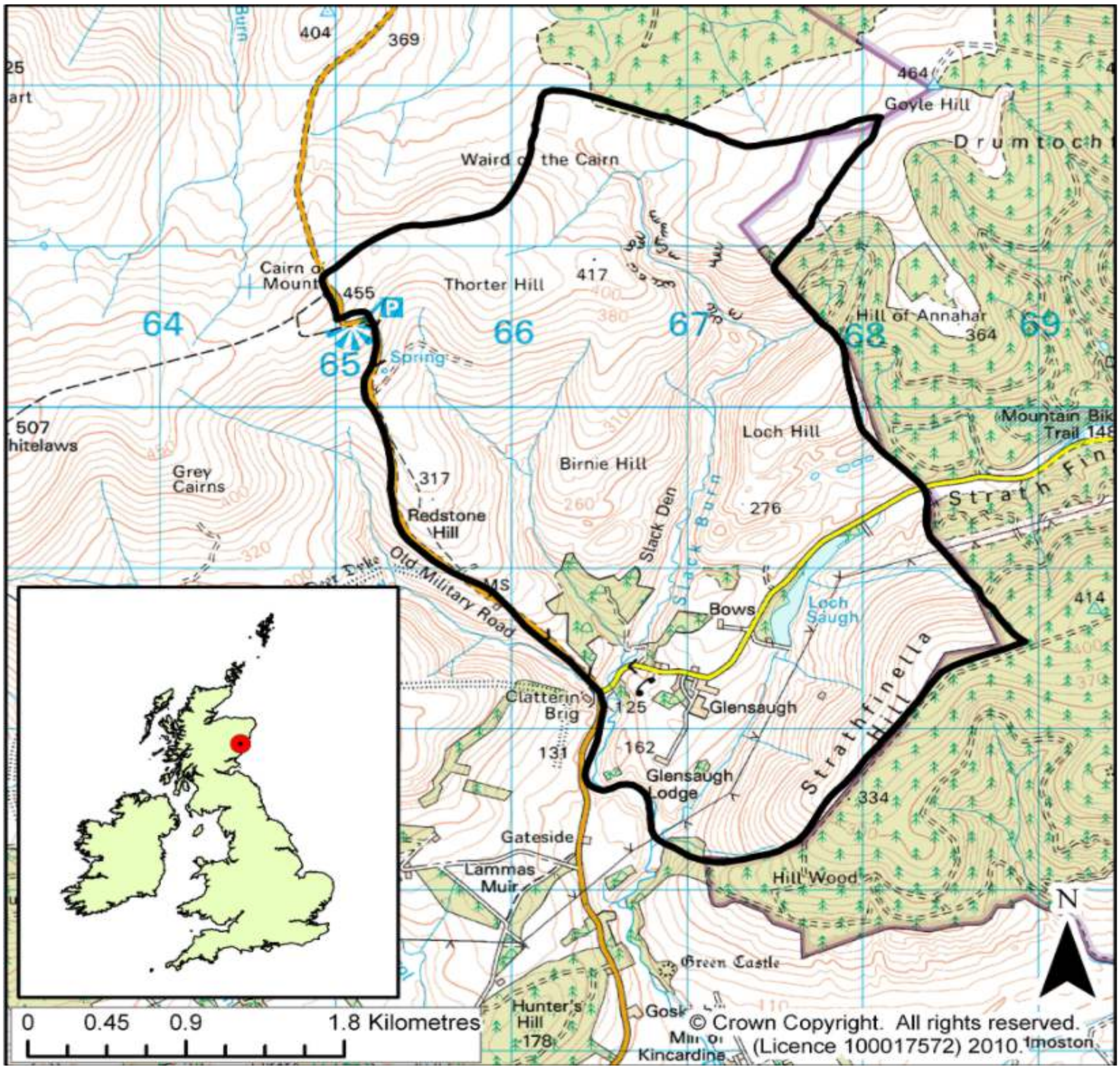
This report summarises the findings of our HydroGlen feasibility study and our plans for Glensaugh's energy future. We are making our findings available to help inform other communities in Scotland about the technical and economic requirements for becoming energy-independent by virtue of green hydrogen generation.

[4] https://www.gov.scot/publications/scottish-government-hydrogen-policy-statement/
[5] https://www.iea.org/reports/world-energy-outlook-2020

2.1. The Site

Glensaugh is located in the Grampian foothills of north-east Scotland, as shown below. The farm covers an area of just over 1000 hectares, with livestock grazing (sheep, cattle, red deer), agroforestry and woodland being the principal land uses. Glensaugh is the home of the James Hutton Institute's Climate-Positive Farming Initiative[6] and our plans for HydroGlen form a key part of this Initiative.

Glensaugh currently generates renewable power through a 50 kW wind turbine, 50 kW of installed solar PV and a 70 kW biomass boiler. The property has a spring-fed water supply.



3. Overall Concept Development - data requirements, energy usage and efficiencies

Glensaugh's energy demands (farm and residential community) were collated and converted to a common unit of energy measurement, the kilowatt-hour (kWh). This information was used in RINA's modelling software to run energy generation and storage scenarios in order to determine the sizing and design of system components. The design brief required the plant to be located within the existing

[6] https://glensaugh.hutton.ac.uk/

steading complex, commercially available components to be used, renewable power to be generated within the farm boundary, and different scenarios to be tested and optimised. Technologies not yet commercially available were not considered for this feasibility study.

Three scenarios were developed to compare different configurations of hydrogen production and battery storage over 12 years of modelled generation and energy usage. The operational lifetime of the project was set at 20 years. For all three scenarios, the model was set to address 100% of residential electrical and fuel demand (including heating), 100% of commercial electrical & fuel demand and 100% of transport fuel demand. An approximate 10% future demand increase was assumed over the 20-year operational lifetime.

3.1. Data and Information Requirements

Data and other information requirements for the HydroGlen feasibility study were as follows:

- Monthly energy usage over a year, for heating and lighting (kerosene/oil, electricity), transport fuel (petrol/diesel/red diesel) and all other electricity demands for the farm and residences
- Potential electricity-generation capabilities of solar and wind in the immediate areas (sites were selected based on the recommendations from a 2020 study by ARCUS[7])
- Environmental data for Glensaugh and surrounds
- Planning requirements
- Health, Safety and Risk controls associated with hydrogen and battery storage-based micro-grids powered by locally generated renewable electricity, including more than 30 pieces of applicable legislation
- Electrical infrastructure and grid connection/export upgrade possibilities and likely requirements.

Table 3.1 summarises the Glensaugh energy data used for this feasibility study. The average month-by-month energy use figures used here do not reflect the peaks and troughs of daily use, which need to be allowed for in the sizing of the system.

Table 3.1. Glensaugh Energy Estimates	**Energy**
Annual transportation fuel use (gas oil, petrol, diesel) for twelve vehicles	61,320 kWh
Annual residential energy demand (kerosene, hot water, electricity) for six cottages	69,287 kWh
Annual commercial energy demand (gas oil, electricity) for nine farm buildings	297,142 kWh

3.2. Energy efficiencies

Energy storage systems have different energy efficiencies, and this formed a key element of RINA's modelling of different system configurations. In general terms, the less energy that is required during the process of conversion of renewable energy to the 'end product', the greater the energy efficiency. Hydrogen, for example, is produced *via* electrolysis, compressed and then stored ready for use; all those steps require energy. Round Trip Efficiency (RTE) is defined as the effective efficiency of an energy storage system in operation, measured under standard conditions.

[7] ARCUS: "Glensaugh - Wind and Solar Feasibility". Report for the James Hutton Institute, May 2020.

The efficiencies of each of the energy storage system components shown in Table 3.2 were used to calculate how much primary electricity generation and storage would be required for each of the three Cases.

Table 3.2. Energy Storage Calculated Efficiencies for HydroGlen modelling		
System Part	**Component**	**Efficiency**
Hydrogen Electrolyser[8] and Storage	Electrolyser	90% (68% in combination with compressor)
	Compressor	75% (68% in combination with electrolyser)
	Fuel Cell	50%
	Round Trip Efficiency	34%
Battery Energy Storage	Round Trip Efficiency	80%
Battery electric vehicle	Round Trip Efficiency	80%
Hydrogen-fuelled vehicle	Round Trip Efficiency	30%

Conversion of energy into battery storage uses less energy than conversion into hydrogen (as reflected in the RTE values), but battery technology suffers from capacity degradation over time and will need to be replaced at least once during the projected 20-year system lifetime.

For modelling of vehicle energy requirements, RINA calculated that a battery electric vehicle would require just 17.5 kWh of primary electricity to match average daily transport requirements, whereas the hydrogen vehicle equivalent would require 46.6 kWh equivalent generated. These differences in energy efficiency need to be balanced against the compensatory benefits of hydrogen use, particularly for transport vehicles, which are discussed in section 9.2.

3.3. System Requirements

The HydroGlen system requires a centralised energy storage facility with a distributed electricity grid, taking advantage of existing electrical infrastructure. System configuration requirements are as follows:

- Modular to facilitate future scaling
- Electrolyser type selected to maximise operability and efficiency for non-continuous (start-stop) operation (many technologies require a long ramp-up/down time and can be damaged by frequent fluctuations in supplied power)
- Modular hydrogen storage of required size to guarantee hydrogen supply for all uses
- Fuel Cell[9] system power output to provide energy for all farm/community needs when no renewable sources are available
- Fuelling facilities to supply vehicles with hydrogen
- Battery storage
- Ancillary equipment selected to maximise reliability (e.g. water treatment package, vents for hydrogen and oxygen, nitrogen and air instrumentation systems, compressors, pumps, safety devices, *etc.*).

Our three modelled scenarios (termed BASE CASE, CASE 2, CASE 3) explored different combinations of power generation, energy storage and end use. The BASE CASE modelled an off-grid scenario; CASES

[8] An electrolyser produces hydrogen gas by splitting water into its oxygen and hydrogen components using electricity.
[9] A hydrogen fuel cell reconverts hydrogen to electricity

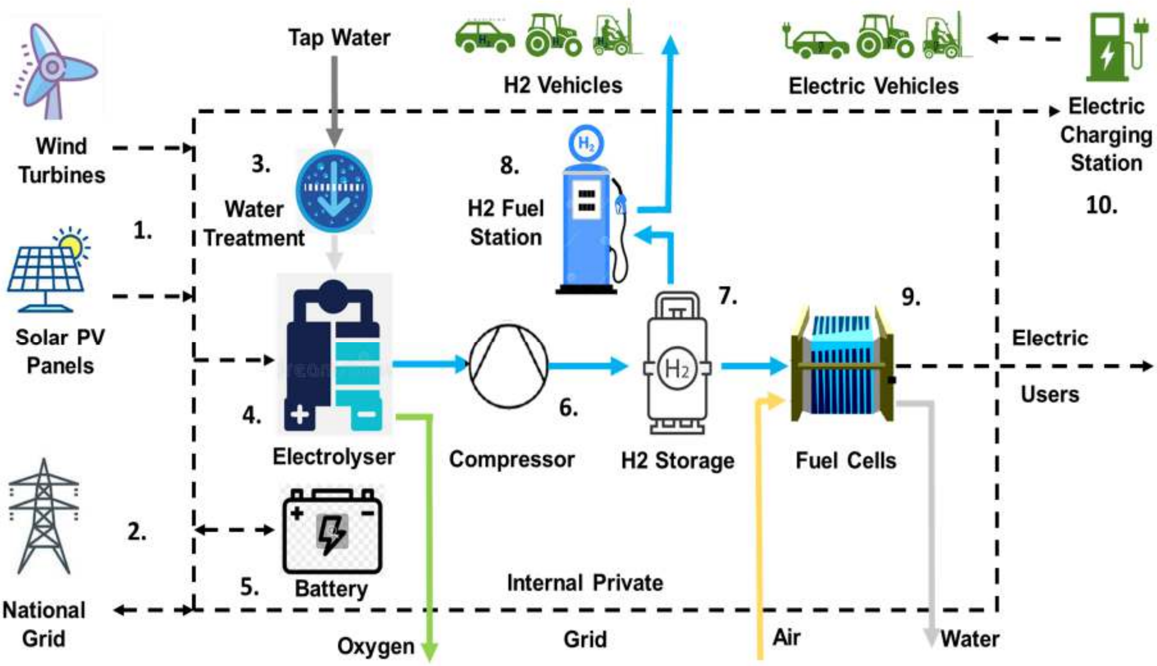
2 and 3 retained a grid connection, but with a requirement for at least 90% of power requirements being met by on-farm renewable-energy generation.

Given the rapid developments in battery electric and hydrogen-fuelled vehicle technologies and the importance of considering both vehicle types in our feasibility study, we required CASE 2 and CASE 3 to be identical apart from their mix of battery electric and hydrogen-fuelled vehicles, so as to demonstrate the effect of this difference on system specification. The BASE CASE vehicle mix selected by RINA maximised available hydrogen for the back-up fuel cell by limiting the number of hydrogen-fuelled vehicles to two.

4. HydroGlen System Model

The diagram below illustrates the HydroGlen system model designed by RINA; the components are the same for all three Cases except for the connection to the National Grid which is not present in the BASE CASE.

Information about each numbered component in the system is given below the following diagram, and detailed specifications are given in Table 4.1.



Component 1. Renewable power generators. The most abundant renewable-power resource at Glensaugh was determined by RINA to be wind, followed by solar. The solar profile is seasonally out of phase with peak demand (winter), but solar PV can act as a ‘top-up’ to balance generating capacity at times when the wind turbine is working at reduced capacity.

Component 2. Grid connection with import/export capability. Present in CASE 2 & 3 only.

Component 3. Water treatment system for demineralisation (purification) of water feed. The existing spring water supply has sufficient capacity to meet the needs of the electrolysers, but the water will need to be purified to provide a feedstock of ultra-pure demineralised ‘demi’ water.

Component 4. Electrolyser: to split water into oxygen and hydrogen. Different commercially available hydrogen electrolysers were assessed. The Proton Exchange Membrane (PEM) technology was considered to be the best option for HydroGlen due to its ready availability and resilience to frequent stops and starts. PEM also produces hydrogen at a higher pressure than alternative types of electrolyser, which reduces the amount of additional compression required for downstream storage (with associated energy saving). Stacks of electrolyser modules were modelled for this system to facilitate scaling.

Component 5. Battery. Batteries can store electricity directly from the renewable generation sources; here the battery (or stack of batteries) serves as a short-term energy storage and local grid-balancing part of the system.

Component 6. Hydrogen compressor. The PEM Electrolyser will produce hydrogen at 30 barg (i.e. pressure in bars above ambient or atmospheric pressure), which will then be compressed to 200 barg for storage *via* a volumetric compression system.

Component 7. Hydrogen storage. The proposed hydrogen storage system comprises 200 barg compressed gas bottle racks; this is a widely available, low-cost technology, with the important advantage of being both modular and scalable, with no requirement for low temperature storage.

Component 8. Hydrogen vehicle refuelling station. Refuelling a Hydrogen Fuel Cell Electric Vehicle (FCEV) takes 3-5 minutes, similar to that for petrol or diesel. A dispenser transfers compressed hydrogen into the vehicle's fuel tank through an inbuilt secondary hydrogen-pressurisation system. Hydrogen Refuelling Stations typically operate at 900 barg, discharging to a vehicle fuel tank at 700 or 350 barg. Hydrogen can also be used for vehicles with internal combustion engines, but these are less efficient than FCEVs and produce tailpipe emissions (particularly NO_x).

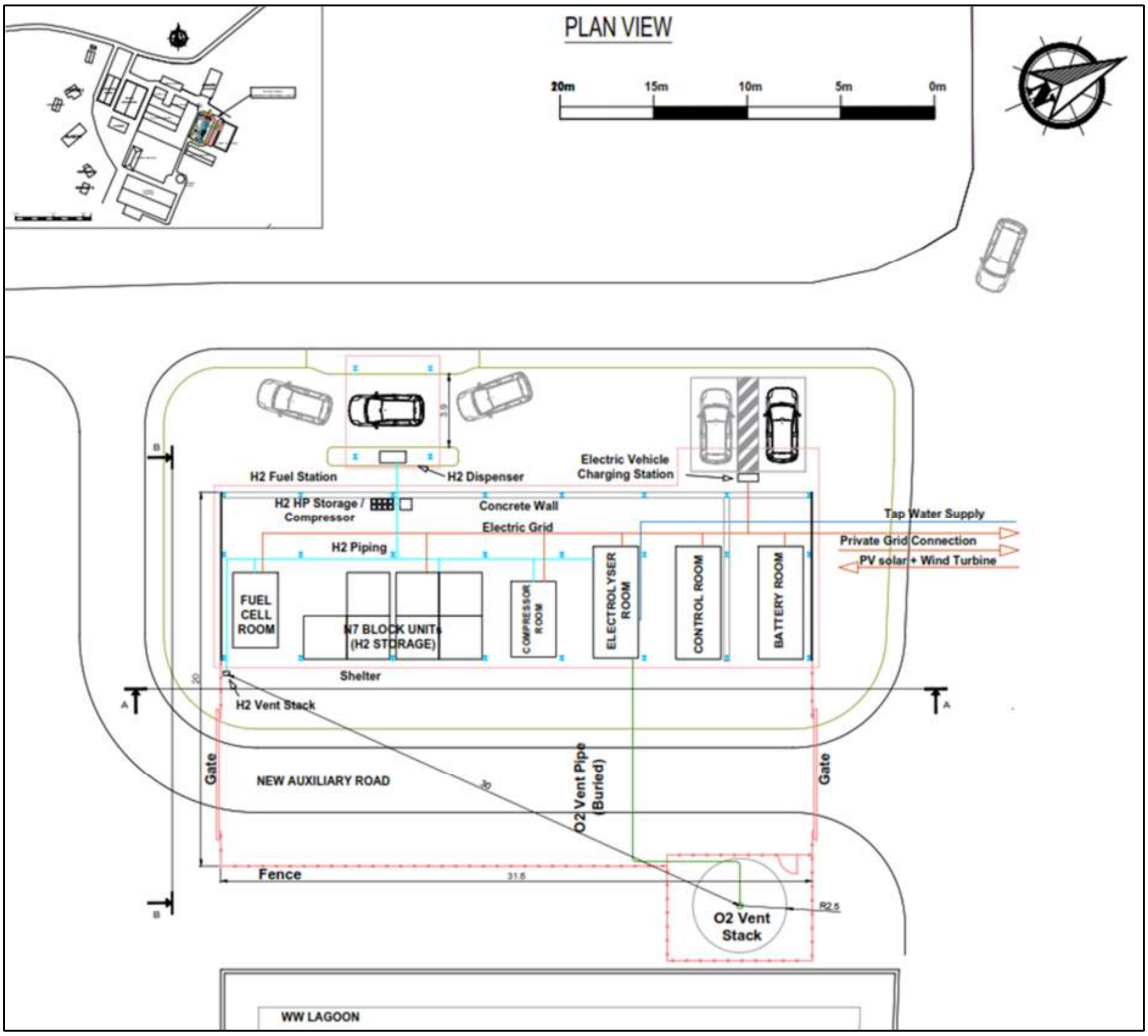
Some refuelling systems are provided inclusive of electrolyser and storage; these will be considered during the detailed design of HydroGlen, but for the feasibility study they were considered stand-alone to simplify modelling.

Component 9. Hydrogen fuel cells for additional power generation by reconverting hydrogen back to electricity. Fuel cells (FC) convert chemical energy stored in the hydrogen to electrical energy (and associated thermal energy), with water as the main by-product. When power is required but is not available directly from renewable generation or battery storage, the fuel cell can convert the stored hydrogen back into electrical energy for use. The PEM fuel cell was recommended by RINA as most suitable for this system.

Component 10. Electric vehicle charging station(s). The electric vehicle charging stations have been modelled on 7.2 kW charging units (other sizes are available), with the number of charging points driven by the number of battery electric vehicles (BEVs) proposed in each Case.

4.1. Infrastructure Layout & Location

The following schematic diagram shows the possible layout and sizing of the hydrogen plant, battery units and refuelling station, based on the footprints of commercially available components. It is proposed to locate this on the periphery of the Glensaugh steading, keeping the new plant away from residential buildings.



4.2. System Specifications

Table 4.1. summarises the configurations of the three Cases as modelled by RINA.

Table 4.1. HydroGlen Configuration Comparison for the three Cases			
Component	**BASE CASE**	**CASE 2**	**CASE 3**
Wind turbine	800 kW	800 kW	800 kW
Solar	50 kW	50 kW	150 kW
Grid capacity (import & export)	0	100 kVa	100 kVa
Hydrogen Fuel Cell Power Rating	100 kW	100 kW	100 kW
Hydrogen Electrolyser	5 x 28.6 kW units	6 x 28.6 kW units	10 x 28.6 kW units
Hydrogen stored energy equivalent	24,000 kWh	16,000 kWh	20,000 kWh
Hydrogen storage volume	929 kg	619 kg	774 kg
Hydrogen Fuel Cell Energy Output	12,000 kWh	8,000 kWh	10,000 kWh
Hydrogen annual production volumes	2,740 kg	5,345 kg	7,650 kg
Battery Power Rating	100 kW	100 kW	100 kW
Hydrogen fuelled vehicles	2	6	12
Hydrogen vehicle refuelling station	1	1	1
Battery electric vehicles	10	6	0
Electric vehicle charging stations	5 x 7.2 kW units	4 x 7.2 kW units	0

Additional renewable energy requirements: an 800 kW wind turbine was considered the most suitable option for all Cases, with CASE 3 also including an additional 100 kW solar capacity. Reliance on a single (intermittently operating) wind turbine brings risk: meteorological data suggest that about one week of low wind speeds will occur within a typical year; and there will be periodic outage for maintenance – both these factors influence energy storage sizing.

RINA designed the hydrogen electrolyser component of the system for their simulations using 28.6 kW 'stacks', to which additional stacks can be added as required. The number of electrolysers recommended and annual production volumes for each Case in the Table reflect their different hydrogen requirements.

In all Cases (most notably the BASE CASE) continuous operation requires considerable hydrogen storage capacity to meet peaks in demand and compensate for intermittency of generation, as reflected in the energy storage sizing. Adding a grid connection for CASE 2 and 3 adds cost in terms of electricity import charges and metering but enables a reduction in total storage requirement for hydrogen. The grid effectively acts as a 'balancing' mechanism to meet short-term peaks in energy demands when these exceed on-site generation and storage. The grid connection also provides an income source through sale of excess power when energy production exceeds demand.

Renewable energy generation will not always satisfy demand: RINA calculated that the peak power deficit (PPD) for any 1-hour period (across the 12-years of modelled energy and weather data) could be as high as 89 kW, meaning that the system would require at least this amount of back-up power. A 100 kW fuel cell and 100 kW battery were recommended for all Cases to ensure sufficient capacity to cover those occasions of peak power deficit. CASE 2 and 3 can also draw from the grid if required.

Hydrogen storage and electric vehicle charging stations have been sized on the basis that it will be possible to refuel all vehicles (in the numbers modelled for each Case: Table 4.1) each day should this be required.

4.3. Estimated System Costs

Estimated capital costs for the core system (excluding vehicles) are presented in Table 4.2.

Table 4.2. Estimated capital costs of system components

Component	**BASE CASE**	**CASE 2**	**CASE 3**
Solar PVs[a] including ancillary civil works	£0	£0	£210,000
Solar replacement cost (degradation allowance)	£105,000	£105,000	£315,000
Wind turbine including ancillary civil works	£1,200,000	£1,200,000	£1,200,000
Battery storage units	£480,900	£480,900	£480,900
Battery replacement (degradation allowance)	£140,670	£140,670	£140,670
Electrolyser system	£272,000	£327,000	£544,000
Stack replacement cost (degradation allowance)	£43,000	£52,000	£86,000
Compressor system	£100,000	£100,000	£100,000
Hydrogen storage	£391,000	£260,000	£326,000
PEM Fuel Cell	£190,000	£190,000	£190,000
Hydrogen vehicle refuelling system	£550,000	£550,000	£550,000
Auxiliary equipment	£100,000	£100,000	£100,000
Electric vehicle charging stations	£28,800	£17,280	£0
Civil works (excluding solar and wind turbine already costed)	£200,000	£200,000	£200,000
Equipment installation cost	£165,000	£159,000	£190,000
Levelised cost of energy[b] (LCoE), £/kWh no revenue	£0.24[c]	£0.14	£0.16

Table notes:

[a] Existing solar panels are not charged to the project. Additional panels are installed in CASE 3.

[b] The levelised cost of energy (LCoE) is the estimated total cost of building and operating the power plant over its estimated service lifetime.

[c] BASE CASE has the greatest LCoE due to zero grid export revenue and system oversizing (to meet infrequent periods of large power demand). Current export tariffs are estimated to potentially reduce the LCoE for CASE 2 and CASE 3 by 3 p/kWh.

4.4. Construction requirements

A high-level outline of the HydroGlen construction requirements is given below.

Wind turbine and solar PVs

- A combination of overhead line and trenching, ducting and backfilling of cables to switch room
- Construction or upgrading of access road to wind turbine site (depending on location)
- Works associated with placement of new solar panels (anticipated to be located on roof space adjacent to existing panels)
- Earthing system (if earthing at the switch room is not feasible)
- Rodent protection around exposed cabling.

HydroGlen plant

- Demolition/disassembly of the existing structures at the proposed site
- Earthworks, arrangement of the ground - slopes, levelling and substrate preparation
- Water disposal system construction
- Construction of concrete foundation where equipment will be assembled
- Concrete base for battery container, fuel cell and hydrogen storage, EV charging stations, including trenching, ducting or bunding
- Construction of asphalted/concrete slab driveway zone (to fuelling station area and for general access)
- Electrical construction needs, including trenching, ducting and backfilling for cabling; upgrades as required to the on-site switch room
- Rodent protection around exposed cabling
- Assembling a shelter to protect the equipment
- External lighting of the Plant Area
- Installation of fence and access gates.

5. Outline Health, Safety and Risk Assessment

The conceptual designs for the three Cases were reviewed to identify associated hazards and to provide a risk register to be updated and implemented in subsequent phases of the project. The process followed the standard HAZID (Hazard Identification) methodology, consisting of a review of the plot plans, process schemes and operating philosophies in order to:

- Identify any hazards arising from the HydroGlen operating system which could pose a risk to people working at Glensaugh, to plant and equipment, or to the environment
- Estimate the magnitude of the risks associated with the hazards identified
- Propose design changes where required to mitigate or prevent hazards occurring

- Identify any further action required (engineering solutions, further analyses, operating procedures) to ensure that all risks are reduced to ALARP (As Low As Reasonably Practicable) level.

Particular attention was paid to any on-site or project-specific hazards that could require concept modification, design changes, or that could be considered ‘show-stoppers’. All potential hazards were identified as Low or Medium Risk, with no ‘showstopper’ hazards identified. The HAZID assessment produced 23 recommendations for specific measures to be taken in addition to the safeguards already present at Glensaugh. All identified hazards and recommendations were captured in a safety checklist, together with technical and operational safeguard recommendations (detailed in RINA’s Technical Report, available on request).

Over 30 pieces of Occupational Health and Safety (OHS) legislation with potential applicability to HydroGlen were identified and summarised by RINA. A list of potential safety-critical consultees was also provided (available on request).

6. Environmental Impacts Scoping Study & Outline Planning Considerations

The objective of this part of the work was to provide an initial assessment of environmental impacts that will need to be considered during the design, construction and operational phases of the HydroGlen project, together with a review of the planning process. The review was based on:

- Anticipated environmental impacts
- Local planning history for similar wind developments and the policies of the Local Planning Authority (LPA)
- RINA’s knowledge and experience of planning applications for renewable developments.

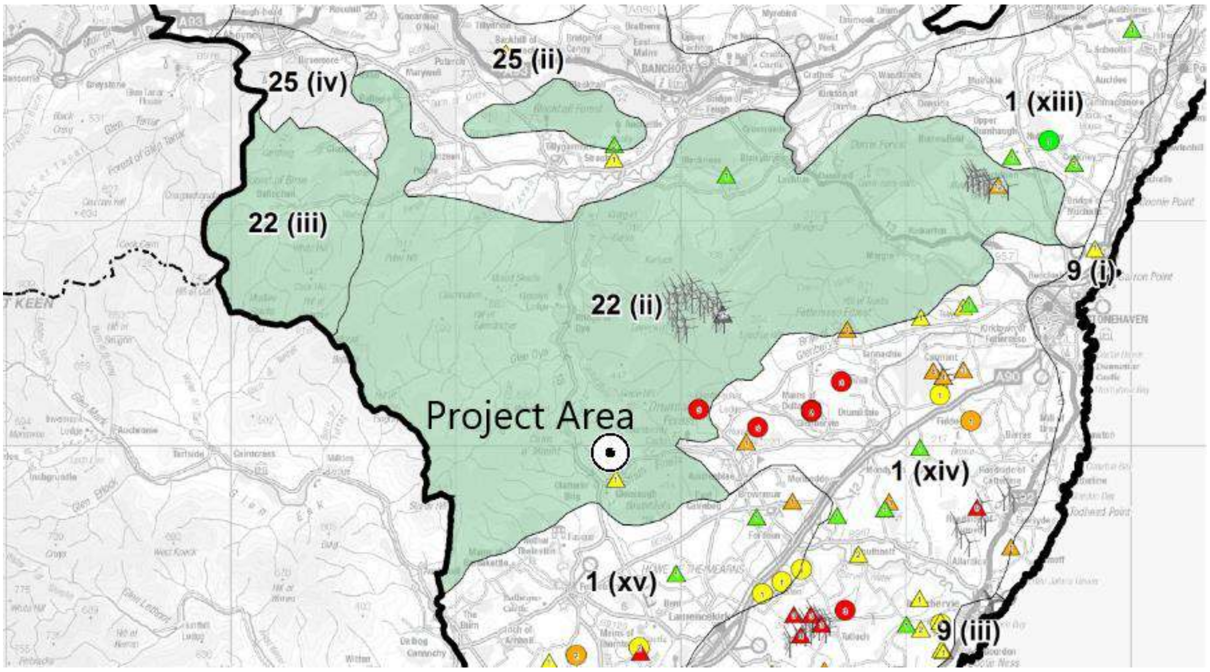
Statutory consultation for HydroGlen will be undertaken by Aberdeenshire LPA as part of the planning process. Statutory consultees (listed in RINA’s Technical Report) will make recommendations relating to the granting, attachment of any conditions to, or refusal of planning permission.

The HydroGlen team will obtain pre-application advice from the LPA, which will incorporate input from statutory consultees on concerns relating to project impacts and requirements for surveys and other documentation that will need to be undertaken and provided as part of the planning application package. It was also recommended to submit a Screening Request to the LPA, once preliminary Project designs are finalised, to establish whether any potential impacts may require the provision of an Environmental Impact Assessment (EIA) as part of the application.

The outline environmental and planning assessment found no ‘showstoppers’; the principal environmental and planning risk for HydroGlen is likely to be the proposed new wind turbine, in the context of the Aberdeenshire Local Development Plan (ALDP) Policy C2: Landscape Capacity Assessment for Wind Development. A comprehensive Landscape and Visual Impact Assessment was recommended. RINA’s Technical Report includes specific recommendations on environmental surveys and site investigations to be undertaken and submitted as part of the planning application process, which are summarised below.

Wind Turbine. Potential environmental impacts of wind turbines relate principally to: noise; shadow flicker (generally within ten rotor diameters from base); landscape and visual; ecology (particularly relating to birds and bats); heritage and archaeology; construction traffic and access.

Early engagement with the relevant planning authority and consultee stakeholders (always recommended) will reveal any additional considerations required. A review of possible locations for the new turbine against sensitive areas and nearby houses ('visual/noise receptors') revealed no concerns. A Strategic Landscape Assessment for Wind Energy Map (below) shows that the site is within an area with medium/high landscape sensitivity.



This will be a priority focus of our pre-planning engagement with Aberdeenshire Council to discuss proposed turbine designs and location with regards to alignment with the landscape elements of the ALDP.

Solar PVs. For CASE 3, which requires an additional 150 kW of solar PV, there is likely to be sufficient roof space available close to the existing arrays. This would constitute permitted development providing standard conditions are met.

Traffic/Vehicle Access. Given the small footprint of the HydroGlen plant and the existing access for commercial vehicles, no significant impacts on local traffic are expected. Early development of a Construction Traffic Management Plan is recommended, particularly in view of 'abnormal load' transportation requirements for the turbine components and potential environmental impacts of any track upgrades required between the public road and the proposed new turbine site (landscape, hydrology, biodiversity).

Flooding. All HydroGlen development areas sit outside any flood risk zone, but Flood Risk Assessments will be undertaken, including recommendations for construction materials to be used and localised sustainable drainage methods (SuDS) to control any run-off, including camber and drainage ditches.

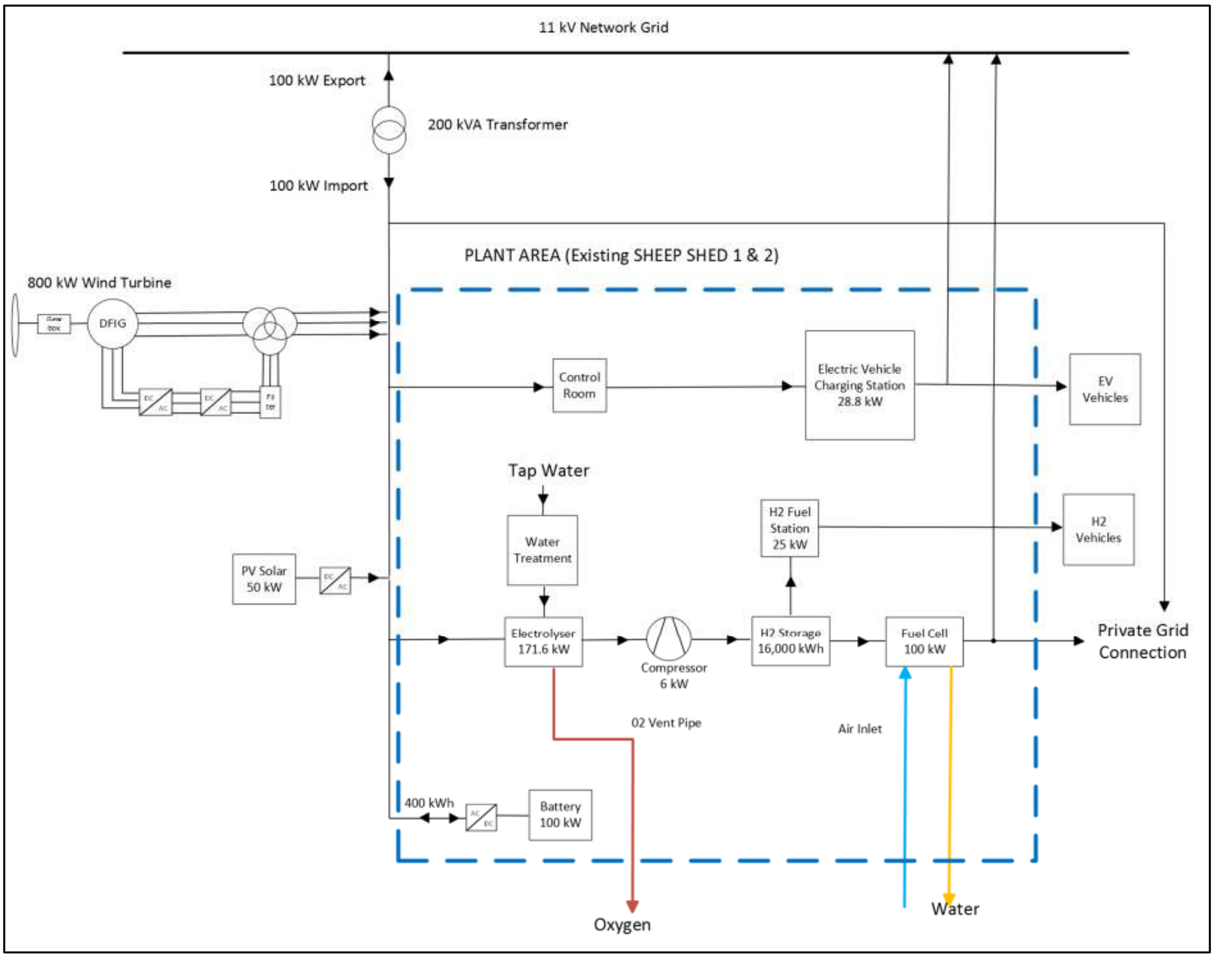
Hydrogen System/Battery System. No planning policies are yet in place specifically for hydrogen or battery energy storage systems within the LDP. The heart of the HydroGlen project is the building containing the hydrogen production and storage system - by locating this within the existing farm compound area and within the footprint of the existing farm buildings at that location, we have minimised potential environmental impacts. A noise impact assessment is recommended because this location is within 200 m of several residential properties.

The Planning (Hazardous Substances) Regulations 2015 sets out the threshold above which hazardous substance consent is required. Part 2 of the Regulations sets a 2000 kg threshold for storing hydrogen; given that the proposed development will not store more than 950 kg at any time, hazardous substance consent will not be required.

7. High-Level Electrical System Model

Electrical system and grid-connection assessments were undertaken to determine technical feasibility and power generation sensitivity of the proposals for HydroGlen. Glensaugh has an existing pole-mounted transformer with a capacity of 200 kVA and is fed from Laurencekirk 33/11 kV substation.

High-level electrical system schematics were drawn up for each Case, showing the ratings, capacities and interconnections of the major components, as well as the modelled grid status. CASE 2 electrical system schematic is included below for illustration as it includes recharging/refuelling elements for both battery electric and hydrogen-fuelled vehicles.



Each of the three Cases comprises a combination of wind, solar, hydrogen, batteries and grid connections. RINA reported that it is technically viable to replace the existing infrastructure at Glensaugh with electrical equivalents and to install the infrastructure necessary for the battery energy storage system, hydrogen production and utilisation for any of the three Cases modelled here. They recommend that a detailed electrical control system study is undertaken to identify a bespoke solution design which will accommodate the energy mix at Glensaugh.

For the configuration of the energy system at Glensaugh, implementation of an Energy Management System (EMS) and Demand-Side Management System (DSMS) is recommended. The EMS would balance the primary generation and storage levels dynamically, based on the site configuration, to ensure that the State of Charge (SoC) of the system never drops below a certain threshold. There are many commercially available products to do this. The DSMS would alert users to the most efficient and effective energy use patterns (e.g. when to charge battery electric vehicles, *etc*). Smart appliances and electrical heating systems could also be linked to a 'smart' DSM to manage local grid loading.

A power system study was conducted to assess the potential for the HydroGlen plant to be accommodated on the SSEN network without significant reinforcement (i.e. potential feeder exceedance, circuit breaker ratings, thermal or voltage violations). It is considered that reinforcement of the 33/11 kV transformer at the local substation is unlikely to be needed, given that the predicted import/export demands (for CASE 2 and 3) are only 100 KW. The Glensaugh metering will need to be upgraded to include forward and reverse power flows. Early engagement with the Distribution Network Operator (DNO), SSEN, was recommended to allow detailed assessments to be made.

8. Next Steps for HydroGlen

RINA's report underpins an economic model that we are now constructing for HydroGlen, including capital costs from key component and service suppliers. Early engagement with stakeholders will help inform all planning and consent considerations and feed into the detailed design phase of development. This includes:

- Undertaking recommended surveys to inform detailed design
- Engagement with supply-chain to finalise project key components and electrical requirements
- Engagement with the Distribution Network Operator (DNO) to determine import/export license requirements for the site
- Engagement in a Screening Request with the Local Planning Authority (LPA).

Following successful completion of these steps, the HydroGlen project will be ready to attract the investment necessary to fund the detailed design and build.

9. Summary Findings and Recommendations

HydroGlen is intended to form a proof of concept for converting an existing farm and community into a low-carbon energy producer, user and exporter. RINA concluded that it is technically viable to replace the existing infrastructure at a Glensaugh with electrical and hydrogen equivalents and to install the infrastructure necessary for batteries, hydrogen production and hydrogen utilisation across power, transport fuel and heating requirements. The detail provided by RINA provides a useful template for other similar applications.

9.1. Comparison of our Three Modelled Scenarios

The BASE CASE demonstrated that an off-grid scenario would require significantly more hydrogen storage to service peaks in energy demand, as compared to CASE 2 and 3 (both of which include a grid-connection). The BASE CASE was designed to maximise available hydrogen needed for the back-up power fuel cell and the resultant modelled system includes just two hydrogen vehicles in the mix, with all other vehicles being battery electric. Incorporating additional hydrogen vehicles into the BASE CASE scenario would simply require scaling up the hydrogen storage and production in accordance with additional vehicle requirements. The BASE CASE has the highest Levelised Cost of Energy (LCoE) of the three cases modelled, driven by the need for the additional back-up storage.

CASE 2 offers an insight into the scale and configuration of a 50:50 mix of electric and hydrogen vehicles, also meeting all other energy demands with direct power, hydrogen and batteries, supported by a grid connection to provide both balancing and export opportunity. CASE 2 requires the smallest volume of hydrogen storage and also offers the lowest LCoE.

CASE 3 demonstrates how a fully hydrogen-fuelled vehicle system would be configured, also meeting all other energy demands with direct power, hydrogen and batteries, supported by a grid connection as in CASE 2. CASE 3 requires a 40% increase in hydrogen production compared to CASE 2 but requires less storage because the hydrogen vehicles also effectively provide hydrogen storage capacity. CASE 3 offers a substantial increase in available hydrogen for a minor LCoE impact due to both the additional electrolysers and an increase in primary electricity generation, represented by an additional 100 kW of solar PV.

For HydroGlen, a system retaining a grid connection with import/export capacity is considered the best option - it simplifies system design; reduces the need for system redundancy to cope with periods of low or zero renewable energy production; contributes green energy to the national grid and facilitates additional revenue generation through grid export.

9.2. Hydrogen and Electric vehicles

Our CASE 2 and CASE 3 scenarios allow direct comparison of a system supporting 100% hydrogen-fuelled energy requirements with one combining an equal mix of battery electric and hydrogen-fuelled vehicles. **We consider it important to design a system that can support both technologies with straightforward scaling of different components as required in future;** technological advancements are happening fast with both types of vehicle and, for high power output farm vehicles in particular, it is challenging to predict the likely future availability and specifications of hydrogen-fuelled versus battery electric. Although battery electric vehicles currently have greater 'tank to wheel' efficiency, batteries have very low energy density compared to hydrogen which means that a high-power-output vehicle like a tractor currently requires a very large and heavy battery pack to achieve diesel-equivalent duty cycles. A prototype hydrogen-fuelled tractor (New Holland) worked for 3 hours on just 8.2 kgs of hydrogen compressed to 350 bar in 2011 (this could be produced in less than 2-hours in our CASE 3 electrolyser configuration). Hydrogen vehicles also benefit from fast refuelling and generally have a longer range than battery electric vehicles. Green hydrogen is described as the cleanest fuel possible[10] (lithium-ion battery production is very energy-intensive) but battery electric vehicles are currently more readily available than their hydrogen counterparts; like-for-like battery electric vehicles are still generally cheaper than hydrogen-fuelled, but prices are predicted to converge by 2030.

[10] https://www.autoexpress.co.uk/car-news/electric-cars/93180/hydrogen-fuel-cell-do-hydrogen-cars-have-a-future

9.3. Process Recommendations Summary

We have put together a series of high-level process-recommendations, resulting from our feasibility study, in the schematic diagram below; this will be of particular relevance for those interested in progressing a green hydrogen future.

Early Stakeholder Enagagement

- Any project is more likely to succeed if key stakeholders are consulted early in the process. HydroGlen benefitted from early guidance from key stakeholders such as Aberdeenshire Council (Sustainability; Industry Support; Transportation; Planning and Environment) who gave excellent advice early in our project planning.
- Key stakeholders may include planning office, local communities, environmental bodies, grid operators/energy providers, statutory consultees, etc.

Renewable Scale

- Due to the relative inefficiencies of converting renewably generated electricity into hydrogen (and via fuel cell back into electricity) it is generally recommended to over-scale the generators compared to primary demand.
- Consider over-specifying to allow for peak demands, future up-scaling and potential export revenue; generally the larger the renewable-generating capacity the more frequently a system will have excess power which can be sold/ exported via grid connection, or converted into additional hydrogen fuel for sale.

Energy usage granularity

- It is recommended that energy data is recorded at the highest granularity possible, for as long as possible, when considering modelling an energy system; this will reduce unneccessary contingency costs/oversizing.
- It is recommended to gather 1+ year of energy use data if possible.
- Energy demand varies minute by minute, and there are pronounced seasonal variations with occasional spikes of energy usage, e.g. during harvest. It is recommended to make records of these 'spikes' where possible to append to annual data.

Grid Connection Options

- In all three Cases presented, HydroGlen is capable of generating all the required energy locally.
- By adding a 100kW grid connection in CASE 2 and 3, the project is able to reduce the total storage requirement onsite and balance potential fluctuations.
- It is recommended that an initial investigation of local available grid capacity is undertaken as this can simplify system requirements and potentially provide an additional revenue stream.

10. Green Hydrogen Production Support in Scotland

This is an important time to consider green hydrogen production in Scotland. The Scottish Government has set world-leading targets for net-zero GHG emissions by 2045 and has highlighted the role that hydrogen will play in meeting energy demands for heating, transport and industrial sectors in the transition to net zero within their *Hydrogen Policy Statement* published in December 2020[11]. *"Our vision is for Scotland to become a leading Hydrogen Nation in the production of reliable, competitive,*

[11] https://www.gov.scot/publications/scottish-government-hydrogen-policy-statement/

sustainable hydrogen and secure Scotland's future as a centre of international excellence as we establish the innovation, skills and supply chain that will underpin our energy transition."

The Scottish Government has pledged to support the development of Scotland's hydrogen production capability to a target of at least 5 GW by 2030, and at least 25 GW by 2045, with £100m funding support to be implemented through their *Hydrogen Action Plan*, to be published soon.

The Scottish Government has already backed large projects such as H100 Fife, Port of Nigg, and the Marine Vessel Hydrogen Transportation and Storage project. To date the primary focus has been on centralised, large-scale projects involving high-volume production of blue hydrogen (i.e. hydrogen created from fossil sources, where the carbon emissions are captured and stored). There is some Government support for green hydrogen Community Energy projects (such as the funding awarded to our HydroGlen feasibility study) and there are indications that this might increase in future; for example, the explicit mention in the *Hydrogen Policy Statement* of the opportunity for remote rural and island communities to produce and use hydrogen, enabling effective decarbonisation and creating substantial local economic benefits. There are some excellent examples of green hydrogen producers at a range of scales in Orkney[12,13], where the first hydrogen development was built by the European Marine Energy Centre in 2016; a Green Hydrogen Hub feasibility study is also currently under way in the Western Isles[14], jointly funded by Comhairle nan Eilean Siar, EDF Energy and the Scottish Government's Low Carbon Infrastructure Transition Programme.

There are major potential benefits of multiple scales of approach to green hydrogen production, augmenting large-scale centralised production units with networks of widely distributed smaller-scale hydrogen producers and users. More than 900,000 rural dwellers in Scotland[15] (11 million in UK) still rely mainly on carbon-intensive fuels[16], presenting an immediate opportunity to contribute meaningfully to both decarbonisation and hydrogen production targets by focusing efforts on rural communities where whole systems approaches to energy can directly address the combined requirements for electricity, heating and transport. There is also an opportunity to deploy and test different green hydrogen implementation options at small scale across multiple projects; where commercially available technologies already provide an economic case for deployment, scaling-up across multiple projects should enable significant cost-savings by increasing competition options for technology suppliers (e.g. increasing the total market volume should reduce the unit-price).

[12] https://www.orkney.com/life/energy/hydrogen
[13] https://www.orkney.com/news/hydro-gin
[14] https://www.welovestornoway.com/index.php/articles-auto-3/18949-hydrogen-future-for-isles-generators
[15] Rural Scotland: Key facts 2018. https://www.gov.scot/publications/rural-scotland-key-facts-2018/pages/2/
[16] HM Treasury Net Zero Review, December 2020.
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