DE-CENTRALISED GREEN HYDROGEN PRODUCTION SITE IDENTIFICATION AND OPPORTUNITIES STUDY

For Scottish Enterprise, South of Scotland Enterprise & Highlands & Islands Enterprise

Scottish Enterprise

HIE
Highlands and Islands Enterprise
Iomairt na Gàidhealtachd 's nan Eilean

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EXECUTIVE SUMMARY

Hydrogen has been identified as a key component on Scotland's transition to net-zero, with a number of production, storage, and distribution projects now in development across Scotland. In particular, Scotland's significant renewable energy capacity creates significant opportunities for 'green' hydrogen production –using renewable energy sources to create a zero emission fuel and energy source through electrolysis.

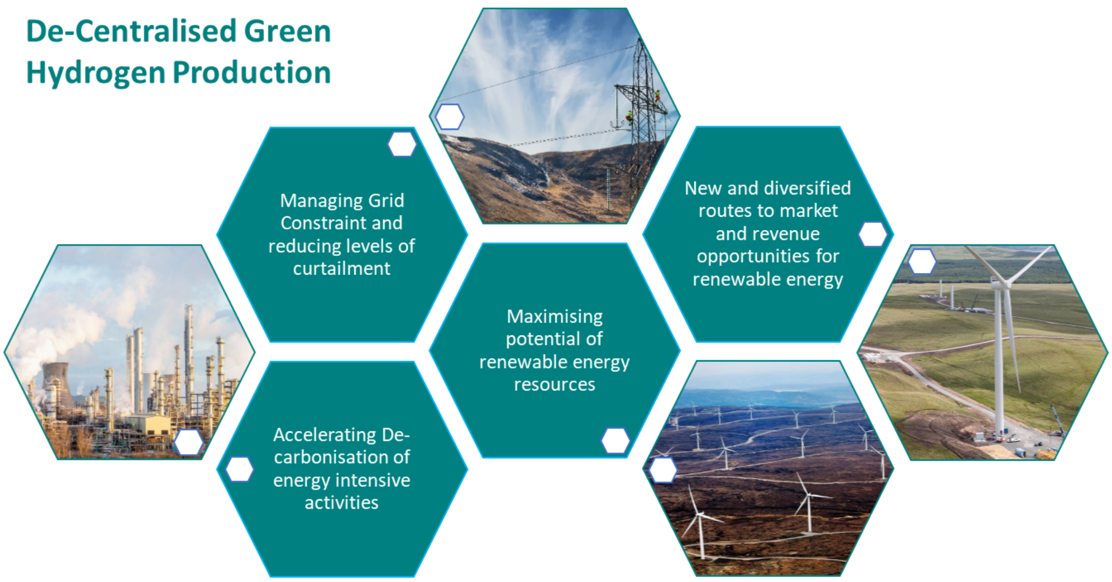
This Report has been prepared to provide an assessment of potential de-centralised green hydrogen production locations across Scotland, with an emphasis on utilising constrained renewable energy. It highlights a range of opportunities across Scotland where core site requirements around land, power and water can potentially be fulfilled and production of green hydrogen may be viable. The demand market for hydrogen and associated commercial viability considerations are continuing to evolve, though use cases and off-take sources are emerging that may complement and stimulate decentralised production.

Decentralised Production

Decentralised production means production of green hydrogen that is co-located to the generation of renewable energy as the source for electrolysis – utilising power from 'behind the meter' to provide a low or no cost source of energy to feed hydrogen production. It is typically at small to medium scale of c. 10-100MW, capable of being delivered in short-medium term, and for off-take to local sources of demand for zero carbon energy.

De-centralised production creates opportunities for hydrogen production at a dispersed and relatively small scale to support local decarbonisation and/or to take advantage of specific instances where there are high levels of renewable energy that cannot be exported to the grid due to constraint. It can be an early action and enabler in developing capacity, knowledge and confidence in Scotland's hydrogen economy by providing 'scale-up' projects that demonstrate deliverability and utility of green hydrogen.

Green hydrogen production brings specific site and infrastructure requirements, principally relating to availability of renewable energy and water supply. Sourcing electricity is typically the largest component of hydrogen production costs, creating a strong incentive and opportunity to utilise constrained energy.



Grid Constraint

Large areas of the of the electrical transmission and distribution network in Scotland experience 'constraint' meaning they operate close to their operational limits, and require generators to reduce ('curtail') their output to maintain stability. Reinforcement and upgrade of grid capacity is ongoing by National Grid (NG) and Distribution Network Operators (SPEN / SSEN) but will be unable to match the anticipated further growth of renewable generation. As a result, constraint will continue over the medium-longer term and building flexibility, responsiveness and ability to link surplus renewable generation to a hydrogen economy will become increasingly important (along with other forms of energy storage such as batteries and pumped hydro storage).

Grid constraint is a dynamic and variable process, subject to variation even within local contexts, depending on nature of grid connection, scale of generation, and modes of management and grid balancing by network operators. In seeking to identify constraint at a site / operator specific level, this Report has developed three strands of analysis to identify locations where renewable energy is (or is likely to be) curtailed such that green hydrogen *could* offer a solution (subject to future commercial viability and incentives).

1. Renewable generation sites participating in **National Grid Balancing Mechanism** – whereby generators are compensated to 'curtail' their output to maintain grid stability.
2. **Planned sites without grid connection** – sites currently progressing through planning system but which do not appear to have confirmed grid connection with either NG, SPEN, or SSEN.
3. Sites with a **Flexible or 'Non-Firm' Grid Connection** – meaning they have a Grid Connection but which is restricted in some form to manage network load.

Clusters

From the analysis of constrained renewable energy generation locations a 'shortlist' of sites that could be suitable for decentralised green hydrogen production have been identified and mapped – including currently operational and planned sites. To focus review on specific locations and geographies, 'Clusters' where there groupings of shortlist sites and/or where there is known grid constraint (as indicated by SPEN / SSEN Heat Maps) have been defined and are shown overleaf.

1. **Dumfries & Galloway**
2. **South & East Ayrshire**
3. **South Lanarkshire**
4. **East Lothian & Borders**
5. **South Lanarkshire & West Lothian**
6. **Loch Ness**
7. **Cromarty & Ross-Shire**
8. **Orkney & Shetland Isles**

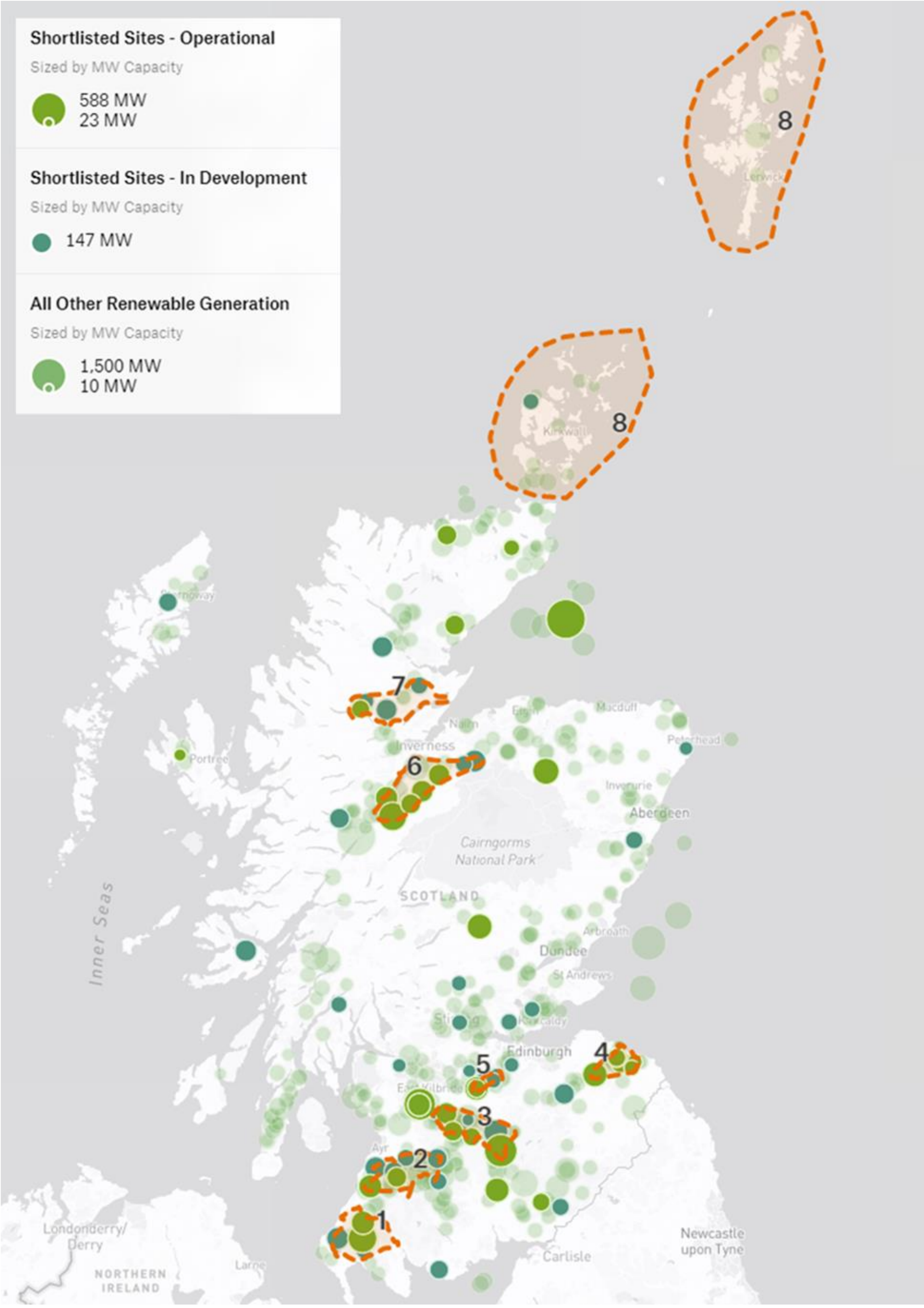


Figure 1. Scotland-wide map showing locations of identified clusters – derived from sub-regional groupings of constrained renewable energy generation. More specific and detailed maps of clusters and analysis of their characteristics and potential for green hydrogen production are set out in Section 4 of this Report.

Factsheets have been developed for each Cluster to detail the scale and spatial distribution of renewable energy, especially constrained energy, along with other key factors relevant to deliverability of de-centralised green hydrogen production, including:

- Existing assets and infrastructures (including vacant land, utilities, transport infrastructures) that could be utilised in green hydrogen production and distribution.
- Planning status and constraints – including major environmental designations.
- Grid infrastructure and gas network infrastructure (Transmission + SGN Network)
- Waterbodies, watercourses and potential abstraction availability, and indication of potential supply from Scottish Water network.
- Local industrial activity or transport that may be suitable for integration as a zero-carbon fuel source.

Summary Conclusions

Through detailed review of decentralised green hydrogen production requirements, grid constraint, and mapping of potential Clusters, the Report concludes that:

- Notwithstanding planned transmission and distribution infrastructure reinforcement, constraint is likely to be a challenge for renewables generation over the medium-longer term (albeit its spatial distribution and extents may be variable). Technologies for utilising or storing excess power that are relatively flexible, modular and responsive, including green hydrogen, will become increasingly important in the future operation of the energy system.

- While subject to commercial viability and site-specific feasibility, decentralised production offers strong synergies and 'win-win' potential to address overlapping challenges around maximising Scotland's renewable energy potential and reducing curtailment, creating new revenue and diversification opportunities for renewables operators, and accelerating the decarbonisation of energy intensive activities and sectors.

- Across review of the Clusters the following commonalities and shared characteristics emerged:
    - A common constraint or challenge across Clusters in the need for ready off-takers and sources of demand for green hydrogen. The hydrogen economy is continuing to develop and mature, and notwithstanding opportunities that are identifiable through 'supply-side' analysis, it is likely that strong opportunity sites will emerge from 'demand side' where there is a strong market and needs case for hydrogen integration.
    - For smaller scale decentralised production that is co-located to renewable energy generation, preferred siting of green hydrogen production is likely to be on or adjacent to existing infrastructures, haul routes / access roads, and/or utilising disturbed land such as construction compounds or restored borrow pits. This will limit potential for environmental impact and reduce complexity in project delivery.
    - In short term and for production at decentralised scale – it is likely that off-take of hydrogen will be via compressed tube trailer for transport to end-user. This is the case for current in-development projects, and reflects the relatively rural and remote locations of most renewable energy generation.
    - For small-medium scale production water requirements are likely to be capable of being met through a combination of ground and surface water abstraction – though operator preference for siting production 'behind the meter' and co-located to existing energy infrastructures may result in being separated from water sources and a preference for a Scottish Water supply with greater certainty.

1. INTRODUCTION

Hydrogen has been identified as a key component of Scotland's transition to net zero. It can be a versatile vector of low-carbon energy with a range of potential applications and uses especially across industry and transport. Scotland's significant renewable energy generation capacity is set to continue growing through coming decades and will exceed indigenous power requirements, creating significant opportunities for green hydrogen production.

A range of green hydrogen production projects are now in development and feasibility across Scotland, including small, localised production to support decarbonisation in specific sectors, as well as large-scale strategic projects linked to ScotWind and exploring export to European markets. Scottish Enterprise (and partner Development Agencies) are actively seeking to support innovation, growth, and inward investment in the hydrogen economy across all scales.

Purpose of Study

Scottish Enterprise's vision for hydrogen is that Scotland is a leading hydrogen producer with an innovative and competitive supply chain in manufacturing and services that anchors jobs, capability and knowledge. Scotland has an excellent reputation as a nation with hydrogen expertise, ambition and action driving investment and export opportunities.

In this context, a key enabling action for Scottish Enterprise in growing Scotland's hydrogen capacity and promoting opportunities is to identify and assess locations which are potentially suitable for green hydrogen production. Ironside Farrar have been commissioned to lead a site identification study, reviewing potential production sites and locations with a specific focus on opportunities for "decentralised production". In addition, a key requirement for the study is to identify and review those locations where renewable energy generation is constrained by grid capacity and/or undergoing curtailment, for which green hydrogen production could provide a combination of benefits.

"De-centralised production" means production of green hydrogen that is co-located to the generation of renewable energy as the source for electrolysis. It is typically at small to medium scale of c. 10-100MW and for off-take to local sources of demand for zero-carbon energy.

The Study is focused on 'Green' hydrogen produced using renewable energy sources (eg. wind) to create a zero-emission fuel and energy source through electrolysis. 'Blue' Hydrogen produced through reformation of natural gas and carbon capture will provide part of the future hydrogen economy and be well suited to certain activities and locations, but is not reviewed as part of this Study.

Green hydrogen production is a specialised process that brings specific site requirements – most fundamentally around the combination of renewable energy and water supply as key feedstocks to the electrolysis process. Demand-side locational factors including a route to market and off-take for green hydrogen, or potential export capability, are also recognised as key influences on future site suitability and selection.

The purpose of this Report is therefore a focused review of existing or currently planned renewable energy projects, identifying where these are constrained by grid capacity, and where these locations align with other requirements for decentralised green hydrogen production. It has been prepared to a specific and well-defined Brief with the following parameters and objectives:

- Identifying and mapping renewable energy generation locations across Scotland, with particular focus on identifying those locations where generation is constrained, or subject to curtailment.
- Spatial and geographic analysis of constrained renewable energy generation locations relative to core green hydrogen production requirements[1].
- Reviewing potential for decentralised green hydrogen production at small-medium scale, within an approximate range of 10MW to 100MW (with the scale of production driven by the availability of input energy)[2].

In the context of the above Brief, it should be noted the Report is not an exhaustive search of all potential green hydrogen production locations across Scotland. It is a spatial-led review of opportunities for a specific type and scale of green hydrogen production, with a focus on grid constraint. Similarly, analysis has reviewed grid constraint at a high-level through review of available National Grid / SPEN / SSEN data but is not a comprehensive technical assessment of grid infrastructure capacity, and the complex overlapping processes of subsidy mechanisms, curtailment payments, and wholesale electricity market movements / pricing. These will influence and shape the future of constraint and hydrogen production in Scotland and require further detailed investigation in coordination with industry and network operators.

The Report provides an independent, spatial analysis of potential locations across Scotland where green hydrogen production could be co-located with renewable energy generation. It has been developed in coordination with Scottish Enterprise (SE), South of Scotland Enterprise (SOSE), and Highlands & Islands Enterprise (HIE), as well as with technical input and advice from Scottish Water (SW) and Scotia Gas Networks (SGN) on their respective utility networks.

It has also been informed by direct engagement with wider stakeholders operating in the Scottish hydrogen economy to provide wider context and background to analysis. It is intended to support SE in further engagement with renewable energy operators and in promoting Scotland as a well-positioned and highly competitive location for hydrogen production. It is intended to provide a resource for Scottish Enterprise and other agencies to inform future planning, engagement with landowners and operators on hydrogen economy opportunities, maximising the potential of existing or currently planned renewables projects.

Methodology & Approach

Responding to the above described Brief, development of reporting has been undertaken principally through collation, mapping, and cross-reference of a range of publicly available data-sets to inform spatial analysis of green hydrogen production opportunities.

As shown in Figure 2, the Report has sought to establish and review in detail the status of renewable energy generation projects across Scotland (based primarily upon BEIS Renewable Energy Planning Database). It has subsequently reviewed their grid connection and/or level of constraint based upon available data, and undertaken a spatial analysis of potential feasibility for green hydrogen

[1] More comprehensive review of the technical feasibility and commercial viability of green hydrogen production in specified locations will be required but is not considered in detail in this site identification study.

[2] Opportunities for larger-scale and more centralised production will arise from ScotWind and continued renewables growth, but are not considered in detail in this study. Further review and identification of large-scale production opportunities will continue through coordination between Development Agencies, Industry, Utility Operators, and Scottish Government in accordance with the Hydrogen Action Plan (2022).

production based upon known hydrogen production requirements around renewable electricity, water, land, and demand / export opportunity. The analysis has outlined opportunities and constraints for decentralised green hydrogen production at a range of 'Clusters' across Scotland, and pointed towards key issues and considerations that can inform further collaboration, engagement, and detailed review of feasibility.

Reporting has been developed in an iterative, staged process as outlined below. More detailed explanation of the method to identifying curtailment and the process of site analysis is set out within Section 3.

Stage 1: Project Inception	• Establish project objectives and outputs in coordination with Client Steering Group • Collate and obtain data sources / mapping / info to support site identification and review.
Stage 2a: Identifying and Mapping Renewable Energy	• Review, filter and map BEIS Renewable Energy Planning Database (REPD) to identify generation locations across Scotland. Including all currently operational sites and those currently in planning system. See Figure 2.
Stage 2b: Identifying and Mapping Constraint / Curtailment	• Cross-refer BEIS REPD to Connection Registers to identify nature of grid connection and potential constraint. (Further detail of the approach to identifying renewable energy constraint / curtailment is provided within Section 3). • Review curtailment levels for renewable energy generation as managed through National Grid Balancing Mechanism. • Identify sites with Flexible / Non-Firm Grid Connections. • Filter and map sites / locations subject to grid constraint and curtailment. • Stakeholder Workshop with hydrogen sector operators / bodies / interests to add wider context and understanding to reporting (see below). • Group sites into sub-regional 'Clusters' for more detailed spatial analysis of opportunities & constraints, and fit with key hydrogen production site criteria.
Stage 3: Spatial Analysis	• Overlay and add to mapping range of local environmental constraints, existing infrastructure / assets, utilities networks, and other factors which may influence site suitability. • Review potential water availability at identified locations – based upon data provided by Scottish Water / SGN. • Share and review emerging findings with Client Steering Group, including cross-reference to parallel research on hydrogen demand locations.
Stage 4: Reporting	• Develop 'Factsheets' for identified clusters with mapping and commentary on key issues, opportunities, and constraints for decentralised production. • Prepare Final Reporting.

Data and sources of information reviewed and which has informed preparation of reporting includes:

- BEIS Renewable Energy Planning Database
- National Grid Transmission Network Connection Register
- Scottish Power Energy Networks (SPEN) Embedded Connection Register
- SPEN and SSEN Distributed Generation Heat Maps
- NatureScot Environmental Designations Mapping
- National Gas Transmission Network Plan
- SEPA Pollutant Release Inventory Database
- Current / Planned hydrogen production projects (provided by Scottish Enterprise on confidential basis)
- Local Authority Planning Registers
- National Grid Embedded Connection Register
- Scottish & Southern Electricity Networks (SSEN) Embedded Connection Register
- Renewable Energy Curtailment Data (collated via Renewable Energy Foundation)
- Historic Environment Scotland (HES) Designations Mapping
- SEPA Flood Risk Mapping
- HydroSHEDS Global Rivers & Lakes

It should be noted that the Report and sites identified within provide a review of potential locations for decentralised production at this point in time, with a focus on locations where renewable energy is currently or is likely to be constrained. It is not an exhaustive list of all locations where renewable energy is constrained, but has sought to identify and focus analysis toward specific locations across Scotland led by review of available BEIS, National Grid, SPEN, SSEN data. Grid constraint and the process of curtailment is a dynamic, interactive process that is not fixed and will shift over time in response to reinforcement and models of network management by National Grid and DNO's.

Through future innovation, legislative & policy reform, and market growth, the technological capabilities and economic incentives around green hydrogen production are likely to change beyond those currently assumed and considered for this Report. It remains a relatively nascent market for which supply-side and demand-side interests are interacting and evolving in tandem, such that new locations suitable for hydrogen production will emerge as the market develops and matures.

Finally, the development of reporting has been led by review of technical data and site analysis, but is not informed by engagement with specific landowners / renewable generation operators. It is intended to provide an overview of key factors influencing potential production suitability, though it should be recognised that the specific siting, scale, and model of production would depend on commercial and operational considerations by the site operators.

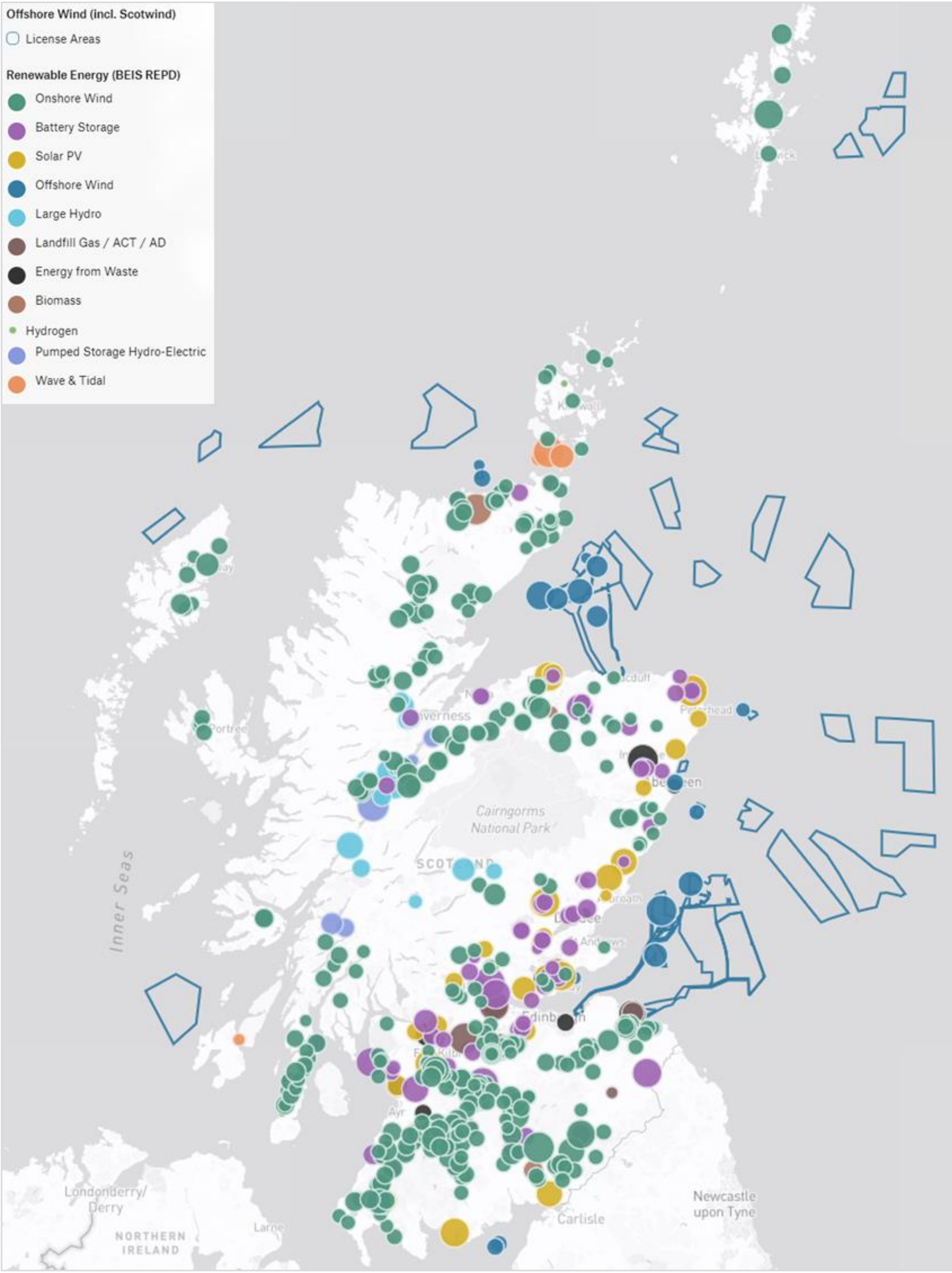


Figure 2. All renewable generation projects in Scotland (above 10MW+) currently operational, under construction, approved, or with planning applications submitted, as listed on the BEIS Renewable Energy Planning Database. Bubble sizes represent the relative scale of renewable energy production (MW) for each technology. While not formally in the planning system Scotwind Leasing Zones have been added given their potential to significantly increase capacity. As renewable energy generation continues to grow it will create opportunities for hydrogen production at a range of scales

Stakeholder Engagement

As noted above hydrogen is an emerging sector with technologies, practices, infrastructures continuing to be developed and tested through a range of pilot and 'demonstrator' projects. There has been a significant body of research and prior investigation into hydrogen as potential future low-carbon fuel source, recognising Scotland's potential to be a leader in this sector. To ensure the Report had regard to this pre-existing knowledge base, a list of key stakeholders and interested parties that was developed with the Client Steering Group to add insight and feedback.

Figure 3. Stakeholder groups and organisations consulted with during the preparation of the Study – including through a Workshop meeting to review emerging findings and key issues for decentralised hydrogen production.

The progression of reporting was subsequently informed by engagement and consultation with these stakeholders in the Scottish hydrogen sector. The purpose of the engagement was to supplement desk-based analysis and technical review with insight and experience from industry operators and other areas of research.

The principal engagement activity was a stakeholder workshop was held in February 2023 to review the approach and methodology to the Report and to add context and wider understanding of opportunities, challenges, and key issues influencing hydrogen site identification and selection. Key issues discussed and areas of feedback from the stakeholder group are summarised below. Engagement meetings were also held with Scottish Renewables and NatureScot (who were unable to attend the workshop) to brief them on the study and emerging outcomes.

In addition to the stakeholder workshop, direct knowledge and info-sharing with Scottish Water was undertaken to add technical understanding of potential water supply availability and capacity at a range of potential locations. Engagement with Scottish Water also sought to explore potential opportunities and synergies that may exist around hydrogen production and water supply, particularly for waste-water treatment works. Similarly, info-sharing with Scotia Gas Networks was supported more detailed understanding of existing gas network infrastructure and where opportunities for blending may emerge, subject to future technical feasibility and legislation.

In addition to engagement with stakeholders and groups, regular Client Steering Group review meetings have been held throughout the duration of the study, attended by Scottish Enterprise, South of Scotland Enterprise, and Highlands & Islands Enterprise. Review meetings have provided oversight and review of emerging project findings, feedback on potential production locations and key issues, as well as wider knowledge sharing from parallel workstreams within the Development Agencies.

STAKEHOLDER ENGAGEMENT SUMMARY	
Theme / Topic	**Feedback / Insight / Knowledge-Sharing**
Hydrogen Production Site Requirements	Anticipated decentralised hydrogen production site requirements (see Section 2) were noted as broadly accurate and reflected current projects across Scotland. Noted that land area requirements may be subject to increase depending on levels of storage, compression and other infrastructures required to support production. Noted that production capacity factors is variable with direct connection to renewable energy generation, and site requirements may differ accordingly depending on site location, source of renewable generation, linked Battery Energy Storage Systems (BESS) and other factors. The resilience and reliability of electrolysis feedstocks (electricity / water) was noted as a key commercial consideration.
Emerging Hydrogen Projects	Emerging hydrogen production, storage, and distribution projects across Scotland were noted and discussed, demonstrating the range of potential applications and markets that may exist within a future hydrogen economy. This included: • North of Scotland Hydrogen Programme – under development by range of private / public partners around Cromarty Firth to serve decarbonisation of local distilling sector. • SGN H100 Programme – pilot development of hydrogen-to-homes heating network in Buckhaven and Denbeath (Fife). • Hydrogen Backbone Link – project led by NZTC to develop export capability across multiple sites through re-purposing and optimising existing pipeline infrastructure, and review options for marine transport, linking sources of supply and demand between Scotland and Europe.
Grid Constraint and Capacity	There are significant levels of grid constraint in a range of locations across Scotland, and this will present opportunities. The nature and extent of curtailment is changeable, as DNO's invest in grid reinforcement and renewable generation capacity continues to grow (especially offshore). It was highlighted that renewable electricity is the most significant cost factor for green hydrogen, and opportunities for 'behind the meter' supply can provide a major incentive. However, significant commercial challenges can remain around up-front investment and matching to locations of market demand, especially at small-scale.
Market Demand	There is a range of ongoing research, knowledge gathering and commercial feasibility testing to develop locations where elements of the hydrogen economy and supply-chain can co-locate and cluster, as outlined in the Hydrogen Action Plan. A key theme that emerged was the importance of end-user demand as a key driver and influencing factor for site identification, particularly at the early stage of developing a market for green hydrogen production. The competitiveness and 'Needs Case' for green hydrogen as a decarbonisation technology must continue to be strengthened, in order to create investable / developable propositions.

2. GREEN HYDROGEN: STRATEGIC CONTEXT & OPPORTUNITY

Scotland has vast resources in onshore and offshore wind, and potential for future at-scale deployment of wind and tidal. Given planned levels of development renewable generation will significantly surpass indigenous demand over coming decades. This will create a need to export electricity (with upgraded transmission infrastructure), electrify current fossil-fuel based processes and technologies, and store and convert electricity into other forms of energy. In this respect, hydrogen provides an attractive means to fully tap the potential of Scotland's major renewable resources and position Scotland as a world leader in green energy. Alongside other means of energy storage or diversification, hydrogen can provide opportunities for 'hybrid' renewable energy production models as well as opening new markets and revenue streams for generators.

Green Hydrogen – Sectoral & Policy Overview

Scotland is committed to achieving net zero greenhouse gas emissions by 2045, as set out within the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 and reflected in the Climate Change Plan (2018-2032 - Update). To do so requires significant levels of innovation, advancement of technologies, and transition to green energy to replace energy demand previously met by fossil fuel sources. Significant progress has been made in the decarbonisation of Scotland's electricity generation through the large-scale deployment renewable energy technologies, especially on-shore wind. This will continue through the further deployment of off-shore wind through ScotWind and continued growth, technical advancement, and diversification of renewable energy technologies.

Crucial to achieving full decarbonisation is to replace fossil fuels and reduce emissions in sectors such as transport, heating, and energy intensive industries which are challenging to fully electrify. It is in these activities and sectors that there is a significant opportunity for hydrogen - making full use of Scotland's renewable energy resources to produce hydrogen and realising a fully decarbonised economy. Scotland has strong fundamental qualities that will support hydrogen production, including major scales of renewable energy, reliable water resources, and infrastructures both physical and non-physical around gas distribution and export that can be transferred to the hydrogen sector.

At UK and Scottish Government levels, and across local authorities, this potential for hydrogen to play a significant role in meeting future energy needs is now well recognised. There is now considerable policy support, ambition, and active development interest in green hydrogen production in locations across Scotland, and at scales ranging from small-scale production meeting local need (eg. Orkney BIG HIT) to much larger, strategic opportunities for international export (eg. Hydrogen Backbone Link). The table below summarises key policy context and priorities around growth of the Scottish hydrogen economy, particularly with regard to decentralised production opportunities.

SCOTTISH HYDROGEN ECONOMY – POLICY CONTEXT	
Policy / Document	**Summary / Key Conclusions relevant to De-Centralised Production**
Scottish Hydrogen Assessment (December 2020)	• Investment in hydrogen production will provide strong economic benefits and contribute to energy transition – with green hydrogen production increasingly dominant as costs reduce. It will play a role in all Scotland's regions – reflecting distribution of resources and geography specific demands for island and rural communities, industrial clusters, and urban areas. • Hydrogen is in early stages as an energy carrier and flexibility should be maintained over future applications. Speed of deployment is key and Scotland should seek to develop advance projects and infrastructures that will allow it to become a centre for production and export of hydrogen and associated skills, products and services. • Early production is likely to be small-medium scale, primarily using on-shore wind and co-located or near to end users. Constrained renewables provides a clear opportunity for green hydrogen production.
Scottish Government Hydrogen Policy Statement (December 2020)	• Ambition to produce at least 5GW of renewable and low-carbon hydrogen by 2030, and at least 25GW by 2045. £100m funding is committed to support development of Scotland's hydrogen economy over the period 2021-2026. • Support for demonstration, development, and deployment of hydrogen and its emergent role in sustainable decarbonisation of industry, transport, and heat. Priorities and actions for the 2020's include: ○ Supporting research, innovation, development and demonstration to build capability – and ensuring supportive policy framework. ○ Supporting low-carbon hydrogen production and transition of existing supply-chain companies to develop technologies in the hydrogen value chain. ○ Establishing hydrogen demand in transport and industrial application and accelerating this demand through supporting actions investment. • Longer term actions through 2030's and 2040's to include scaling-up of production for wider range of domestic applications and export, reducing costs, developing competitive supply-chain and supportive infrastructures for refuelling, transportation, and pipelines.
Scotland Hydrogen Action Plan (December 2022)	• In the short term, Scottish Government will focus activity and investment to accelerate hydrogen production from constrained onshore wind • 13 Regional Hydrogen Energy Hubs are identified with potential of hosting entire hydrogen value chain, from production, storage and distribution, to end-use. • Priority uses likely to include users / sectors / activities where there are fewer alternatives such as steel & metals fabrication, distilleries, refineries and chemical processes, and other manufacturing / production processes requiring high-temperature heat. Less preference towards domestic heating and light road vehicles for which hydrogen is relatively inefficient.
Draft Energy Strategy & Just Transition Plan (January 2023)	• The growth of the hydrogen economy is dependent on supply and demand developing in concert, as well as enabling infrastructure to produce, store and distribute hydrogen products. • The growth of a strong hydrogen sector offers significant opportunities for regional and local economic benefit, creating new high-quality green jobs in our rural communities, islands and cities, and new opportunities for those currently working in high carbon sectors.
National Planning Framework 4 (February 2023)	• Significant weight is given to tackling global climate emergency and it encourages, promotes and seeks to facilitate all forms of renewable energy development, including hydrogen. • The National Development for 'Energy Innovation Development on the Islands' specifically identifies the potential of the Outer Hebrides, Shetland and Orkney for renewables generation and hydrogen production and infrastructure. It can play a key role in decarbonisation of these areas, strengthening energy security, and creating a low-carbon economy. • The potential for hydrogen to support decarbonisation within 'Industrial Green Transition Zones' at Grangemouth, St Fergus and Peterhead (National Development 15) is also strongly supported.

As demonstrated within the Hydrogen Action Plan (2022) there is a wide range of emerging hydrogen projects – see Figure 5 below.. There are particular clusters within the North-East and Orkney Isles which have been early adopters and innovators in hydrogen production and utilisation, though opportunities exist across Scotland and will continue to emerge as the market for hydrogen matures. As well as growth of supply chain capacity, the future development and realisation of these opportunities will in large part be responsive to market demand and confidence.

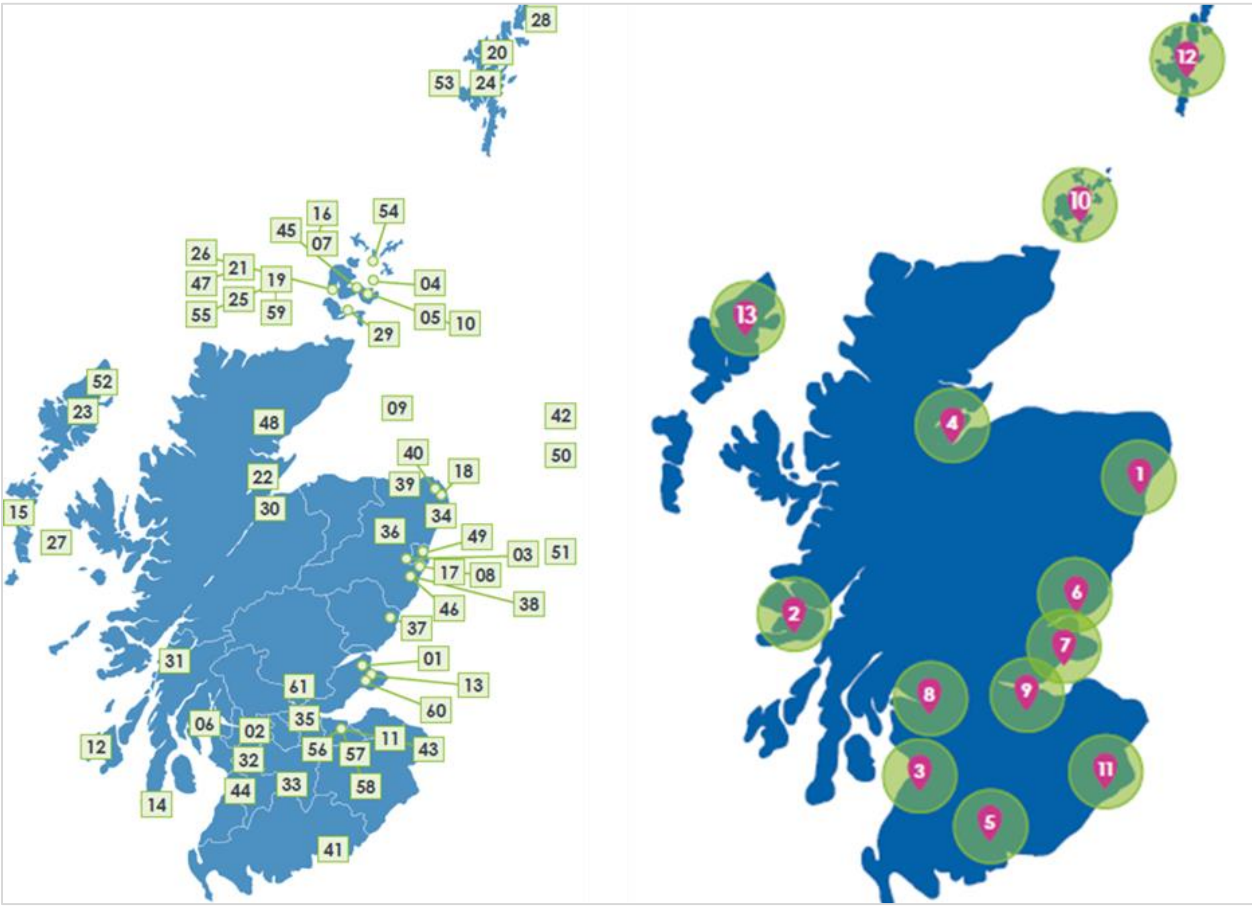


Figure 4. Hydrogen Action Plan (2022): Current & Planned Hydrogen Projects (left) and Potential Regional Hydrogen Hub Locations (right).

In addition to policy context set by Scottish Government, wider research and sectoral studies by agencies, stakeholders, and academia have recognised the critical role in decarbonising the energy system and its significant economic potential as part of energy transition. The following documents and research have been reviewed and provided context to reporting:

- Future Energy Scenarios (National Grid ESO, 2022)
- Offshore Wind Industry Council and Offshore Renewable Energy Catapults Offshore Wind and Hydrogen: Solving the Integration Challenge (2020)
- Development of early, clean hydrogen production in Scotland (Scottish Enterprise, NZTC, and OreCatapult, 2021)
- Deep Decarbonisation Pathways for Scottish Industries (Scottish Government, 2020)
- Decarbonising Scotland’s Industrial Sectors and Sites – A Paper for Discussion with Scottish Energy Intensive Industries (Scottish Government, 2019)
- Creating a Pipeline for Industrial Decarbonisation in Scotland (Element Energy, 2020 (accessed via ClimateXChange)

- Cost Reduction Pathways of Green Hydrogen Production in Scotland (Ove Arup & Partners, 2022 (accessed via ClimateXChange))
- The potential for hydrogen to reduce curtailment of renewable energy in Scotland (Graeme Hawker & Gareth Oakley, 2022 (accessed via ClimateXChange)).
- Net Zero Power and Hydrogen: Capacity Requirements for Flexibility: A Report to the Climate Change Committee (AFRY, March 2023)
- Feasibility study into water requirements for hydrogen production (SGN & Ramboll, 2022)
- Renewable curtailment and the role of long duration storage: Report for Drax (LCP, 2022)
- The Clean Hydrogen Ladder: An Introduction (Liebreich Associates, 2021)

De-Centralised Production Opportunities

While there a wide range of potential production, distribution, and utilisation opportunites within the hydrogen economy, the primary focus of this Report is identifying and exploring opportunities for 'decentralised' hydrogen production. While not defined by strict parameters, decentralised production would typically be distributed and dispersed across a range of locations and have the following characteristics:

- Co-located to renewable energy generation and utilising power from 'behind the meter' – meaning utilisation of on-site generation without passing through a meter or being exported to the grid. Electricity is therefore transferred directly to an electrolyser and can provide a low/no cost source of energy to feed hydrogen production.

- At small-medium scale of approximately 10-100 MW (though exact parameters and scale of production would vary by location and in response to demand)

- Capable of being delivered in short-medium term – drawing from pre-existing / currently planned sources of renewable energy and benefitting from the modular and scalable nature of electrolysers compared to other energy infrastructures. In many instances decentralised production will utilise and link to infrastructure and assets that have been developed around renewable energy generation such as access routes, sub-stations, and cable ducts.

- Produced for distribution to nearby sources of demand for green hydrogen as a zero-carbon fuel, or in certain locations for export and longer distance transport to off-takers.

De-centralised production creates opportunities for hydrogen production at a dispersed and relatively small scale to support local decarbonisation, and / or to take advantage of specific instances where there are high levels of available renewable energy that cannot be exported to the grid. In a future hydrogen economy these models of decentralised production will play a significant role in delivering decarbonisation across Scotland especially in more remote and rural locations where it can form part of 'whole-systems' approach to energy and create local economic benefits.

De-centralised production is also a potential early action and enabler in developing capacity, knowledge, and confidence in Scotland's hydrogen economy. It can provide effective 'pilot' and 'scale-up' projects to demonstrate the deliverability and utility of green hydrogen, supporting subsequent expansion and large-scale deployment over time. It will also have an important 'market-making' function, establishing capabilities, stimulating and meeting early demand, and laying foundations for long-term growth of a hydrogen supply-chain in Scotland.

It is recognised that within the above broadly defined characteristics there will be different types and modes of production and not all characteristics will apply equally to all potential locations. As the hydrogen sector grows and matures the specific nature of decentralised production models will diversify and be tailored to meet specific supply-side or demand-side opportunities, and to respond to other economic incentives driving production. The above listed characteristics are intended as a broad guide to shape site identification and review, alongside more specific technical production criteria for power, water, and land (see Section 3).

Case Studies: De-centralised Production

As shown above, there are a range of hydrogen production projects currently in development across Scotland, and at various stages of readiness, certainty, and definition. Demonstration and pilot projects have been developed, such as Aberdeen City Council's 'H2 Aberdeen' Programme and SGN's H100 Project in Fife, though there is now increasing momentum and interest in commercial-led production opportunities.

Examples of decentralised production are now emerging– including projects currently in development at Whitelees Wind Farm (East Renfrewshire) and Gordonbush Windfarm (Highland), as well as at Strathallan (Perth & Kinross) and Hammars Hill (Orkney – producing ammonia).

Whitelees[3] and Gordonbush[4] have been reviewed as case studies of innovative and private sector-led decentralised production[5]. While still under development, they provide a model of decentralised production that is co-located to existing renewable energy generation ('behind the meter') and can help mitigate grid constraint, support decarbonisation, and diversify revenue as part of a 'hybrid' renewables generation model.

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[3] Information obtained and summarised from Scottish Power Renewables – Planning & EIA Documentation: https://www.scottishpowerrenewables.com/pages/whitelee_solar_hydrogen_bess_.aspx

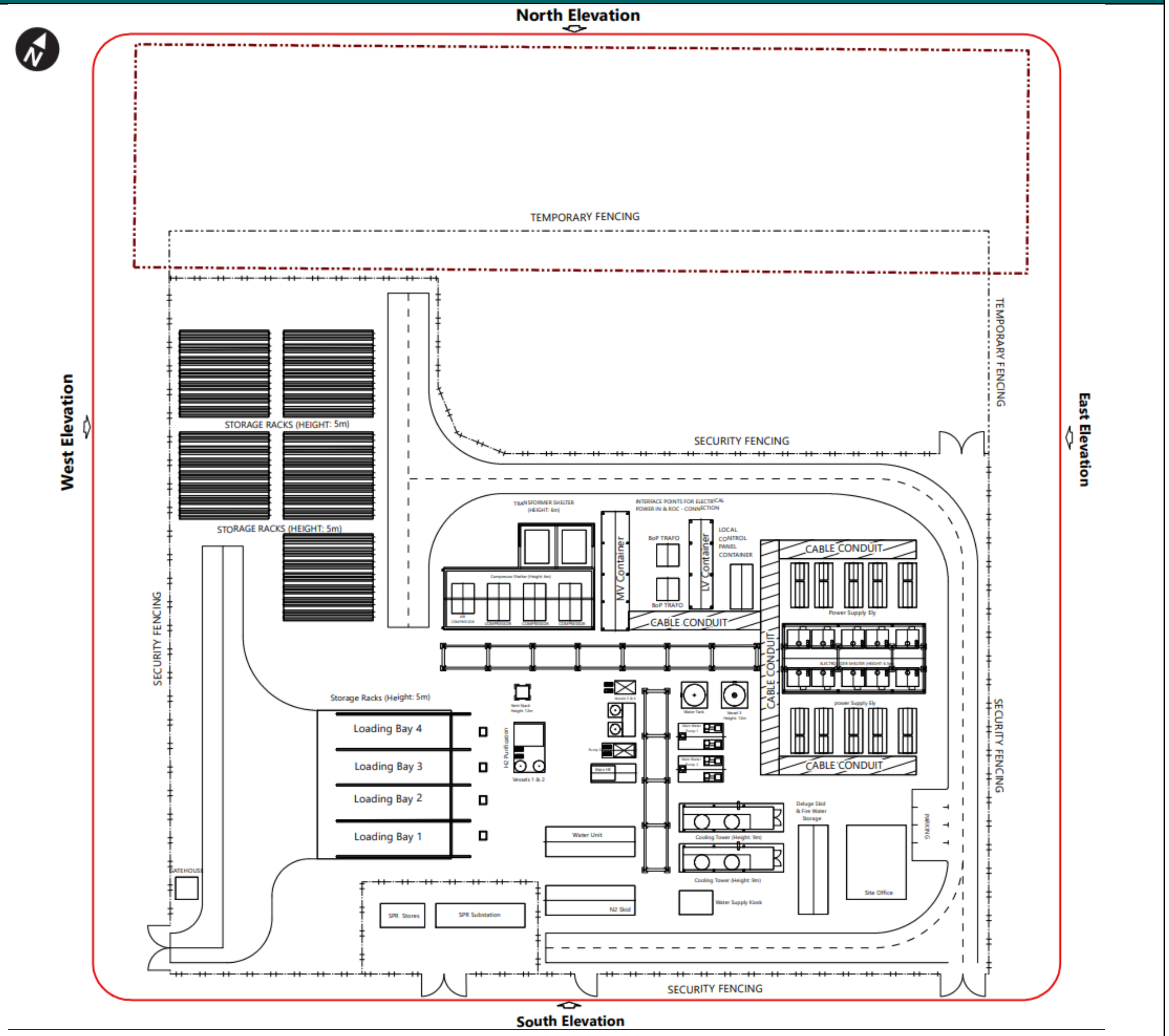
[4] Information obtained and summarised from SSE Renewables – Planning & EIA Documentation: https://www.sserenewables.com/onshore/green-hydrogen-co-location/gordonbush-wind-farm/

[5] It is noted that water demands quoted for the two case studies show considerable variation. This is likely due to difference in definition / measurement of total requirement though it is not possible to determine exact rationale for difference from available planning documentation which provides only a high-level total figure.

WHITELEES GREEN HYDROGEN PRODUCTION

Scottish Power Renewables is developing a co-located hydrogen production facility (along with Solar & BESS) at Whitelees Windfarm in East Ayrshire & East Renfrewshire.

Land	1.44 hectare production site – co-located with proposed 40MW solar array to support hydrogen produuction. Situated at the northern edge of the overall Whitelees site / landholding. A 1.5km link/haul road is proposed to connect to the site. The site is situated outside of statutory environmental designations and well separated from nearby sensitive receptors. Specific siting informed by analysis of local peat depths.
Production	20MW Electrolysers producing c. 10,000kg of green hydrogen per day
Water	Demand up to c. 480,000 ltrs/day – expected to be supplied by mains water supply.
Market / Export	To fuel public transport and heavy freight vehicles as part of 'Green Hydrogen for Glasgow'. Distributed from site via tube-trailers utilising link/haul road and via road network (M77)
Energy Infrastructure	Co-located to Whitelees Wind Farm (539MW) and linked to development of Solar PV Farm (40MW) and BESS (50MW) to act as supplementary source of energy for green hydrogen production facility and increase capacity factor.



GORDONBUSH GREEN HYDROGEN PRODUCTION

SSE Renewables is developing a green hydrogen production facility at Gordonbush Windfarm in Ross-shire. An EIA Screening and PAN Notice were submitted in 2022 but a full planning application is not yet submitted.

Land	1.87 hectare production site. Utilising previously disturbed and recently re-instated land associated with construction and access to the existing wind farm. Directly adjacent to existing access track to wind farm, approximately 2.5km south-west of the nearest turbine.
Production	15MW electrolyser capacity, producing around 8,000 kg of hydrogen per day – to be compressed and temporarily stored on site prior to off-take.
Water	Demand up to c. 144,000 ltrs/day of water per day – anticipated to be met through groundwater abstraction (borehole) located within the footprint of the facility. Exact details of the water supply to be confirmed and remain under review.
Market / Export	Off-take via compressed H2 tube trailer to local industrial / energy intensive users – utilising existing track and local road network
Energy Infrastructure	Co-located to Gordonbush Wind Farm (109 MW).SSE's first subsidy free wind farm in Scotland and currently subject to curtailment. Development of complementary BESS explored but not taken forward as part of the project.

3. HYDROGEN PRODUCTION SITE REQUIREMENTS

The production of green hydrogen is a specialised process that brings specific development and infrastructure requirements, principally relating to availability of renewable energy and water supply. Understanding of these requirements and how they may be delivered has been developed through sectoral research, case study review, and stakeholder and client group input.

- **Power** – fundamental to production of green hydrogen is availability of renewable energy as a direct electrical feedstock to the electrolysis process. While the grid is rapidly decarbonising, green hydrogen production should be fed directly by renewable electricity to ensure hydrogen produced will have zero carbon content.

  Sourcing electricity is typically the largest component of hydrogen production costs, with opportunities to minimise this a major advantage. As a result it is likely that purchasing electricity from the grid (as opposed to sourcing from 'behind the meter' renewables) would bring potentially significant additional costs and challenge the competitiveness / commercial viability of production. Prior research commissioned by ClimateXChange (2022) highlighted that avoiding grid transmission charges / retail prices for electricity would be key to making green hydrogen competitive.

  The Climate Change Committee's 2023 Report 'Delivering a Reliable De-Carbonised Power System' highlights that zero-carbon electricity continues to have highest value (in terms of CO2 savings) when displacing fossil generation and meeting 'core' electricity demands that already exist in buildings and industry, and from efficient electrification such as electric vehicles or heat pumps. Production of hydrogen from zero-carbon electricity "*should therefore only be based on extra zero-carbon electricity capacity or from zero-carbon electricity sources where it is not possible to connect to the grid (e.g. 'stranded' renewable capacity that cannot feasibly connect to the electricity system*". In current energy systems context at least, there is therefore a priority to utilise 'surplus' renewable energy where possible for green hydrogen, rather than diverting renewable energy from the grid.

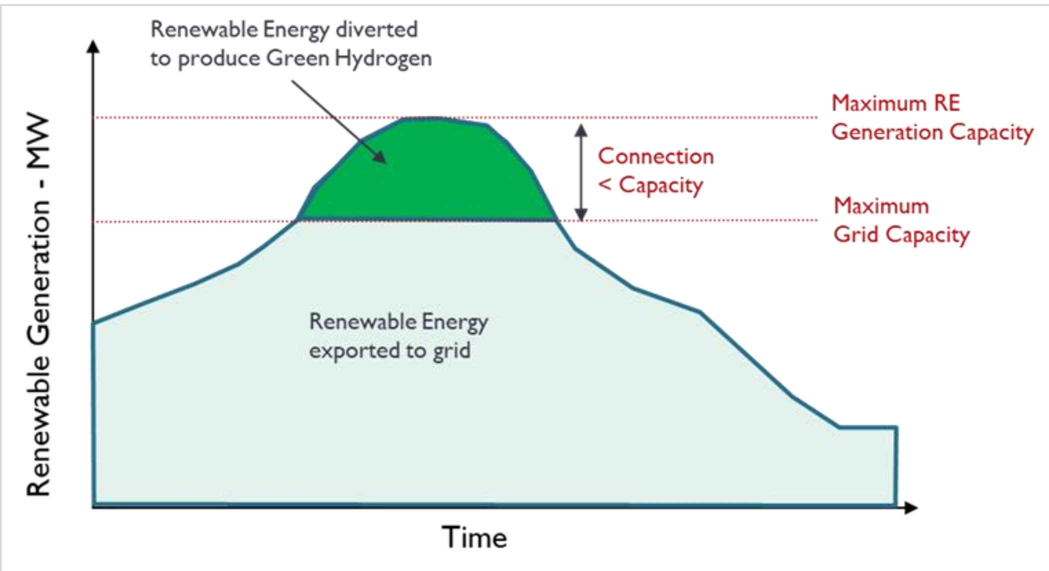


Figure 5. Illustrative concept graph (not to scale) showing principle of diverting constrained renewable energy towards green hydrogen production during periods where generation exceeds capacity to export to the grid. Levels of generation, constraint, and hydrogen production will vary in the specific circumstances of each site and depend on operator, market mechanisms / incentives, and will change over time.

- **Water** – the electrolysis process requires significant quantities of de-ionised water from which hydrogen is split from oxygen. Water can be obtained from multiple sources including surface water and groundwater abstraction, seawater abstraction and de-salination, and from mains / potable water supply where infrastructure exists and has capacity to do so. Production facilities typically include water treatment / purification technology to ensure water quality is suitable for electrolysis, though exact pre-treatment requirements will depend on electrolyser technology and water source being used.

- **Land** – the production of hydrogen via electrolysis requires a level, developable area of land that is separated from sensitive receptors and suitable for development of energy infrastructure. For decentralised production this is most likely to be co-located or proximate to renewable energy generation – though in many cases (especially at smaller scales) will have relatively small footprints allowing for some flexibility in siting within the very large footprints and landholdings associated with on-shore wind farms. Specific siting of production locations will depend on a number of factors including:

    - Local environmental / ecological designations or assets which may be impacted by hydrogen production
    - Ground conditions including peatland or carbon rich soils
    - Accessibility for construction, operations & maintenance, and ability to export hydrogen to end-users (primarily through road transport, though for some sites rail or marine export may be feasible)
    - Local water availability and abstraction sources, or water supply infrastructure.
    - Siting of complementary renewables / grid infrastructure assets (Solar, BESS, sub-stations) within hybrid renewable projects
    - Commercial and operational considerations for site operator / developer including land ownership and availability

- **Demand / Export** – notwithstanding the ability to supply hydrogen (influenced by power, water, land), hydrogen production will only be viable where there is a source of local demand, or where it can be efficiently exported. This may include meeting local need to decarbonise energy intensive industries, providing a zero-carbon fuel source for public transport (buses / ferries / trains), or blending into existing gas networks to serve domestic and wider applications of gas. Transport applications may rely on smaller volumes of production than industrial applications and be better suited to decentralised, small scale sites.

  In Scotland, distances are likely to be relatively short and transport of compressed hydrogen via tube-trailer appears to be emerging as the most common form of export for small-medium production, at least in the short-term based on case study review and stakeholder feedback.

Technical Site Requirements & Characteristics

To inform the search, identification, and review of the suitability of potential production locations more specific technical criteria relating to the above characteristics have been established. These are derived from previous Scottish Enterprise commissioned research into hydrogen production (Scottish Enterprise / WOOD (2021)) and have been referenced against emerging case studies of decentralised green hydrogen production. The table below sets out the necessary development criteria for each of the core hydrogen production requirements: Power, Water, Land, and Demand / Export capability.

The criteria assume a broadly linear relationship between scale of electrolyser production and associated site requirements for water and land area. As green hydrogen production remains an emergent technology with few commercially developed projects and subject to ongoing technical innovation site requirements may change in future, and are liable to vary by site.

As a result of stakeholder feedback and input, and review of planned projects (see Case Studies below), land area requirements have been increased slightly from those originally established, and a wider range applied in order to reflect potential for different operator models and future change in requirements.

HYDROGEN PRODUCTION SITE REQUIREMENTS	10MW	20MW	50MW	100MW
Power (MWe) Direct Connection to renewable energy source for green hydrogen production via electrolysis.	**10+**	**20+**	**50+**	**100+**
Raw Water (Ltrs/day) Water requirement as electrolysis feedstock. Mains supply, effluent, and/or abstraction from groundwater, surface water sources. Water will be filtered and purified through reverse osmosis prior to utilisation in hydrogen production.	**76,800**	**153,600**	**384,000**	**768,000**
Land Area (ha) Developable land (and infrastructure) for electrolysers and associated equipment, conversion, compression and storage. Area requirements may vary depending on extent of on-site storage and other infrastructure required to facilitate production and distribution depending on operator.	**0.5-1.5**	**0.5-1.5**	**1.5-3.0**	**3.0 – 6.0**
Demand / Export Route to market and/or means of 'off-take' for produced green hydrogen.	• Local industrial / transport / energy-intensive uses suitable for hydrogen integration – hydrogen distributed via compressed tube trailer in most cases. • Pipeline connection / existing gas network blending • Connection to port infrastructure for marine export.			

Derived from Hydrogen Production & Export Locations – Site Requirements Study (February 2021) (WOOD on behalf of SE / HIE / SOSE).

Notes:

- Original area requirements have been increased based on stakeholder feedback
- Water requirements assume a capacity factor for electrolysis of 98%. In many instances this may not be achievable given intermittency of renewable energy generation (wind / solar) with the result that water demand is lower than figures presented. This may vary considerably across sites and depending on scale of electrolyser capacity relative to renewable energy generation capacity, extent of constraint / curtailment, and other factors. Higher figures are retained as an upper limit and to test maximum potential parameters.
- The addition of electrical storage (eg. battery) to an electrolyser may increase capacity factor of production by reducing intermittency of output from renewable sources. Capacity factor is the ratio of actual production output over a given time, relative to the potential production output if it had operated at full capacity over that time period.

Renewable Energy – Curtailment & Grid Capacity

As a result of the significant increase in renewable generation over recent decades, and the cost, complexities and time involved in reinforcing the gird, large areas of the electrical transmission and distribution network[6] in Scotland experience 'constraint'. This means that they operate close to their operational limits in terms of thermal capacity, fault level, or voltage bandwidth. In order to manage these issues of constraint on the network and ensure stability of the grid, network operators (National Grid / SPEN / SSEN) have to 'curtail' energy generation – instructing generators to reduce or restrict their output.

The vast majority of constrained renewable energy curtailment in Scotland is wind energy. Prior analysis by LCP (on behalf of Drax (2022)) estimates that across the period 2020/2021 5.8TWh of on-shore wind generation was curtailed across Great Britain, of which Scottish generation accounted for 94% in 2020 and 80% in 2021. Given the scale of planned renewable generation projects, it is likely that constraint will continue to impact the Scottish grid for the foreseeable future. A key focus of the brief for this Report has been to identify where this constraint on the grid occurs as specifically as possible, and where opportunities for green hydrogen production may subsequently arise.

It is recognised within Scottish Government's Energy Strategy & Just Transition Plan (2023) and Hydrogen Action Plan (2022) that the scale of constraint on Scotland's grid, together with net-zero ambitions and need for energy transition create clear opportunities for greater synergistic working and hybrid solutions across the energy system. Building greater flexibility, responsiveness, and ability to link surplus renewable generation to a hydrogen economy will be important to the future balance of Scotland's grid.

The diversion of renewable energy that would otherwise be constrained to hydrogen production can provide complementary 'win-win' solutions to managing and minimising grid constraint, reducing the cost of a fundamental green hydrogen input, and supporting wider decarbonisation objectives.

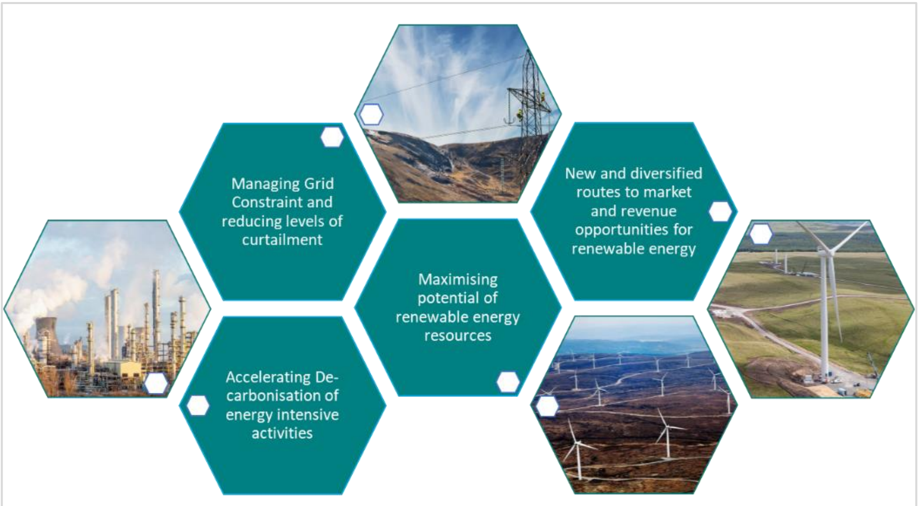


Figure 6. Potential overlapping and wide ranging benefits of green hydrogen production utilising constrained renewable energy. However, the growth of green hydrogen production to fully realise these benefits will be led by the market, depending on a competitive needs-case for hydrogen utilisation and new demand sources emerging.

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[6] The Transmission Network (owned by SHET / SPT and operated by National Grid Electricity Transmission) is the long-distance, high-voltage network for transportation of electricity across the United Kingdom, equivalent to the Motorway in a road network. The Distribution Networks (operated by SPEN in Southern and Central Scotland and SSEN in Northern Scotland) transport lower-voltage electricity over smaller distances, and distribute power to urban areas / consumers / businesses. Renewable generation can be connected directly to the Transmission Network, or 'embedded' into the Distribution Network.

Alongside the above benefits and opportunities, it is important to highlight that the production of green hydrogen will continue to interact directly and indirectly with the electricity and wider energy markets. Regulations, mechanisms and incentives within those markets will impact how and where hydrogen will be produced, determine levels of risk exposure, investment returns and opportunity costs, and influence future operator models for renewable generation[7].

Furthermore, the availability of curtailed energy to feed green hydrogen production will compete with other options for management and modes of storage including battery storage, longer duration storage especially pumped hydro-storage (eg. Coire Glas), inter-connector exports, and potential demand-side response capabilities. This spatial and geographic analysis has not considered in detail the Commercial Case for green hydrogen production utilising curtailed renewable energy, but the above issues will be a key influence and should be subject to further review and investigation.

Managing Constraint and Curtailment

The specific processes through which curtailment is currently instructed and managed vary between National Grid and Distribution Network operators SPEN and SSEN and may vary depending on the nature of constraint, network management, cost incentives, and other technical factors affecting grid stability and balance.

At the Transmission level, National Grid's Balancing Mechanism is the primary mode of constraint management whereby generators connected to the National Transmission System are compensated to reduce their output to ensure the system remains balanced and operable within safe limits. At the Distribution Level SPEN and SSEN also manage constraint through upgrades to grid infrastructure (often delivered in partnership with generators in response to a specific proposals), and through 'Non-Firm' or 'Flexible' connections whereby generation output may be reduced at certain times.

They are also developing Active Network Management (ANM) solutions, which involve more complex real-time monitoring and control of constraint to allow more generators to connect and to make efficient use of renewable generation relative to demand. ANM solutions have been successfully trialled in East Lothian and Orkney, and are proposed to be implemented in Dumfries & Galloway.

The process of curtailment serves an important function in the operation of the grid -but in the case renewable generation means that zero carbon energy is being discarded. Subject to commercial feasibility this presents an opportunity for that 'surplus' renewable energy to be diverted towards green hydrogen.

Managing constraint on a longer-term horizon, a number of grid infrastructure reinforcements are planned across Scotland to respond to increase generation and create new capacity for export of electricity. There are a range of planned upgrades to the Transmission Network at various stages of planning and certainty, including development of new sub-stations, new and upgraded circuits and new technologies to control power. Key planned projects include:

[7] The nature and specific levels of curtailment necessary to allow for economically hydrogen production viable require further investigation and are beyond the scope of this study. However, prior research undertaken by TNEI (on behalf of Scottish Enterprise) has indicated that a constrained wind farm experiencing less than 15% curtailment is unlikely to be financially viable. However, this may vary depending on curtailment payments available, subsidy environment, other cost factors associated with hydrogen production, and the market value of hydrogen. A viable and competitive cost of producing green hydrogen is likely only in certain locations and instances, will in large part depend on local demand or off-take capability, and may be subject to high levels of commercial risk.

- ‘Eastern Link’ HVDC connecting Torness to Hawthorn Pit in County Durham, along with associated sub-stations and converter stations. It is being jointly delivered by SPEN and National Grid Electricity Transmission (NGET) to address need for increased interconnection and guarantee security of energy supply as renewable energy generation continues to increase. The Project is anticipated to be delivered around 2027 subject to final consenting and construction works. A further ‘Eastern Green Link 2’ between Peterhead and Drax in England is in the early stages of development, with delivery anticipated around 2029.
- Shetland HVDC Link is currently under construction providing c. 260km of sub-sea cabling and Switching Station (at Caithness) to connect the Islands to the National Transmission system. The Project has been developed to enable >600 MW of planned generation on the Islands to come forward, including large-scale Viking Wind Farm (443 ME).
- Options assessment and planning is ongoing by SSEN Transmission for a potential 1.8GW Western Isles Link, connected from Stornoway to a Beauly HVDC converter station. The process of site optioneering, feasibility review, and stakeholder consultation is ongoing.

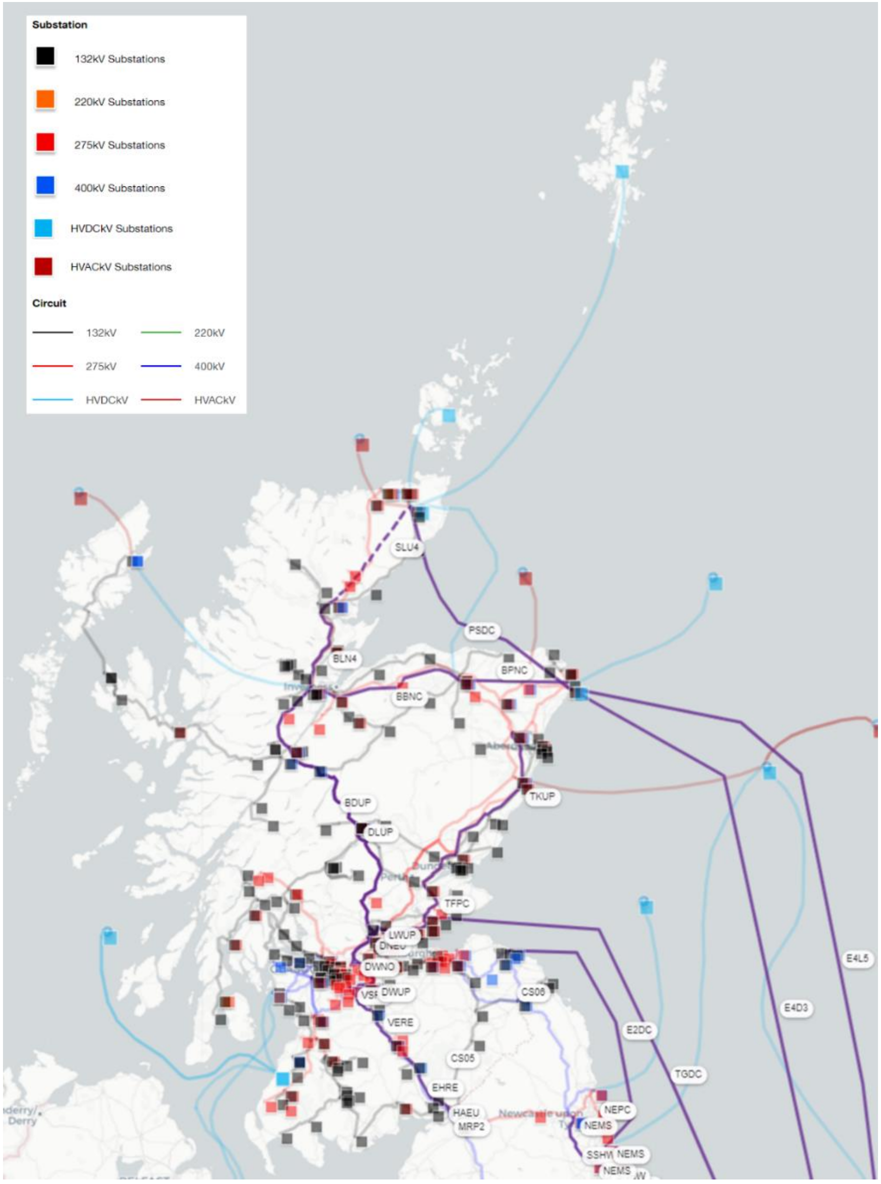


Figure 2.Illustrative Plan from National Grid Network Options Assessment (2021/22 Refresh). Showing electricity transmission system and options for grid reinforcement upgrades and investments through the period up to 2031, including planned sub-sea HVDC links from east coast to enable greater export of renewable energy.

Across the Distribution Network a number of smaller scale reinforcements and upgrades are planned and being delivered. The scale and spatial extent of grid constraint is therefore dynamic and variable over time. It a consequence of interlinked processes around grid management, infrastructure investment, renewables deployment, and the function of wider energy markets and policy making. Grid Constraint may therefore be transitory in timing and location as these dynamics and pressures evolve in response to one another and shape the future of network capacity and production.

Electrolysis for green hydrogen can by nature be modular and scalable compared to other options for managing curtailment (except batteries). To address locationally specific instances of constraint, it may offer an interim, small-scale solution to reduce curtailment within short-medium term timescales while longer-term grid reinforcement is planned and delivered. To some extent 'competing' for this electricity and providing an alternative means of managing constraint, there are significant levels of planned battery storage development across Scotland. This includes very large scale (500MW) proposals with the potential to add significant storage capacity to the grid, as well as co-located battery storage being developed by renewable operators to manage constraint.

Areas of Constraint

Grid constraint is a dynamic and variable process, subject to variation even within local contexts, depending on nature of grid connection, scale of generation, and operational models of different generators. Most typically, constraint is experienced in those relatively rural regions which have undergone significant growth in renewables generation at a pace faster than planned grid reinforcements highlighted above can be delivered. This includes:

- South-West Scotland – including significant areas of South and East Ayrshire and Dumfries & Galloway. The area has a significant number of operational wind farms plus additional consented and progressing through planning. The network is noted to be operating at near full capacity. Reinforcement works are planned to add capacity but anticipated to only satisfy currently contracted generation and constraint is likely to continue.

- Highlands – where the historic presence of hydro-electric generation has been supplemented by significant development of onshore wind with favourable load factor conditions, but constrained by limited grid network capacities.

- Islands – Inner and Outer Hebrides and Orkney and Shetland Isles all experience significant constraint and limited ability to export electricity as a result of pre-existing 33kv connection. Sub-sea grid connection infrastructure is being planned and developed to address this and maximise the potential of the significant potential renewable energy resources across the Islands.

To support informed planning of future connections and management of constraint SPEN and SSEN both produce Distribution Network 'Heat Maps' to indicate where their network capacity is constrained. The plans below show the at a high-level where this occurs at Grid Supply Points across the Distribution Network.

Grid Supply Points denoted as 'Red' are operating close to capacity, with the result that a local grid connection is unlikely and/or will require extensive reinforcement works.

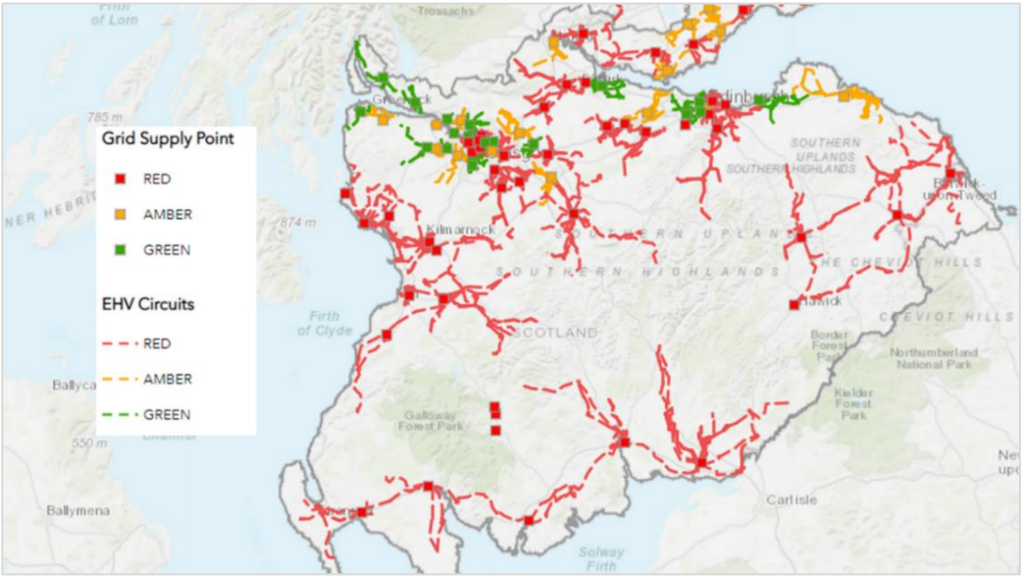


Figure 3. SPEN Distribution Generation Heat Map (Jan 2022) – The Distribution Network experiences significant levels of constraint in South and East Ayrshire, and in Dumfries & Galloway where there has been major deployment of on-shore wind.

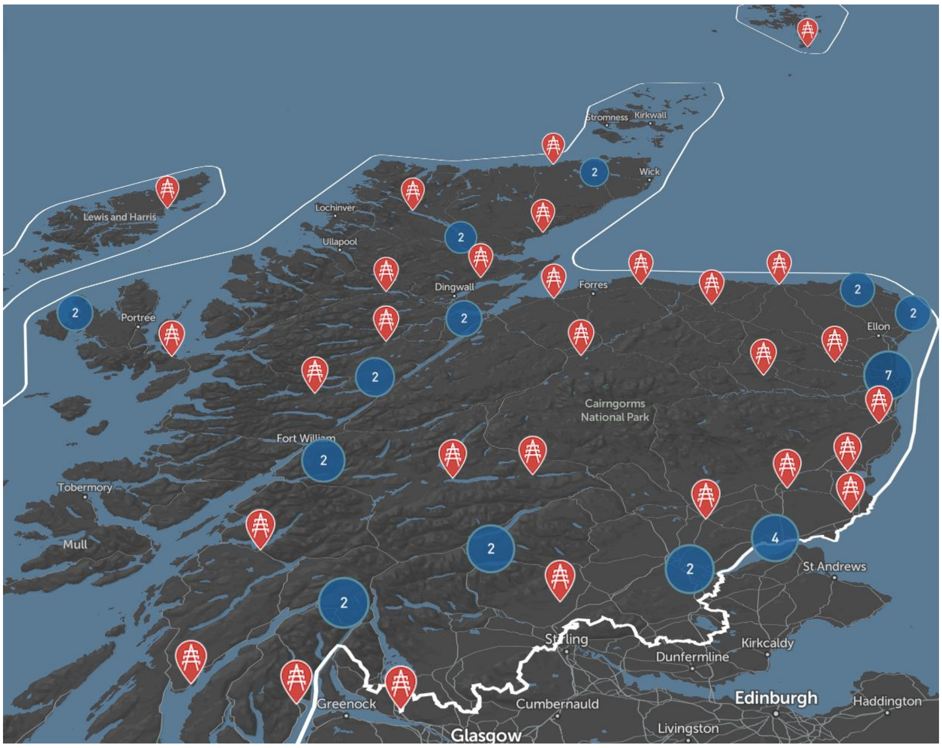


Figure 4. SSEN Distribution Generation Heat Map. Showing all Constrained or Partially Constrained Grid Supply Points across the SSEN Distribution Network – 66 GSP's in total are constrained and 6 GSP's are partially constrained.

There is less direct information on network constraint related to the Transmission Network (owned by SHET and SPT and operated by NGET), though it is noted that curtailment is typically most cost-effective and safer through reducing (and compensating) Scottish wind generation output and instructing other generation assets closer to sources of demand elsewhere in the UK to increase their output.

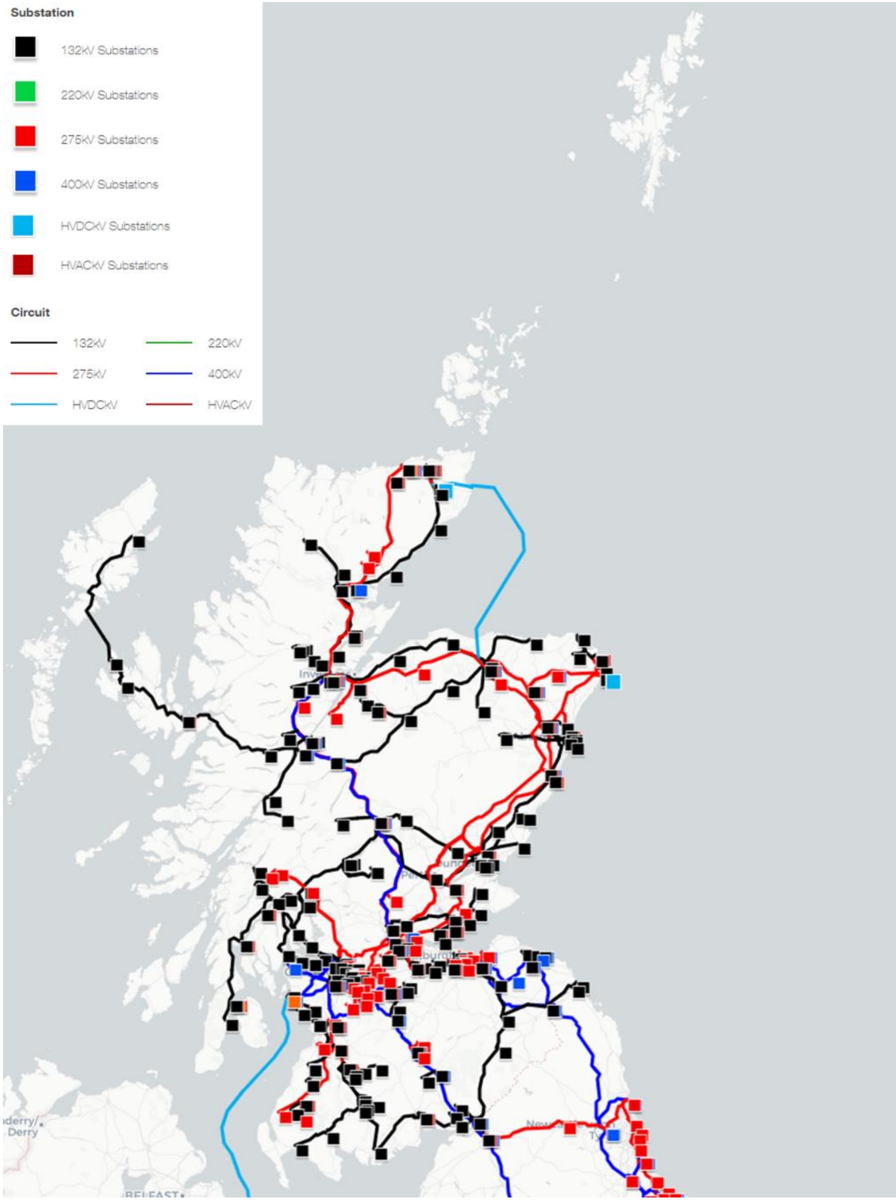


Figure 5.Current illustrative plan of National Grid Transmission infrastructure- showing approximate sub-stations and circuit routes (levels of constraint at individual sub-stations are not shown). Significant areas of north and south-west Scotland are served by 132kv Substations and circuits limiting their ability to export electricity despite significant renewable energy resources.

In addition to review of broad patterns of grid constraint through Network Operator 'Heat Maps', reporting has also sought to identify constraint where possible at a site / operator specific level, in order to directly inform potential locations for decentralised production[8]. The process of identifying constrained renewable energy has involved three strands of review and analysis, as set out below.

1. National Grid Balancing Mechanism

As noted above, the Balancing Mechanism serves an important function in the operation of the National Grid, ensuring balance of supply and demand and overall system stability. It involves larger scale renewable generators (which have access to the National Grid Transmission Network) being instructed and compensated to curtail their production to maintain grid stability. The vast majority

[8] Identifying constraint at a site specific level is complex and liable to change over time depending on future grid infrastructure reinforcement, economic incentives arising from the energy market and network management, and changing site operational models.

of curtailment via the Balancing Mechanism takes place in Scotland due to constraint on the network, and the relative cost effectiveness of curtailing renewable energy in those locations. A map of those Scottish renewable energy generators participating in the Balancing Mechanism is shown below.

The Balancing Mechanism operates as an ongoing pay-as-bid market– with a complex auction process and incentive mechanisms which influence where and to what extent curtailment occurs, and the extent to which these generators may be incentivised (or not) to produce green hydrogen[9]. The guarantee of compensation offered through the Balancing Mechanism reduces risk for renewable energy generators, and there remain several 'unknowns' over how 'behind the meter' green hydrogen production from curtailed energy would interlink with Balancing Mechanism and be regulated.

For the purposes of this analysis, it highlights generation locations where renewable energy is being discarded, such that green hydrogen production *could* offer a solution (subject to future commercial viability and incentives)[10]. In order to narrow the analysis towards areas experiencing strongest levels of curtailment, further review has focused on those locations with an average of at least 50MWh/day of curtailment (30 locations out of the 84 total participating in Balancing Mechanism). These are shown on Figure 10 below.

[9] In terms of the balancing mechanism – review of historic curtailment payments indicates an average price of approximately £70MW/h - though for some sites significantly lower. This indicates that as a 'rule of thumb' producing hydrogen would have to be of equivalent value to £70MW/h in order to be competitive with current Balancing Mechanism, albeit this figure would vary by site and operator and is liable to change in response to reform of the Balancing Mechanism and levels of compensation offered.

[10] It should be noted that UK Government has initiated a 'Review of Electricity Market Arrangements' through which a range of options for future operation of the wholesale electricity market are being consulted. This may lead to future reform of incentive mechanisms, subsidies and support arrangements, and management of capacity across the grid. Any reform of the Balancing Mechanism and curtailment payments made to renewable generators directly would shape the future deployment of renewable energy, as well influencing the economic viability of hydrogen production from curtailed renewable energy.

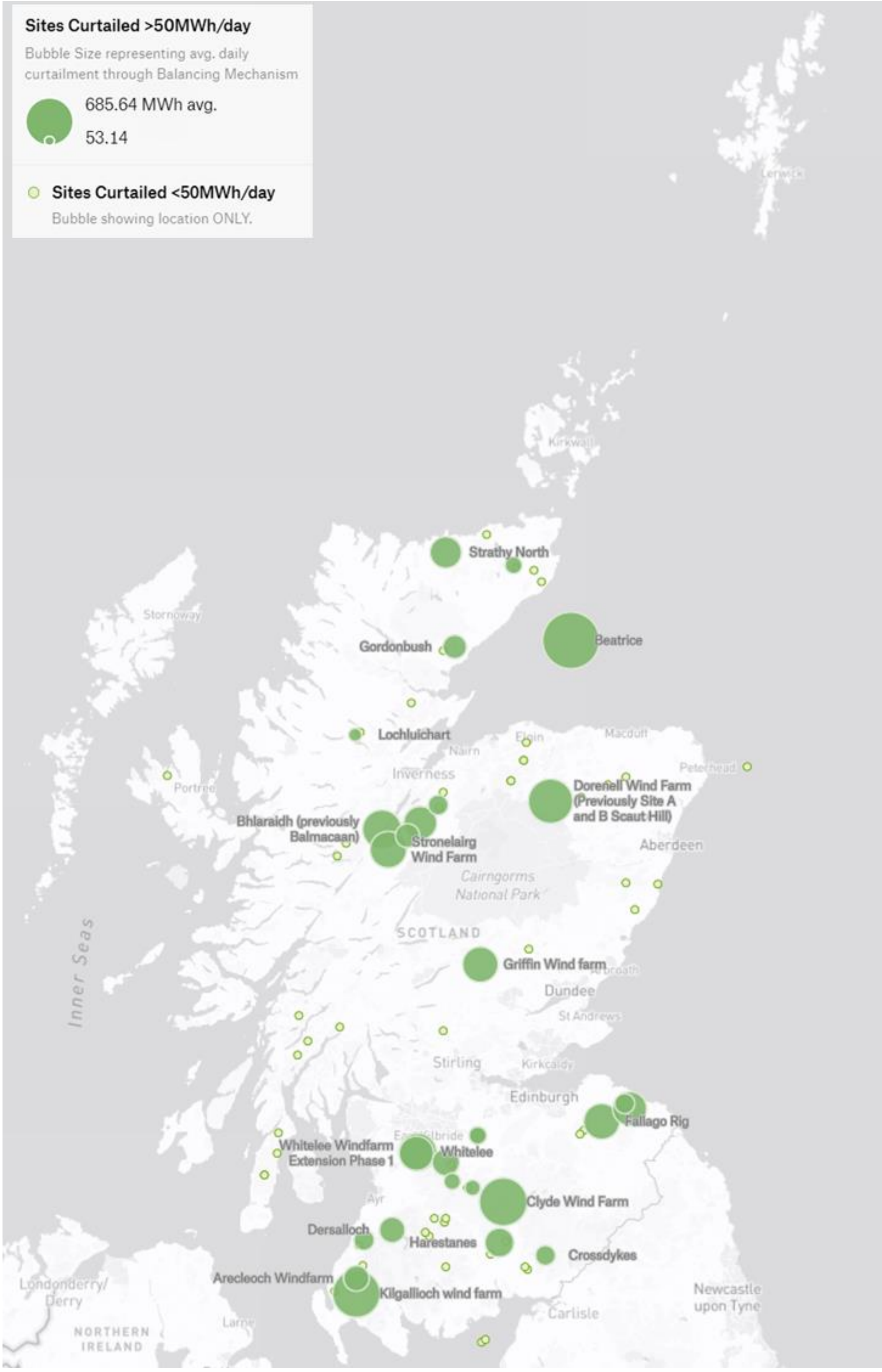


Figure 10. The bubble size shows average level of curtailment (MWh/day) since commencement of operation - for sites curtailed by more than 50MWh. This represents an average level of curtailment, though levels may vary significantly across different times depending on balance of supply and demand, market price mechanisms, and other network operational factors. The location of other sites curtailed on average less than 50MWh/day are shown for reference.

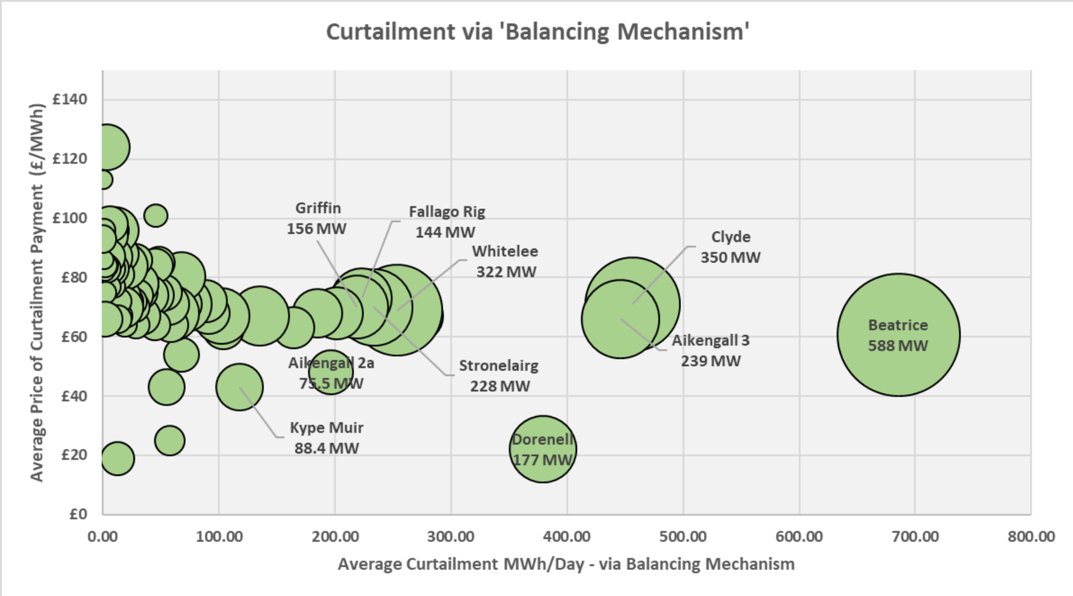


Figure 11. Curtailment via NG Balancing Mechanism. Bubble size represents the overall generation capacity of the wind farm. Average curtailment (MWh/day) since operation is represented on the x-axis, while the average price of curtailment payment (£/MWh) is on the y-axis[11]. While variable by site, the average curtailment payment is around £70/MWh which would in the current market be the effective 'opportunity cost' of producing green hydrogen from curtailed renewable energy.

2. Planned Sites without Grid Connection

In addition to those operational sites participating in the Balancing Mechanism, there is a significant number of renewable energy projects currently progressing through the planning system, or which have achieved planning permission and are currently awaiting construction. These have been identified and reviewed through the BEIS Renewable Energy Planning Database (REPD), searching for sites that are at least 10MW+ in scale and are either

- Under Construction / awaiting construction
- Planning permission granted (including via appeal)
- Planning application submitted

To identify where these projects may be subject to constraint the REPD database has been cross-referenced with Connection Registers maintained by National Grid and DNO's SPEN and SSEN[12]. In the majority of instances planned projects have secured a grid connection or are currently in the 'Scoping' process. However, in certain cases proposed or approved projects are not listed on connection registers and appear to not have a grid connection. These projects have been mapped and reviewed[13] as potentially strong candidates for green hydrogen production that is sourced from constrained renewable energy[14]. The locations of these sites are shown below on Figure 13.

[11] Balancing Mechanism data purchased from 'Renewable Energy Foundation' (REF), which collates and aggregates data from National Grid, BEIS, and bmreports.com. For ease of reference and naming certain locations which have been extended or delivered across multiple phases (eg. Clyde Wind Farm) have been combined and considered as a single location. REF is a registered charity promoting sustainable development and effective energy policy making. It has previously been critical of wind power generation and subsidy mechanisms / curtailment compensation mechanism in place for renewable generators.

[12] National Grid Transmission Entry Capacity (TEC) Register accessed and downloaded November 2022. SPEN and SSEN Embedded Capacity Registers accessed and downloaded November 2022. Connection Registers provide information on generation and storage resources that are connected, or accepted to connect, to the relevant network.

[13] To narrow the study and site search, review has removed from more detailed consideration those sites for which planning permission has lapsed, 'edge-case' sites which are very close to 10MW threshold, and known private wire connections intended not to have a grid connection. A number of stand-alone battery storage projects were identified through this search, though were not included for further consideration as they are not co-located with renewable energy and could not support fully 'Green' Hydrogen production.

[14] Cross-referencing and search has sought to capture and include all development phases, extensions, revisions, and re-powering of renewable energy generation sites. Due to the number of sites (1195 Scottish location on REPD) and the collation, entry and maintenance

It is likely that such projects may secure a grid connection in future, or a ‘Flexible / Non-Firm’ connection (see below). However green hydrogen production ‘behind the meter’ on such sites could offer an early ‘route to market’ for projects or allow an operator to secure a reduced grid connection at lower cost or in a quicker timescale[15].

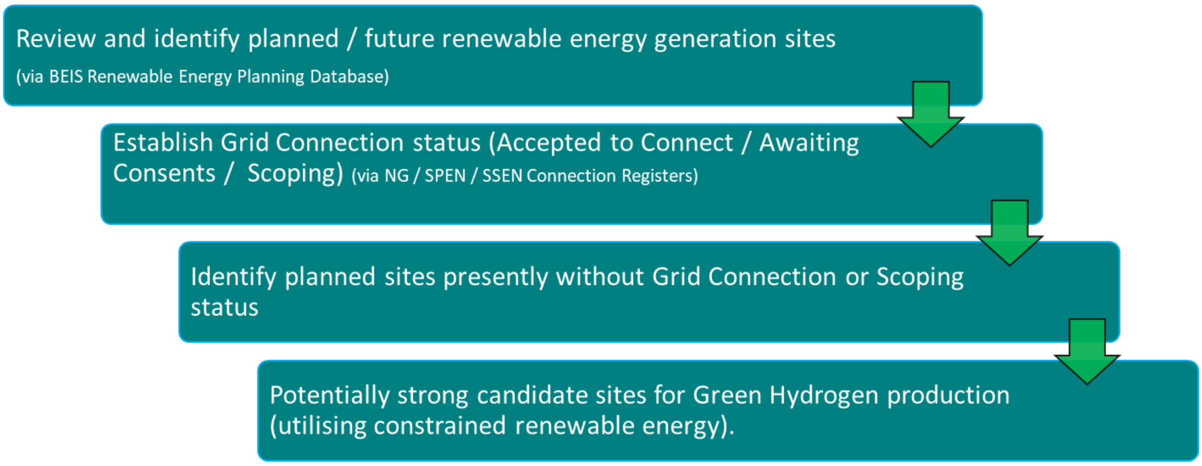


Figure 6. Methodology process for identifying planned renewable energy sites presently without Grid Connection Status.

3. Flexible Grid Connection

Flexible or ‘Non-Firm’ connection means advance agreement with Network Operator that grid connection is restricted in some way around output, typically in constrained areas of the distribution network. It reflects an agreement between generator and distributor that the connection is restricted to manage network load – often in return for a quicker or cheaper connection, in many cases on a temporary basis before progressing to a ‘Firm’ Grid Connection.

As derived from SPEN and SSEN Connection Reigsters, there are currently 12 sites of 10MW+ with flexible connection that could be complementary to hydrogen production. These sites are clustered in locations where SPEN has initiated a process of Active Network Management.

It is anticipated that this will increase in future as the Network Operators seeks to manage grid capacity more actively while grid reinforcement projects are planned and delivered. In particular there are a significant number of planned projects listed as ‘TBC’ in terms of their connection but which are likely to be subject to a form of Flexible Connection.
Figure 13 below shows the location and scale of these sites with a Flexible Grid Connection, along with those sites that currently appear to be without a Grid Connection as identified through the analysis above.

of data by different data-holders (BEIS, NG, SPEN, SSEN) there is a risk of errors in the data, such as multiple or changes names for sites, outdated project status, or inconsistent location data. As far as possible data collation, review and cross-referencing has sought to identify and correct errors.

[15] In certain instances a grid connection may not be secured for operational reasons not obtainable from available data, such as a private wire connection or a longer term development programme. The exact status of grid connection and/or the extent of engagement and forward planning undertaken with Network Operators would need to be determined on a site-by-site basis through review with site operators.

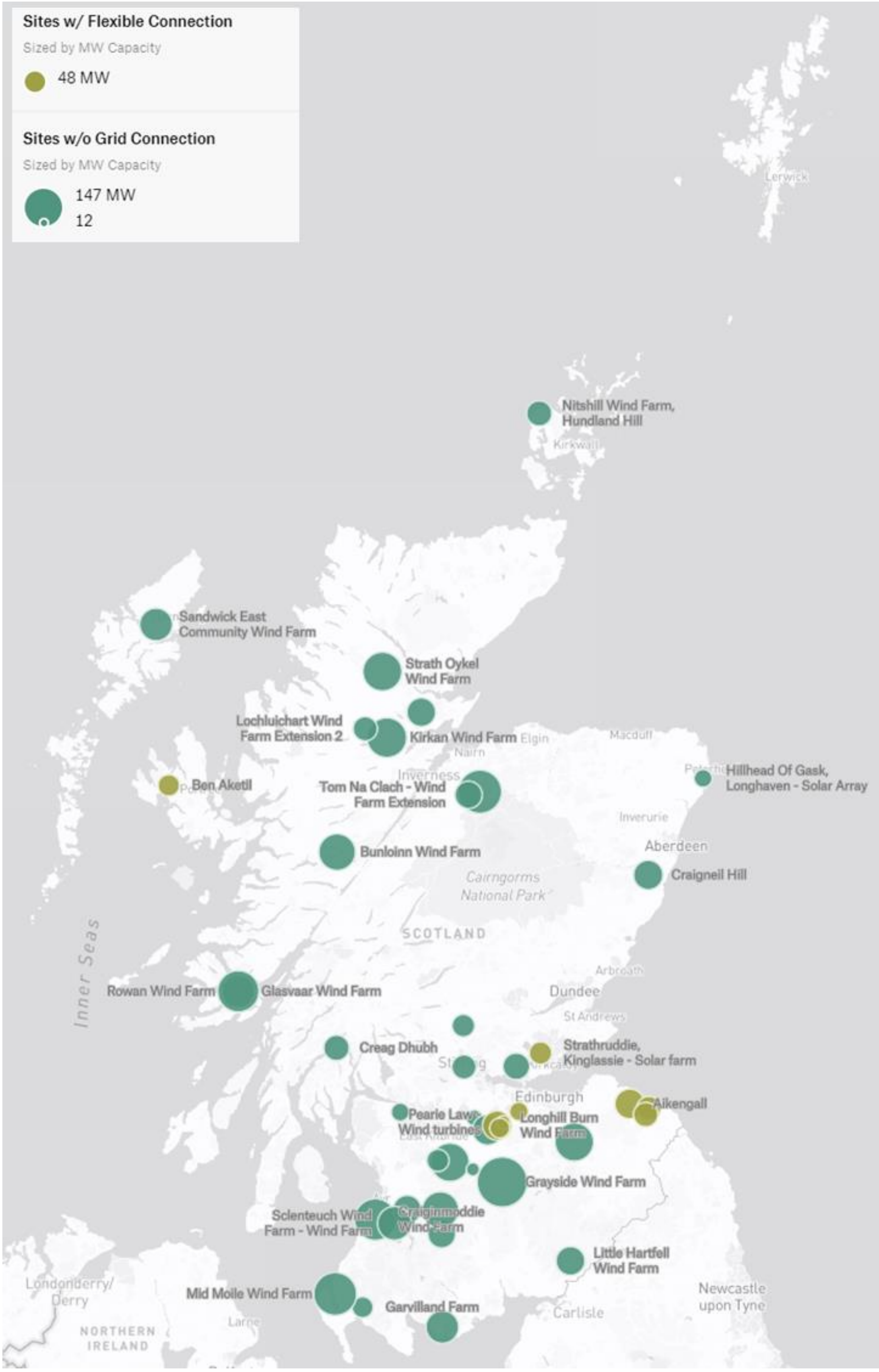


Figure 7. Map of emerging shortlist sites – derived from analysis of planned sites currently without a grid connection and those sites (planned or operational) with a 'Flexible' or 'Non-Firm' connection as shown on SPEN / SSEN Connection Registers.

4. DE-CENTRALISED HYDROGEN – SITE IDENTIFICATION

Cluster Locations and Sites

From the analysis of constrained renewable energy generation locations a 'shortlist' renewable of sites that could be suitable for decentralised green hydrogen production have been identified and mapped[16] (see maps in Section 3 above), where one of the following criteria is being met:

- Operational sites participating in the Balancing Mechanism (>50MWh / day)
- Planned / in development sites currently without a grid connection (>10MW)
- Planned or operational sites which have a 'Flexible' or 'Non-Firm' grid connection as listed in relevant Connection Register (SPEN / SSEN)

In order to focus review on specific locations and geographies, 'Clusters' with a number of shortlist sites and/or where there is known grid constraint (as indicated by SPEN / SSEN Heat Maps) were defined. The Clusters show sub-regional groupings where there is constrained renewable energy generation with the potential for decentralised models of green hydrogen production. An overview plan of the identified Clusters is shown below.

1. Dumfries & Galloway

2. South & East Ayrshire

3. South Lanarkshire

4. East Lothian & Borders

5. South Lanarkshire & West Lothian

6. Loch Ness

7. Cromarty & Ross-Shire

8. Orkney & Shetland Isles

Cluster boundaries are not intended to be definitive or 'hard-edged' but have sought to group proximate renewable energy projects that are linked by common features / geography, with an illustrative border defined approximately by roads, local authority boundaries, or specific geographical features.

[16] A data-sheet of all Short-listed sites (whether within or outside of Clusters) is appended to this Report for reference. This is not an exhaustive list of all locations where generation capacity is constrained. Some forms of constraint are not visible through available data or can only be approximated, and there may be other locations not currently planned for renewable energy generation, but to which constraint would be a key factor in determining their viability.

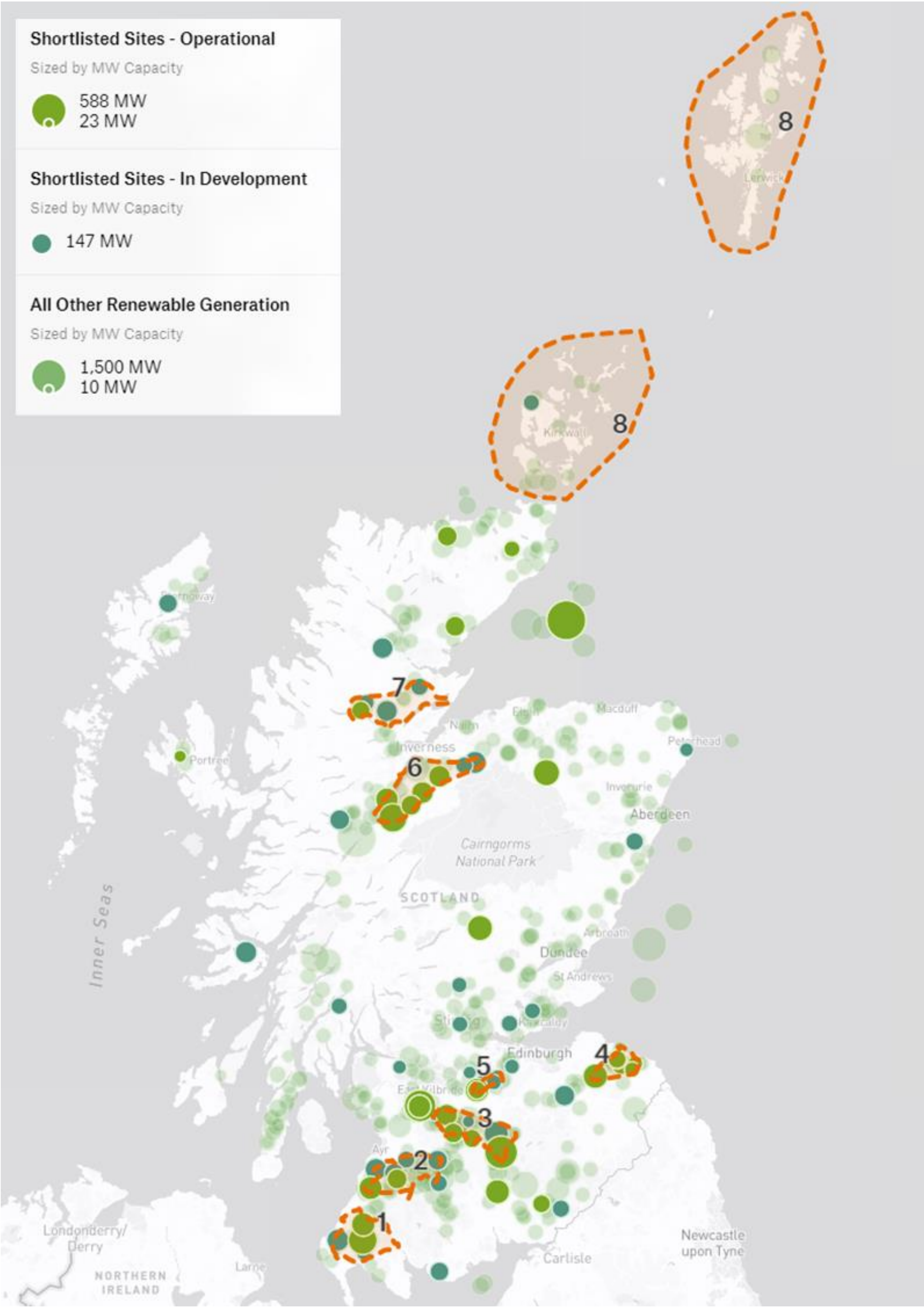


Figure 8. Scotland-wide map showing locations of identified clusters – derived from sub-regional groupings of constrained renewable energy. More specific and detailed maps of clusters are shown below and later in this section.

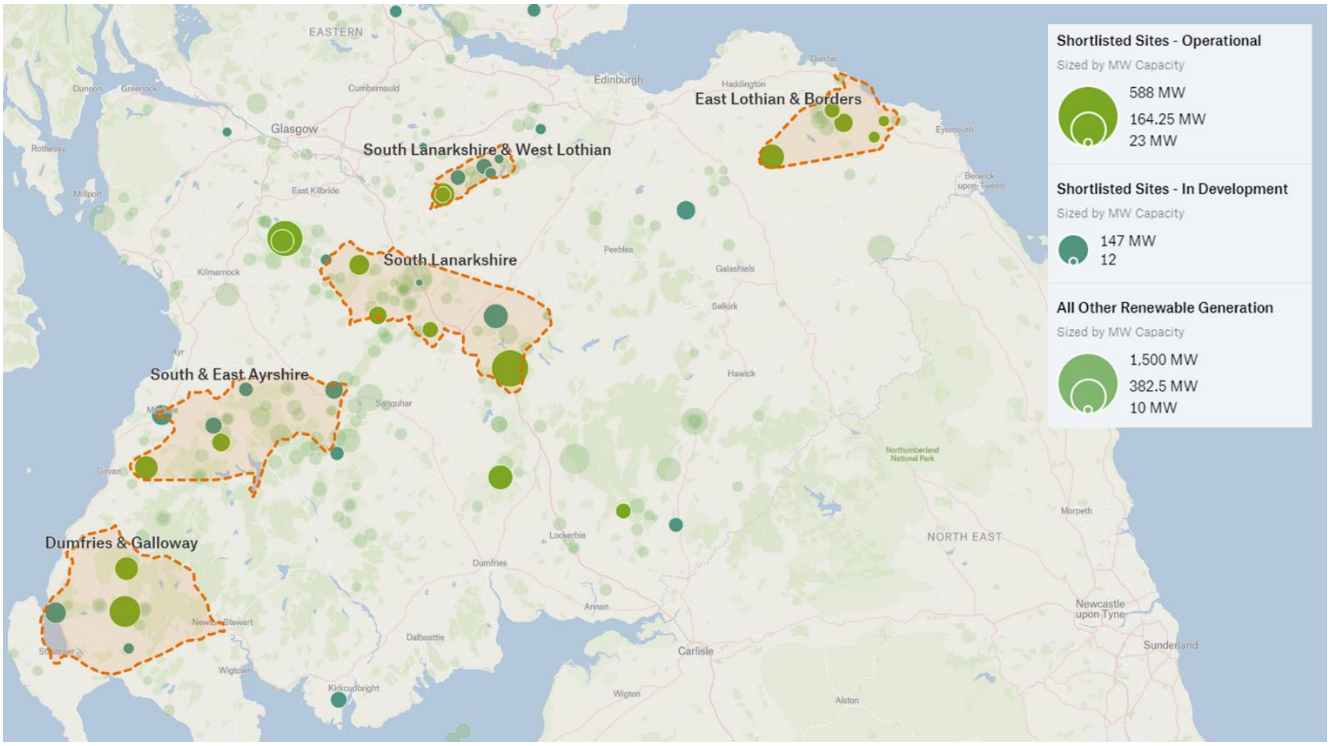


Figure 9. Clusters 1-5 covering sub-regional groupings of constrained renewable energy generation across Southern and Central and Scotland.

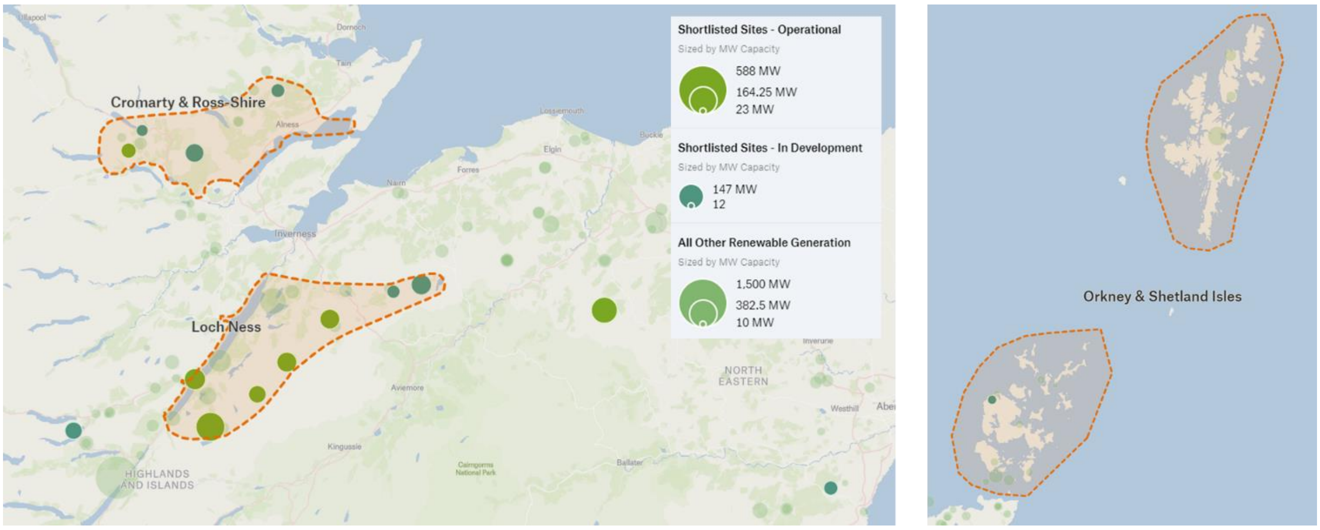


Figure 10. Clusters 6-8 covering sub-regional groupings of renewable energy generation across Northern Scotland, and Orkney & Shetland Islands.

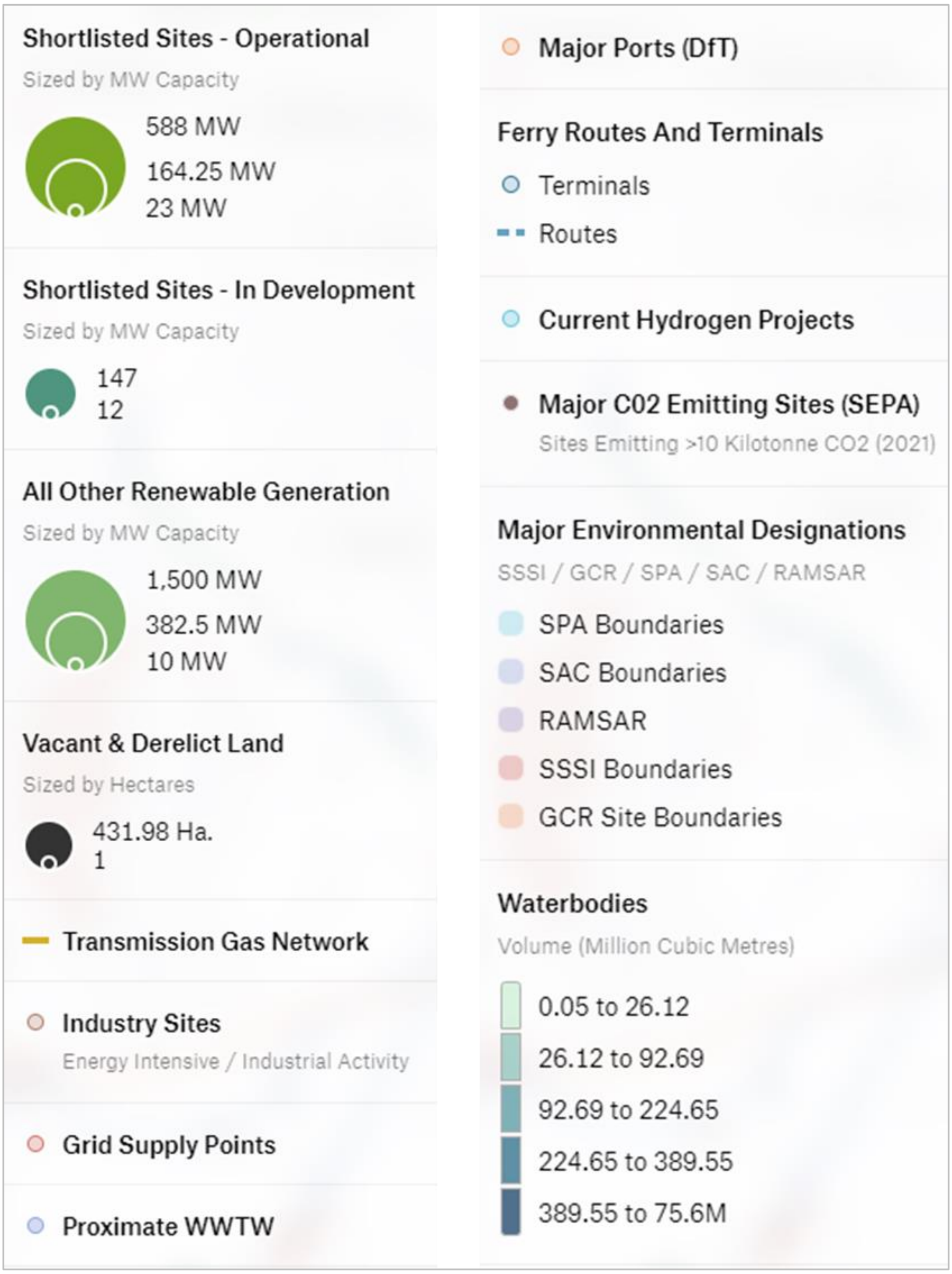
Cluster Review: Hydrogen Production Potential

Within the defined geography of each Cluster more detailed review of key criteria and green hydrogen production requirements has subsequently been undertaken, especially around availability of water for electrolysis, and the potential for off-take of hydrogen either to a local source of industrial / transport demand or through export. Review has also included wider assessment of opportunities and constraints from a land, planning, and environmental perspective which may influence suitability for green hydrogen production.

The full list of topics, criteria and development factors considered for each Cluster are tabled below. Detailed Factsheets for each Cluster presenting full analysis are appended to this Report.

Key Details & Characteristics	**Local Authority**	What are the relevant Local Authorities for the Cluster?
	Site Operators / Owners	Who are key operators / developers active in the cluster with potential for hydrogen production?
	Development Status	Are sites currently operational, under construction, consented, or currently in the planning process?
	Existing Assets / Infrastructures	What assets and infrastructure are present in the area – eg. brownfield land, other land use activities, utility infrastructures?
	Access & Connectivity	What transport infrastructures are present in the area (road / rail / marine)?
Land & Planning	**Land Availability / Developable Sites**	Where are principal developable areas? Are there other users / sensitive receptors that may limit site suitability?
	Planning Status / Constraints & Designations	What Local Development Plan (LDP) and other environmental / planning designations are present that may influence site suitability? This may include Sites of Special Scientific Interest (SSSI), Special Protection Areas (SPA), Special Areas of Conservation (SAC), Geological Conservation Review Sites (GCR), or Ramsar Sites (Wetlands of International Importance)
Power & Utilities	**Renewable Energy**	What is the total renewable energy generation present in the area?
	Grid Infrastructure	Is there other grid infrastructure present – Grid Supply Points (GSP) or Primary Sub-Stations (PSS)? Are these subject to constraint?
	Gas Network	Is there proximate gas network infrastructure? HP / IP Gas Mains?
	Water Bodies / Abstraction Availability	What is the local availability of water for abstraction – ground and surface water?
	Main Supply (SW) Availability	Is there headroom capacity at local water treatment works to provide a mains supply?
Local Demand & Export	**Local Industrial Demand**	Are there local energy intensive industries (EEIs) or other activities that may be suitable for hydrogen integration as a source of demand?
	Transport Integration Opportunity	Is there local transport infrastructure to which hydrogen could be integrated or provide a means of export?
	Proximate H2 Projects / Initiatives	Are there other hydrogen economy projects / initiatives in the vicinity which could support a 'cluster' and/or shared physical and skills infrastructure?

An overview plan of the renewable energy generation locations within each Cluster and relevant local infrastructure / designations / industry are shown in the following section, along with a summary of key opportunities and constraints around green hydrogen production. A key for renewable energy, infrastructure, and environment features shown on overview mapping is provided below for reference.



Cluster 1: Dumfries & Galloway

Cluster 1 is located in the south-west of Dumfries & Galloway, including on-shore wind farms situated in the hills to the east of Loch Ryan. It includes operational wind farms Kilgallioch (239MW) and Arecleoch (120MW) which are participants in the Balancing Mechanism and subject to curtailment. Garvilland Wind Farm and Mid Moile Wind Farm currently have planning applications submitted but do not yet appear to have a grid connection.

Key Opportunities

- Proximity to Loch Ryan Port / Ferry Terminals to which hydrogen could potentially be integrated subject to future energy demand / technology scenarios, as well potential off-take from energy intensive industries (Glass, Paper, Pharmaceuticals) to the north in Ayrshire.
- Multiple operational and planned on-shore wind farms in the area – opportunities for collaboration and sharing of production, storage and distribution infrastructure. Scottish Power Renewables operate multiple large-scale assets in the area and are actively exploring / piloting hydrogen production at other locations across Scotland.
- Likely to continue to experience levels of grid constraint / curtailment in future years – local grid network is highly constrained and will be subject to Active Network Management by SPEN. Opportunities to produce hydrogen from curtailed renewable energy will continue to emerge.
- Relatively few sensitive receptors or potentially conflicting land uses in the area

Key Constraints

- There is limited local industrial demand / energy intensive users to which hydrogen could be integrated as an off-take. Lactalis (Creamery) and Crafty Distillery have been identified as potential off-takers but subject to future feasibility and demand.
- Relatively remote and separated from other potential clusters of future demand in Central Belt.
- There is limited opportunity for surface water abstraction as reservoirs / waterbodies in the Cluster are either in use as reservoirs or subject to environmental designation (SAC / SSSI) which may constrain ability for abstraction. Groundwater abstraction and/or mains supply from Scottish Water may be preferred.

Cluster 2: South & East Ayrshire

Cluster 2 is split between South & East Ayrshire, covering a large rural area with significant former coal mine workings around Dalmellington. It includes operational wind farms Hadyard Hill (120MW) and Dersalloch (69MW) which are participants in the Balancing Mechanism and subject to curtailment. A number of proposed wind farms are currently progressing through the planning process and appear to be without a grid connection. These include Craiginmoddie (92MW), Sclenteuch (54 MW), Polquhairn (34 MW), and Lethans Wind Farm Extension (66MW).

Key Opportunities

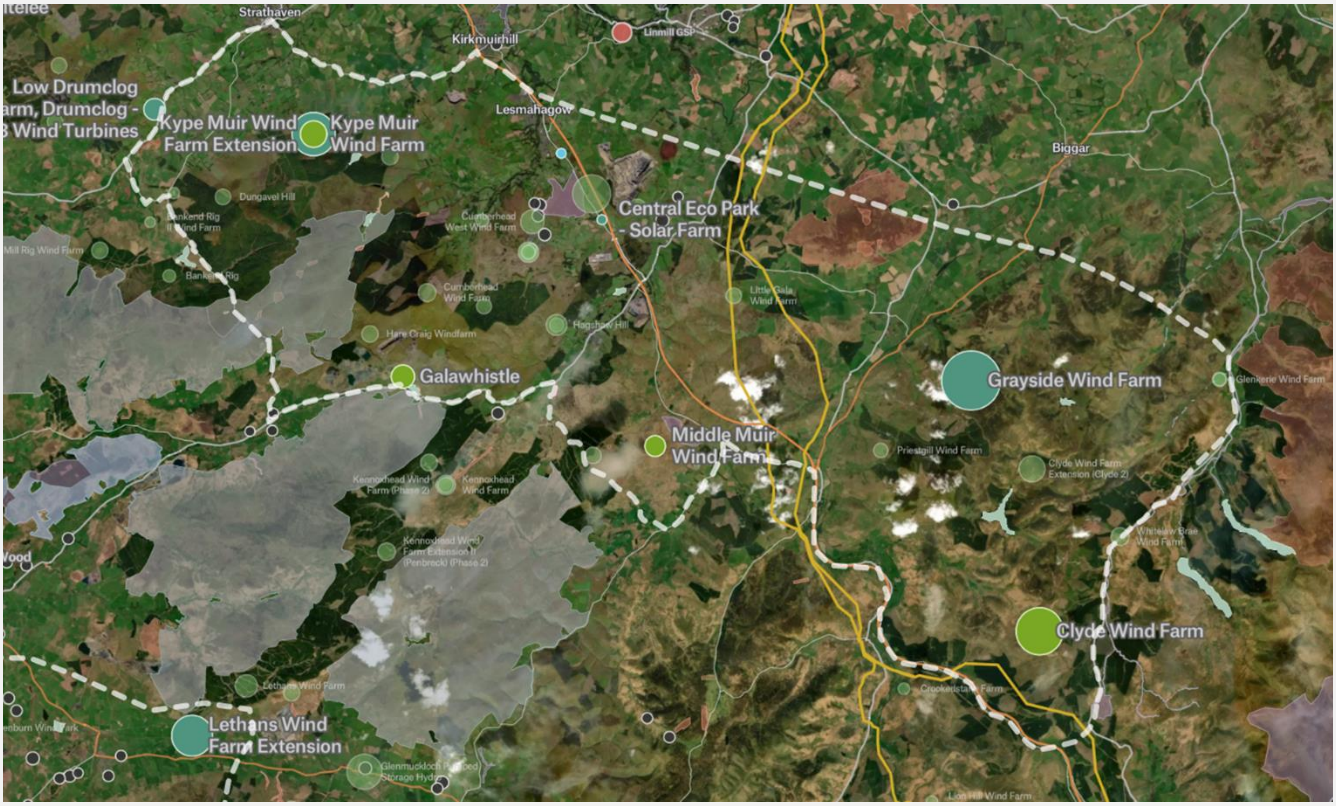
- Proximity to Loch Ryan Port / Ferry Terminals to which hydrogen could potentially be integrated subject to future energy demand / technology scenarios.
- Large number of operational and planned on-shore wind farms in the area – opportunities for collaboration and sharing of production, storage and distribution infrastructure. Range of operators includes Scottish Power Renewables, SSE, and Falck all of whom are actively progressing hydrogen production projects elsewhere.
- There are significant quantities of vacant and derelict land at the centre of the Cluster, associated with former mine workings (Benbain / Chalmerston). These are proximate to Sclenteuch and Polquhairn Wind Farms in particular and could offer suitable production sites, subject to further review.
- The area is likely to continue to experience levels of grid constraint / curtailment in future years – local grid network is highly constrained and will be subject to Active Network Management by SPEN. Opportunities to produce hydrogen from curtailed renewable energy will continue to emerge as generation capacity grows.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- There are a several waterbodies at the south of the Cluster, as well as Rivers Nith and Doon, which could offer abstraction potential for small-medium scale hydrogen production. BGS Mapping indicates that groundwater abstraction yields are likely to be relatively high especially towards the east of the Cluster.
- Girvan Distillery (and surrounding cluster of production land uses) is situated at the western edge of the Cluster and a potential off-take opportunity, subject to future feasibility and demand.

Key Constraints

- Aside from Girvan Distillery (noted above) there is limited local industrial demand / energy intensive users in the immediate locale to which hydrogen could be integrated as an off-take. Off-take demand may emerge from industrial activities / processes in Ayr / Irvine, or further afield in the Central Belt.
- Relatively limited gas network infrastructure in the area – limiting opportunities for blending as a potential market for export / demand.

Cluster 3: South Lanarkshire

Cluster 3 covers a large area at the rural, southern edge of South Lanarkshire where there has significant development of onshore wind capacity. It includes a number operational wind farms which undergo curtailment through the NG Balancing Mechanism, including Galawhistle (66MW), Middle Muir (51MW), and Clyde Wind Farm + Extensions (350MW).To add to existing generation, wind farms are proposed at Low Drumclog (20MW), Grayside (147MW), and Kype Muir Extension (75MW) but appear to be without grid connection and may therefore be strong candidate sites for hydrogen production.



Key Opportunities

- The M74 Motorway crosses through the centre of the Cluster, and is a key arterial route for road freight / cargo between Scotland and England. This includes a major service station / truck-stop at Lesmahagow. Subject to future feasibility and economics, hydrogen may emerge as a key zero-carbon fuel for vehicle freight movements and re-fuelling would be a significant opportunity in this location.
- There is a large number of operational and planned on-shore wind farms in the area – opportunities for collaboration and sharing of production, storage and distribution infrastructure. Range of operators includes Banks Renewables and who are actively progressing hydrogen production projects elsewhere.
- The area is likely to continue to experience levels of grid constraint / curtailment in future years – local grid network is highly constrained. Opportunities to produce hydrogen from curtailed renewable energy will continue to emerge as generation capacity grows.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- The River Clyde (close to Grayside Wind Farm) and Douglas Water cross through the centre of the Cluster and could offer surface water abstraction potential. BGS Mapping indicates that groundwater abstraction yields are likely to be relatively high especially towards the west of the Cluster.
- National Grid Gas Transmission pipelines cross though the centre of the cluster – with the nearest inter-change / compressor station to the south at Elvanfoot. Subject to future technical feasibility and legislation to allow for hydrogen blending, this could provide an export opportunity for green hydrogen production.

Key Constraints

- Aside the M74 freight vehicle movements and potential blending into gas network - there is limited local industrial demand / energy intensive users in the immediate locale to which hydrogen could be integrated as an off-take. Off-take demand may emerge from industrial activities / processes further afield in the Central Belt, and would be well connected via the M74 for tube-trailer transport.

Cluster 4: East Lothian & Borders

Cluster 4 covers the rural Lammermuir Hills area on the border between East Lothian and the Scottish Borders. It has been an early location for development for onshore wind with Aikengall operational since 2008 and expanded several times, as well as Fallago Rig (144MW) since 2013. As well as those windfarms undergoing curtailment through the NG Balancing Mechanism, several wind farms have a ‘Flexible / Non-Firm’ Connection– these include Aikengall, Quixwood Moor (30MW), and Penmanshiel (28.7MW)

Key Opportunities

- The area around Torness is a cable landing site and substation for Berwick Bank Wind Farm which will provide a major quantity of renewable energy and may attract interest / opportunities for green hydrogen production –which decentralised models within the Cluster could complement.
- There are several operational wind farms in the area undergoing constraint – and this has been subject to prior Active Network Management in coordination with SPEN. Opportunities for collaboration and sharing of production, storage and distribution infrastructure around hydrogen could complement and add to this.
- Tarmac Cement Works is situated at the edge of the Cluster. It is an energy intensive industrial process and one of the major CO2 emitters in Scotland. The potential for hydrogen integration to support decarbonisation is a potential opportunity, subject to future feasibility and demand.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- National Grid Gas Transmission pipelines cross though the cluster – between Aikengall and Fallago Rig windfarms. However, with the nearest inter-change / compressor station is 11km north of the Cluster at East Fortune. Subject to future technical feasibility and legislation to allow for hydrogen blending, this could provide an export opportunity for green hydrogen production.

Key Constraints

- Aside from Tarmac Cement Works and potential blending into gas network - there is limited local industrial demand / energy intensive users in the immediate locale to which hydrogen could be integrated as an off-take. Off-take demand may emerge from industrial activities / processes further afield in the Central Belt, and would be well connected via the A1 for tube-trailer transport.
- There are relatively limited opportunities for water abstraction in the area. Existing reservoir is situated near to Aikenall, Fallago Rig and Crystal Rig Windfarms though appears to still be in use by Scottish Water. BGS Mapping indicates that groundwater yields are relatively low.
- Proposed Eastern Link HVDC Cable is proposed to make landfall at Torness and connect to Hawthorn Pit. Subject to timing of delivery and future grid operation, this may reduce levels of constraint and curtailment for those windfarms connected to the National Grid (Fallago Rig, Aikengall II, Aikengall II)

Cluster 5: West Lothian & South Lanarkshire

Cluster 5 covers a semi-rural hinterland at the southern edge of the Central Belt for which there is significant potential growth in renewable energy generation capacity. Black Law wind farm (and extension) has been operation at the western edge of the Cluster since 2004, and more recent development of Pearie Law (1) (19MW) and Harburnhead (52MW) since 2016 has added capacity. 6 additional wind farms either benefit from planning permission or are currently under consideration, including 3 with a 'Flexible / Non-Firm' Connection (Longhill, Woolfords, and Pearie Law (2)) and 1 currently without a grid connection.

Key Opportunities

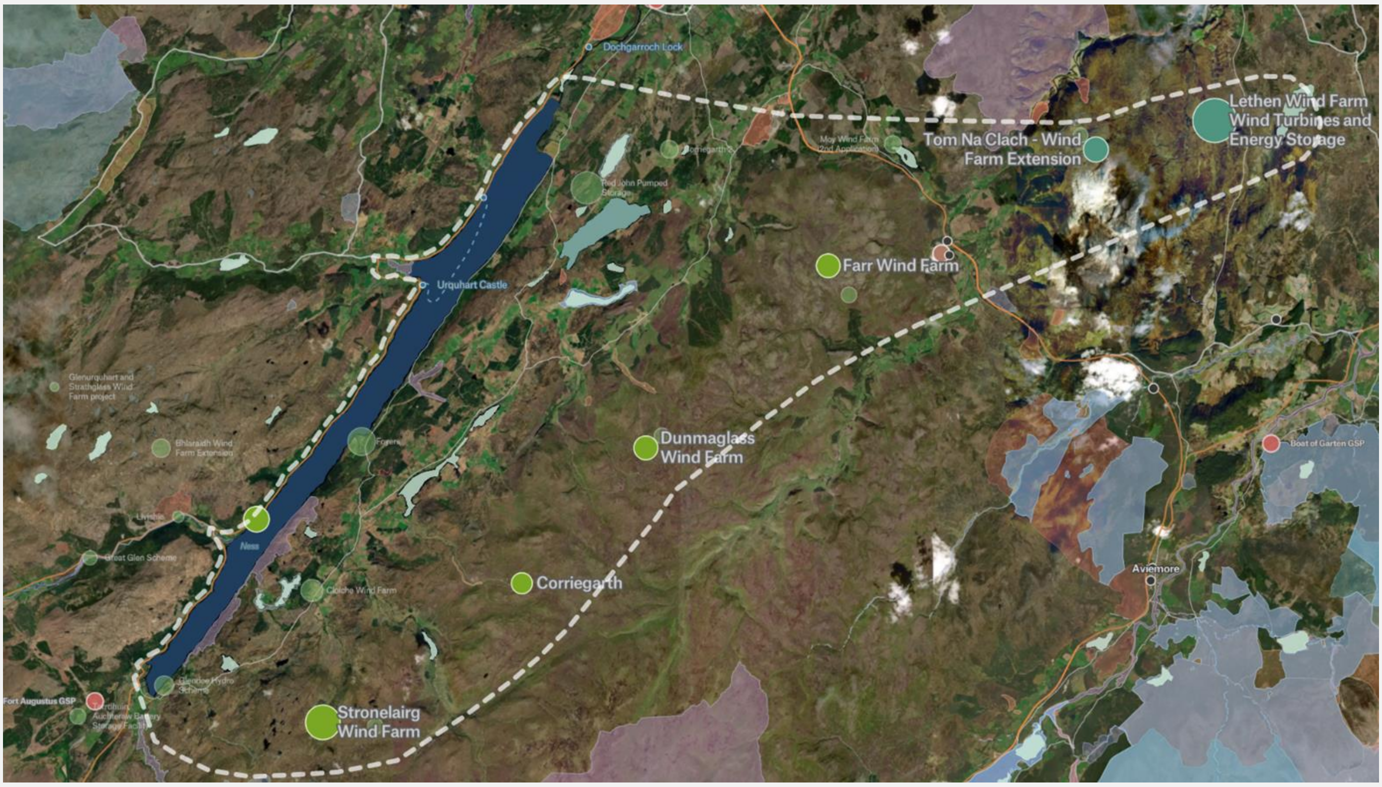
- The Cluster is located in close proximity to the Central Belt and a wider range of potential off-takers than many other more remote locations for green hydrogen production. The M8 is 6km north of the Cluster, and Edinburgh / Glasgow / Grangemouth are all within <1hr drive for tube-trailer distribution.
- There are several operational wind farms in the area undergoing constraint with additional capacity likely to be added which will subject to Active Network Management in coordination with SPEN. Opportunities for collaboration and sharing of production, storage and distribution infrastructure around hydrogen could complement and add to network management processes.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- National Grid Gas Transmission pipelines cross though the cluster – between Black Law and Gladsmuir Hills Wind Farm (proposed). The nearest inter-change / compressor station is at the northern edge of the Cluster, next to Knowton Farm on the outskirts of Shotts. Subject to future technical feasibility and legislation to allow for hydrogen blending, this could provide an export opportunity for green hydrogen production.

Key Constraints

- There are relatively limited opportunities for water abstraction in the area. Existing reservoir (Scottish Canals owned) is the principal source of potential abstraction and is in close proximity to planned wind farm development at Pearie Law, Woolfords Farm and Longhill Burn – but may be constrained by SSSI designation and operational requirements by Scottish Canals. BGS Mapping indicates that groundwater yields are moderate and would depend on location specific review.

Cluster 6: Loch Ness

Cluster 6 incorporates large upland area along the eastern edge of Loch Ness. The area has a number of large operational wind farms including Stronelairg (228MW), Blaraidh (110MW), Corriegarth (70MW), Dunmaglass (94MW) and Farr (92MW) all of which are subject to curtailment through the NG Balancing Mechanism. Planned wind farm development at Tom Nan Clach (Extension) (31.5MW) and Lethen (102MW) appear to be without a grid connection.



Key Opportunities

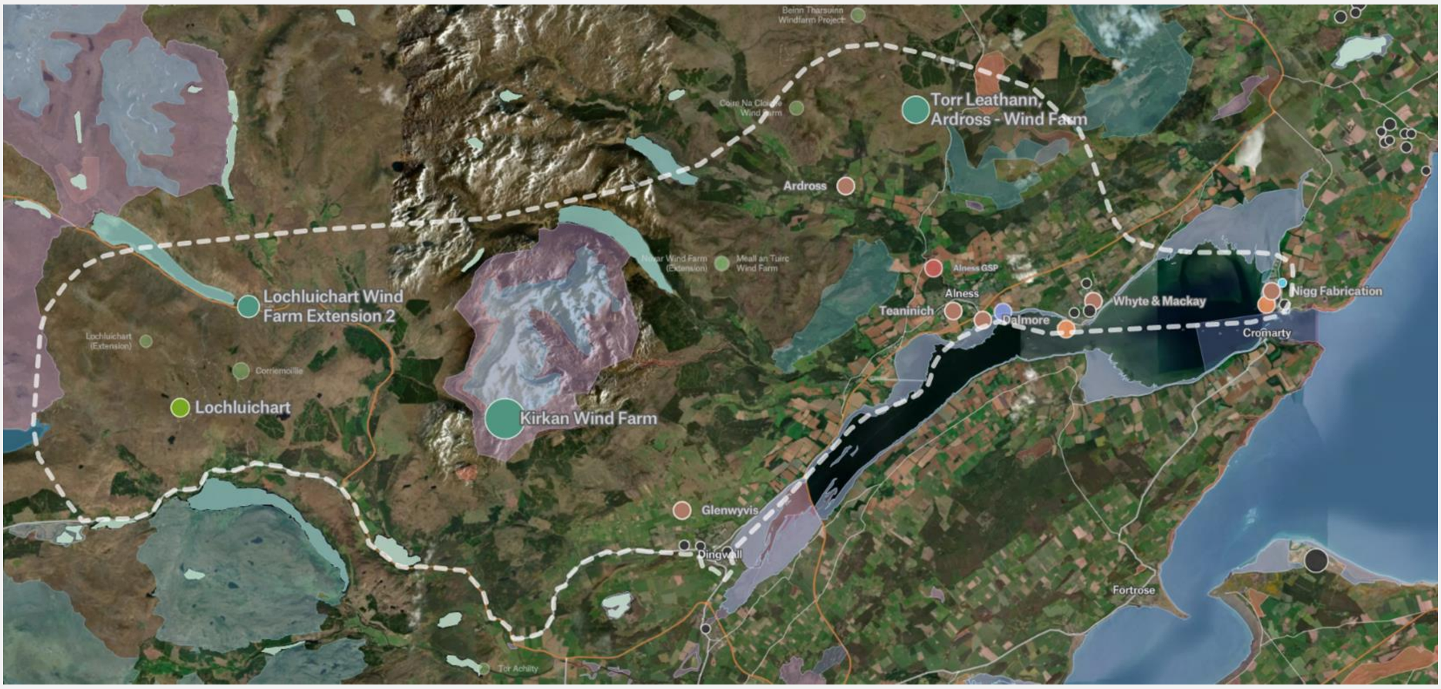
- Loch Ness is the largest freshwater body in the UK and currently subject to relatively low levels of abstraction. It offers an opportunity to support hydrogen production, albeit specific siting of hydrogen production to simultaneously optimise renewable energy and the very large levels of water availability would require further feasibility review. Elsewhere within the Cluster there are several watercourses and waterbodies which could serve as a source of water abstraction.
- There are several operational wind farms in the area undergoing constraint with additional capacity likely to be added. Opportunities for collaboration and sharing of production, storage and distribution infrastructure around hydrogen could complement and add to network management processes. In particular, SSE operate several large wind farms in the area and are actively progressing hydrogen production projects elsewhere.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- While there is limited energy intensive industrial activity in the area, it is proximate to the major cluster of distilleries in the Speyside / Highland region. A range of distilleries are located within a <90 min drive of the Cluster and could be supplied with green hydrogen via tube trailer distribution. A number of programmes / initiatives within the Distillery sector are being progressed to accelerate decarbonisation and there is a potentially significant demand for hydrogen. In particular, Tomatin Distillery is located within the Cluster and in close proximity to Farr, Glen Kyllachy and Tom Nan Clach Wind farms.

Key Constraints

- A number of the existing and planned wind farms are in remote and upland locations – which may be challenging to access and distribute hydrogen from via large-scale tube trailer though access tracks will be designed for HGV / construction access so not considered a significant constraint.

Cluster 7: Cromarty & Ross-Shire

Cluster 7 covers the area around the Cromarty Firth and upland areas. Led by the major port infrastructure at Invergordon (PoCF and Nigg (GEG) the area is already a cluster of renewable energy supply chain activity (especially offshore wind) and is actively promoting hydrogen production through Opportunity Cromarty Firth / North of Scotland Hydrogen Programme (NOSH). There are operational wind farms at Corriemollie (54MW), Meall an Tuirc (53MW), Coire Na Cloiche (30MW), and Beinn Tharsuinn (30MW). Lochluichart Wind Farm (51MW) currently undergoes curtailment through the NG Balancing Mechanism, and a proposed extension appears to currently be without a grid connection. Similarly, planned wind farms at Kirkan and Torr Leathan are progressing through the planning system but currently without grid connection.



Key Opportunities

- As noted above, the Cromarty area is already being actively promoted as a location for hydrogen production. Through the NOSH Programme a production site has been identified and is being developed in partnership / collaboration with existing cluster of Distillers in the area for whom hydrogen offers a significant decarbonisation opportunity. Future decentralised production within the Cluster can complement and add to this (subject to demand) and strengthen the competitiveness of Cromarty as a renewables hub.
- Major port infrastructure at Invergordon and Nigg creates a range of potential opportunities and synergies for hydrogen production, either as a zero-carbon fuel source for marine transport, or as a means of transporting hydrogen to reach export markets.
- The major scale of planned offshore wind in the Moray Firth will attract interest and opportunity for potential hydrogen production around Cromarty. De-centralised production utilising curtailed renewable energy can act as an enabler / pilot / demonstrator of capability to support future scale-up of production.
- There are several operational wind farms in the area undergoing constraint with additional capacity likely to be added. Opportunities for collaboration and sharing of production, storage and distribution infrastructure around hydrogen could complement and add to management of curtailment.
- There are relatively few sensitive receptors or potentially conflicting land uses in the area.
- As noted above, there is a pre-existing grouping of Distilleries in the region currently prioritising decarbonisation. NOSH Programme is being developed with this sector as primary off-takers for early phase development and (compared to other clusters) there is a strong likelihood of potential future demand from this sector.

Key Constraints

- A number of the existing and planned wind farms are in remote and upland locations – which may be challenging to access and distribute hydrogen from via large-scale tube trailer though access tracks will be designed for HGV / construction access so not considered a significant constraint.

Cluster 8: Orkney & Shetland Isles

Cluster 8 encompasses the Orkney and Shetland Isles – where decentralised production is already emerging and forming part of energy transition. A range of small-scale renewables generation across the islands offers potential to support decentralised production, and larger-scale wind farms such as Viking and Yell are now under development and will bring further opportunities.

Key Opportunities

- Orkney and Shetland have been early innovators and leaders in promoting Hydrogen economy. Orkney BIG HIT has demonstrated a model of decentralised production serving local demand for transport / heating and accelerating decarbonisation. There will be further opportunities for decentralised production to complement and/or extend this programme. Larger-scale ORION programme across the Shetland Islands is exploring opportunities for production, storage and distribution utilising existing skills and infrastructure. Plans are also in development for a Flotta Hydrogen Hub, for large-scale production and export of green hydrogen utilising power from nearby offshore wind.
- Major port infrastructure and the network of ferries / marine transport across the Islands creates a range of potential opportunities and synergies for hydrogen production, either as a zero-carbon fuel source for marine transport, or as a means of transporting hydrogen to reach export markets.
- Major renewable energy resources currently yet to be utilised to full potential. Delivery of Shetland HVDC will enable and support further deployment of renewable generation, albeit reducing overall levels of constraint.
- Strong planning policy and development framework for renewable energy generation – both from NPF4 (National Development status) and Orkney and Shetlands Islands local authorities who are active in developing capacity and promoting hydrogen economy.

Key Constraints

- Relatively limited water availability from ground and surface water sources – though most renewables generation is in close proximity to coastline and may be capable of utilising sea-water abstraction.
- Added transportation / distribution logistics for decentralised hydrogen on remote island locations requiring combination of marine and road infrastructure – though unlikely to pose major constraint at small scale production and has been successfully resolved in current test / pilot programmes (BIG HIT).

Future Demand & Use Cases

The Report has identified and reviewed a range of potential 'supply-side' opportunities for production of green hydrogen utilising constrained renewable energy. Of equal importance is the 'demand-side' utilisation of green hydrogen - where it can be viably integrated into industrial processes and activity, transport and movement, or exported safely and efficiently.

Notwithstanding the supply-side factors of renewable energy generation, water availability, and land & infrastructure, those locations where decentralised production is most likely to emerge will also be where there is a strong needs case for local decarbonisation and an identified industrial or transport off-taker. The figure below extracted from the Scottish Government Hydrogen Action Plan (2022) highlights the most likely sector opportunities and use cases for hydrogen, considering end-to-end efficiency, availability of alternatives, and complexity of integration from a technical and logistical perspective.

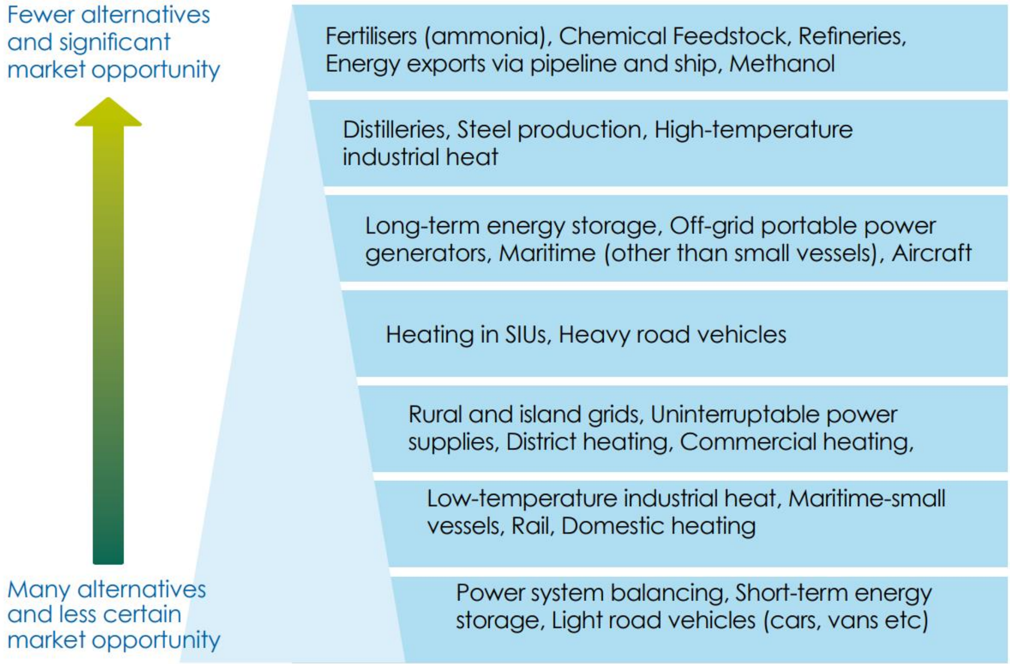


Figure 11. Hierarchy of potential hydrogen uses and applications (© Scottish Government)

In each of these instances, green hydrogen must be competitive with other forms of energy storage or zero-carbon fuel sources that are seeking to play a role in decarbonisation. It must have a 'winning' use case that attracts demand for it as a cost-effective, convenient, safe source of energy. Review of emerging hydrogen economy projects, and stakeholder engagement have both highlighted that a key locational driver for early hydrogen production will be demand-led. Within and around Clusters reviewed in this Report, energy intensive industrial and production activities such as distilleries have been highlighted where these could offer a source of local demand for decentralised production.

Establishing in further detail where the most viable use cases for green hydrogen may emerge across Scotland (and at what scale) will be critical to supporting growth of the sector and further defining preferred production locations. To advance this, Scottish Enterprise are progressing detailed review of potential future hydrogen demand locations and clusters across Scotland. This will include technological and spatial review of transport and industrial activities that could provide a source of hydrogen demand, which can complement the spatial analysis of decentralised supply-side opportunities identified through this Report.

5. CONCLUSION

The review of grid constraint and decentralised green hydrogen production has highlighted a range of potential opportunities across Scotland where core site requirements around land, power and water can be fulfilled and production of green hydrogen may be viable. The demand market for hydrogen and associated commercial viability considerations are continuing to evolve, though use cases and off-take sources are emerging that may complement and stimulate decentralised production.

Key Findings

Across the review of grid constraint, decentralised production requirements, and identification of clusters, key findings that emerge from the Report are summarised below:

- There are potentially significant opportunities for curtailed renewable energy in Scotland to contribute towards green hydrogen production. Transmission (National Grid) and Distribution Networks (SPEN / SSEN) are both constrained (with subsequent curtailment of renewable energy generation), and this is not confined to a specific geography but a challenge in a range of locations across Scotland. The heavily constrained nature of the grid network in Scotland means that flexible and responsive technologies, including hydrogen, will become increasingly important in the future operation of the energy system.

- Notwithstanding planned transmission and distribution infrastructure reinforcement, constraint is likely to be a challenge for renewables generation over the medium-longer term (albeit its spatial distribution may vary). Given the time, cost and complexity in delivering reinforcements to grid capacity, this will be unable to match planned growth of renewable generation especially from offshore wind.

- While subject to commercial viability and site-specific feasibility, decentralised production offers strong synergies and 'win-win' potential to address challenges of:

    - Maximising the potential of available renewable energy resources by sourcing from constrained generation, and reducing levels of curtailment.
    - Strengthening the investment proposition for new and existing renewables generation in the context of changing subsidy and market incentives, offering new revenue streams and ability to diversify.
    - Accelerating the decarbonisation of energy intensive activities / sectors, especially in more rural locations.

- Through the process of filtering and reviewing sites experiencing constraint, onshore wind emerged strongly as this is the most common and largest scale renewable technology, and most frequently curtailed. This reflects its predominance as the largest scale and most frequently deployed renewable technology. Other technologies such as hydro-electric and Solar PV are subject to lower levels of curtailment but may still present future opportunities for green hydrogen production, subject to operational and commercial viability.

- Examples of hybrid electricity and hydrogen (and other renewables) production models are now emerging in response to grid constraint. Planned projects at Whitelees (SP Renewables) and Gordonbush (SSE) demonstrate potential models of production which are likely to be replicated elsewhere at renewable generation sites across Scotland. A significant number of on-shore wind farms are developing co-located BESS capacity which could be complementary to hydrogen production by enabling greater capacity factor and offering optionality in how renewable energy is stored, utilised, distributed depending on market conditions.

- Grid constraint is dynamic and variable both over time and across geographies, depending on delivery of reinforcement of grid infrastructure, innovation in network management by NG / SPEN / SSEN, changing economic incentives associated with grid balancing, and the impact of further renewables generation growth including Scotwind. Reporting has sought to identify areas of constraint and curtailment at this point in time, though the most suitable and preferred locations for utilising constrained renewable generation may continue to evolve and shift over time. De-centralised green hydrogen production has the potential to be relatively modular and scale-able (compared to other forms of energy storage) and provide flexibility that is responsive to the transient and shifting nature of grid constraint.

Clusters and Key Issues Emerging

Based upon analysis of available BEIS, NG, SPEN, and SSEN data, a range of potential clusters have been identified where there are groupings of renewable energy generation that are constrained. With suitable policy and economic incentives there is the potential for deployment of decentralised production across each of these locations – though scale and mode of operation will vary depending on local context, demand, and specific operator considerations.

- Detailed review of production opportunities and constraints across the Clusters highlights the following commonalities and key issues:

    - **Water Availability -** For production at small-medium scale, there is water availability across locations through a combination of ground and surface water abstraction – however operator preference for siting of production 'behind the meter' is likely to direct towards co-location with existing infrastructure (sub-stations / compounds / haul-routes etc) associated with on-shore wind generation which are further removed from water sources. The scale of requirement is potentially capable of being met through potable supply (Scottish Water) in some instances and locations, and this may prove preferable to ensure guarantee of supply (subject to site specific review with Scottish Water).

    - **Off-Take & Distribution** - In the short term and for production at decentralised scale it is likely that off-take of hydrogen will be via compressed tube trailer for transport to an end-user. This reflects the relatively rural and remote locations of most renewable energy generation where direct integration to gas infrastructure, marine / rail export, or to a directly co-located end user are limited, and the degree of flexibility and range to meet multiple sources of demand through road transportation (albeit with limitation on volumes / capacity).

    - **Demand** - Across the majority of Clusters, a common constraint or challenge is the need for ready off-takers and sources of demand for green hydrogen. This is to be expected given the nascent stage of development and integration of hydrogen into industrial and transport processes but will remain a key challenge. Notwithstanding opportunities that are identifiable through 'supply-side' analysis, it is likely that strong opportunity sites will emerge from 'demand side' where there is a strong market and needs / business case for hydrogen integration.

- **Consenting & Environment** - As might be expected, existing renewable energy generation sites are typically well separated from sensitive receptors or major environmental designations. In most cases co-located (or proximate) production sites at small-medium scale are unlikely to be significantly constrained by planning and environmental matters, though appropriate Control of Major Accident Hazards (COMAH) Regulations and Hazardous Substances Consent (HSC) considerations may still apply.

- **Siting -** At many renewable generation sites, preferred siting for hydrogen production is likely to be on or adjacent to existing haul routes / access roads, potentially utilising disturbed land such as construction compounds or restored borrow pits. Utilising existing infrastructure and assets will limit potential for environmental impact and reduce complexity / risk for project delivery – for example new cable routing to link electrolysers to generation can follow access routes.

Next Steps & Recommendations

Building on the data and findings produced through this Report, potential next steps and areas for further consideration, investigation, and engagement both by Development Agencies and wider partners could include:

- Continued review and stakeholder engagement around the economic viability of green hydrogen production at small-medium / decentralised scale. This spatial study has not considered detailed commercial or economic factors but these will continue to shape site suitability and operator interest. Key issues for consideration may include:

    - Wholesale electricity market pricing and operation of National Grid Balancing Mechanism (the opportunity cost to hydrogen production for many large-scale windfarms). This is potentially subject to reform (REMA) and will influence future incentives.
    - Future evolution of subsidy and other forms of support for renewables generation, and how this may influence hydrogen production.
    - Costs of production for green hydrogen production (in light of future renewable generation capacity / capacity factors / electrolyser technologies etc), economies of scale, and potential commercial return scenarios.
    - Future growth of hydrogen economy and sources of demand seeking green hydrogen to accelerate decarbonisation. Noting green hydrogen must demonstrate robust use case and 'win' its way into the market ahead of other modes and means of decarbonisation. Where uptake of green hydrogen as a zero-carbon energy source will emerge remains uncertain, but analysis by Scottish Government and Scottish Enterprise has highlighted potential hubs of demand across Scotland.

- Engagement and collaboration with 'early-movers' in green hydrogen Production such as Scottish Power Renewables, SSE, Storegga to identify lessons learnt from current projects and key challenges to be overcome in implementing decentralised production.

- Further detailed review of identified Clusters and/or locations - assessing in more granular detail the specific locational constraints, opportunities and operational considerations that will determine siting of small-medium scale production locations. This could be progressed in coordination with local authorities, development agencies, utility providers and renewable energy operators.

- Engagement with operators and developers of identified constrained renewable energy sites to review potential hydrogen production opportunities and understand potential constraints, challenges, and support that can be offered to bring forward production. This could include active coordination and ‘match-making’ between sources of demand and renewables operators to develop the strongest and most viable opportunities for decentralised production.

- More detailed technical review and modelling of future grid constraint and curtailment, accounting for changing nature of electricity market incentives and operation of the Balancing Mechanism. This could be undertaken through collaboration and engagement with SPEN, SSEN, and National Grid to support more nuanced and comprehensive understanding of grid constraint assuming full ScotWind deployment, planned grid reinforcements and network management, and future energy demand scenarios. This could include exploration of incentives and market mechanisms to encourage green hydrogen production from curtailed renewable energy.

APPENDICES

A. Cluster Factsheets & Mapping
B. Engagement Workshop Slide-Deck
C. Shortlist Sites Planning & Curtailment Summary Data-sheet

Mapping produced using data from the following sources:

- SEPA information licenced under the Open Government Licence v 3.0
- NatureScot information licenced under the Open Government Licence v 3.0
- British Geological Survey (HydroGeology) information licenced under the Open Government Licence v 3.0
- National Gas Transmission – Transmission Network Shapefile (© National Gas Transmission)
- HydroLAKES V1.0 licensed under a Creative Commons Attribution (CC-BY) 4.0 International License (Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications, 7: 13603)
- HydroRIVERS V1.0
- Lehner, B., Grill G. (2013). Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186
- Department for Business, Energy & Industrial Strategy – Renewable Energy Planning Database (REPD) (28 October 2022)
- Scottish Government – Vacant & Derelict Land Survey (Site Register) (September 2022)
- SGN – Gas Distribution Network. Used in agreement with SGN for the purposes of this study to demonstrate indicative location of network infrastructure.