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UK Hydropower Resource Assessment 2022

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British Hydropower Association

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Contents

Executive Summary

This project brings together data from various sources of the installed capacity and location of hydropower installations in the UK and compares these against the values forecast in previous reports. This has been complemented by a survey of British Hydropower Association members and invited non-British Hydropower Association members to consider the appetite for further investment in hydropower and the hurdles faced by the sector.

The report's aim is to provide an evidenced assessment of the potential of additional hydropower generation as part of a portfolio of low carbon electrical generation technologies to support the UK's target of net-zero. As with all renewable generation technologies, the answer of how much of the resource can be captured and at what cost and within environmental constraints is a complex area dependent on many factors. However, the report proposes an additional deployment of 1000 MW (1 GW) as an achievable target under a supportive policy framework. This would allow hydropower generation of circa 3 GW (a 1 GW addition to the installed base of circa 2 GW in 2022) that could provide an estimated 1.5 % of the increased annual electrical demand of the UK in its net-zero future.

Hydropower has been providing electricity to the UK for over 100 years and our analysis suggests it has cumulatively saved the need to generate 300 TWh from other sources, leading to an estimated saving of 160 million tonnes of CO_2 equivalent emissions over that long time period; for comparison the UK territorial emissions were nearly 450 million tonnes of CO_2 equivalent[1] in 2019. This points to the longevity of hydropower, a key differentiator from other renewable technologies, where investment will typically lead to a very long-lived electrical generation asset with replacement timeframes far greater than other renewable generation such as solar panels and wind turbines. The analysis of hydropower capacity and dates of installation suggests that half of the UK's current capacity was initially installed prior to 1962 (60 years ago).

The project considered earlier hydropower generation assessments, one of which was the Salford Study, which in 1989 suggested a further viable 322 MW of hydropower could be installed in the UK. In the 33 years since its publication, over 500 MW of hydropower has been commissioned, thus significantly passing the forecast. More recently, there have been detailed studies of the potential hydropower resource for Scotland such as the 2008 study by Nick Forrest, The Scottish Institute of Sustainable Technology and Black and Veatch titled 'Scottish Hydropower Resource Study' and the 2012 whitepaper by Nick Forrest and baby Hydro. In addition, there have been detailed studies for England and Wales including the 2010 report from the British Hydropower Association and IT Power, and the Environment Agency's report in 2010 of the Potential Sites of Hydropower Opportunity. These studies have differing approaches and inputs and unsurprisingly have different estimates for the potential of hydro in the UK.

Since these previous assessment reports of hydropower generation were published, much has changed in the energy policy landscape of the UK. The level of ambition has increased with the UK having set a net-zero target by 2050; the levelised costs of wind and solar PV generation have decreased considerably; the UK has left the European Union and security of supply for energy has once again become a major area of focus.

From the Business, Energy and Industrial Strategy Energy Trends publication[2] in the 12 years from 2010 to 2021 the estimated UK hydropower capacity increased from 1647 MW to 1891 MW, an increase of 244 MW (these values do not include capacity for pumped storage). Over the 5 years from 2017 to 2021 output from hydropower averaged about 1.8% of the supply of electrical energy in the UK but, as the electrical demand is forecast to increase through the electrification of heat and transport demand, if hydropower capacity is not increased, its overall share of supply will decrease to below an estimated 1%. A target of 1.5% of annual UK electrical demand being generated by hydropower in a net-zero system would necessitate a 50% increase of its existing capacity, taking it from 2000 MW to 3000 MW, the proposed target of additional capacity of this report. Sector estimates on the cost of delivering this additional 1 GW of capacity range between £4.5 billion and £6 billion, the majority of which would be spent within UK supply chains, creating and sustaining jobs within the sector.

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[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf

[2] Renewable electricity capacity and generation (ET 6.1 - quarterly) – 'Annual' worksheet https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1086802/ET_6.1_JUN_22.xlsx

In the summer of 2022, the UK government launched a consultation titled a 'Review of Electrical Market Arrangements'[3], as well as publishing a report on the 'Benefits of long-duration electricity storage'[4]. Both of these focus on the benefit of low-carbon flexibility for generation, i.e., the ability to increase and decrease generation over different timescales to better match electrical demand. In addition, these documents are underpinned by an increased focus on security of supply. The publicly available generation output for hydropower suggests that the majority of hydropower is currently operated with some daily flexibility to better match its output to the higher demand periods within a day. In addition, hydropower is also seasonally well matched to electrical demand with a higher output in winter than in summer. These characteristics point to hydropower not only being a useful means of low-carbon flexibility, but increasingly being an important source of generation when other low-carbon sources are simply unavailable. Hydropower generation can (and does) generate electricity overnight when solar (without storage) simply cannot, it can generate over longer periods of time (days to weeks) when there are low-wind spells, and it generates more in the winter than in the summer, which is a benefit to help match the seasonal heating profile for the UK. These are all advantages as part of a future UK net-zero electrical generation portfolio.

The survey undertaken for this report provides insights on various hurdles the sector faces to build new hydropower schemes, and although many of these can be considered through the lens of financial reward, several are based on the upfront costs in terms of permitting and risks that a scheme may not eventually prove viable. There is a view that a more proportionate system of costs for consents could be helpful particularly for smaller hydropower schemes.

A sound representative estimate from the sector survey suggests 217.5 MW could be built by 2030 under a favourable policy environment by the 49 survey participants, which if scaled up by extrapolating across the whole UK would be up to 1.4 GW. However, extrapolating up to the existing installed base is highly uncertain and although it is broadly consistent with mid-level estimates from previous detailed resource assessments the view in this report is to suggest a more conservative value of 1 GW of additional capacity for hydropower, that would generate an estimated 1.5 % of the UK's net-zero annual electrical demand.

The results from the survey led to:

- an estimation that nearly 50 MW of additional capacity could be added to the system by expanding hydro sites that are already operational and the confirmation that 19 MW of projects have the necessary consents but have stalled at final investment decision (from the sites of survey respondents)
- the identification that the main hurdles to new hydropower projects are a lack of ongoing financial certainty in a post-FiT framework, difficulty in gaining consents, particularly from the Environment Agency, and obtaining grid connections, especially outside England
- a relationship between the hydropower capacity able to be built by 2030 (rounded to the nearest 10 MW) and the levels of financial support per MWh

Guaranteed 15-year price	***Survey respondents' total deployment by 2030***
£120 per MWh	120 MW
£140 per MWh	220 MW
£160 per MWh	400 MW

In summary, hydropower generation has helped to decarbonise the UKs electricity system for over 100 years; it has yet to fully develop to the levels that have been suggested in previous reports; it has an engaged sector that wishes to develop more; its generation characteristics have an increasingly important role in terms of security of supply as part of an overall net-zero generation portfolio. This all points to the need for the sector to continue to try to find a supportive policy framework with policy makers in order to encourage further deployment. Such a policy could consist of either a Contracts for Difference arrangement or enhanced Smart Export Guarantee, so that new schemes get access to a guaranteed rate of return, which would make many more locations financially viable for hydropower.

[3] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements

[4] https://www.gov.uk/government/publications/benefits-of-long-duration-electricity-storage

Report Recommendations

The report makes five recommendations:

1. The UK should target a 50% increase in its hydropower capacity of 1 GW from its existing 2 GW -> 3 GW, so that the sector provides a 1.5% share of the annual electrical demand in a net-zero energy system in 2050.

2. The department for Business Energy and Industrial Strategy should continue to engage with the British Hydropower Association on the relative merits of different funding mechanisms to incentivise 1 GW of additional deployment. For example, to consider Contracts for Difference type agreements vs Smart Energy Guarantees vs other options. The survey of BHA members as part of this report supports the level of certainty provided through a bankable policy such as a Contract for Difference, is a more favourable approach than an upfront grant. Although, upfront grants could be more favourable for small schemes, to help offset some of the initial costs such as consenting and electrical grid connections

3. Consideration should be given to a more coordinated approach to hydropower projects for planning and consenting and a greater sharing of best practice between the devolved environment agencies. Consideration should be given to more proportionate levels of consenting fees which do not disproportionally reduce investment in the sector at the smaller scale of development. Consideration should be given to more proportionate levels of valuation office business rates which do not disproportionally reduce investment at certain capacity levels, and a greater sharing of best practices between the different valuation offices across the UK

4. There should be a single publicly available dataset for all hydropower installations in the UK that defines a unique reference number for each installation. This could be utilised by BEIS, Ofgem, Environment Agencies and Valuation Offices throughout the UK to link this unique reference number to different data. It would be useful if this publicly available dataset had at a minimum: the capacity of the installation, the location of the installation and the date of commissioning. This would help to manage the problem of slightly (or even very different) hydropower sitenames that exist between different public bodies

5. A new detailed resource and techno-economic hydropower assessment should be commissioned and co-ordinated by BEIS with input from relevant bodies from the Scottish Government, Welsh Parliament and Northern Ireland Assembly. This would make use of up-to-date LIDAR data, weather data (with consideration of climate change impacts) and other assumptions to reflect advances in hydropower system designs, the wider electrical generation portfolio, electrical network connections and the challenges of reaching net-zero. The study could also consider low-head and pico-micro sized installations

Background to the report

The Energy Informatics Group at the University of Birmingham was commissioned by the British Hydropower Association to undertake an assessment of the future potential of hydropower in the UK. The scope of the work was based on the following work packages:

1. A detailed assessment of the existing hydropower installations in the UK
2. An assessment of previous studies into the hydropower potential of the UK
3. A comparison of installed capacity versus previous reports' views of the hydropower potential of the UK
4. An analysis of the historical operation of hydropower output at a half-hourly level and consideration of how this might benefit future UK efforts to decarbonise
5. A survey to BHA members (and selected non-members) to consider a sector view of the hydropower potential and barriers to its development

The sections of this report detail the analysis and approach undertaken in the corresponding work packages, with an executive summary, recommendation and discussion sections. Appendices are used for more detailed descriptions.

The team in the Energy Informatics Group at the University of Birmingham comprising of Dr Grant Wilson, Dr Joe Day and Geraint Phillips undertook the analysis between May to July 2022 with ongoing input and feedback from Simon Hamlyn [CEO], Jamie Needle [Vice Chair] and Alex Reading [Chair] from the British Hydropower Association .

The project is grateful to members of the British Hydropower Association for taking the time to provide input to the survey and to staff at various devolved regulators in England, Scotland, Wales and NI, Ofgem, BEIS, the Renewable Energy Foundation, Hallidays Hydropower International, Nick Forrest, Kenny Hunter, Martyn Cowsill, Peat Allan, Rachel Feilden and Anthony Battersby.

Section 1: Assessment of existing hydropower installations in the UK

The aim of this section was to provide a greater level of detail on the hydropower installations that exist in the UK as of May/June 2022. A summary of the method is presented in this section, with a more detailed methodology provided in appendix A.

There were three main types of data that the project needed: the capacity of hydropower generation that had been built, when it had been built and where it had been built. With greater accuracy of this existing generation data, the historical reports that had previously considered the future of hydropower capacity could be analysed with greater certainty.

A starting point for a value for how much hydropower generation capacity exists in the UK is from the Digest of UK Energy Statistics (DUKES) 2021 dataset[5] and the 'Database' worksheet tab of the spreadsheet '5.11 Power Stations in the United Kingdom'[6]. This details 126 hydropower generation stations from Major Power Producers that sum to 1446.1 MW and in the worksheet titled 5.11 there is an aggregate capacity value for Other Generators of 413.5 MW. Therefore, from the DUKES data alone, there is a total capacity between the Major Power Producers and Other Generators of 1879.7 MW. There is also a year of commission for the Major Power Producers, and location at the level of an English Region, Scotland, Northern Ireland or Wales. There is no year of commission or location data for the aggregate value for Other Generators

Table 1 - Digest of UK Energy Statistics hydropower generation data

	Total capacity	Minimum capacity	Maximum capacity	Number of stations	Year of Commission values	Location Data
Major Power Producers	1446.1 MW	0.05 MW	152.5 MW	126	Yes	English Regions, Scotland, Northern Ireland, Wales
Other Generators	413.5 MW	-	-	?	No	-
Total	1879.7 MW					

A number of datasets with more detailed data were explored and found to have other useful data, but the most important if they were available were:

- The site name that was helpful to cross check between different datasets
- The date of commissioning or operation that was helpful to determine the rate of deployment and as a cross check for sites with similar names
- The capacity that was helpful to determine the rate of deployment and as a cross check for sites with similar names
- The location of the installation, helpful to determine the areas of deployment and compare to previous studies

[5] Digest of United Kingdom Energy Statistics (DUKES) 2021: main chapters and annexes A to D dataset. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1060152/DUKES_2021_dataset.xlsx

[6] 5.11 Power Stations in the United Kingdom - GOV.UK https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1006721/DUKES_5.11.xls

The Renewables and CHP register datasets from Ofgem for the Renewable Energy Guarantees of Origin, Renewable Obligation and Climate Change Levy schemes were used as the main sources of data for the site name, capacity, commissioning date and a site name postcode (if available from address data which was the case for sites with a capacity > 50 kW). Separate files from the Renewables and CHP register[7] were downloaded and combined into a single file. Similar to the 5.11 Major Power Producers dataset, these files have more technology types than just hydropower, so, the Technology Name column was limited to those rows that contained 'hydro' in the text[8]. All REGO and CCL hydropower stations had a status Name of 'Live' whereas three RO hydropower stations had a value of 'Preliminary' and were removed at a later stage.

Increases in hydropower capacity have taken place in waves or cycles of investment, from the initial post-war investment under public ownership mainly in the Highlands of Scotland, through to the investment from 2010 encouraged under the FiT.

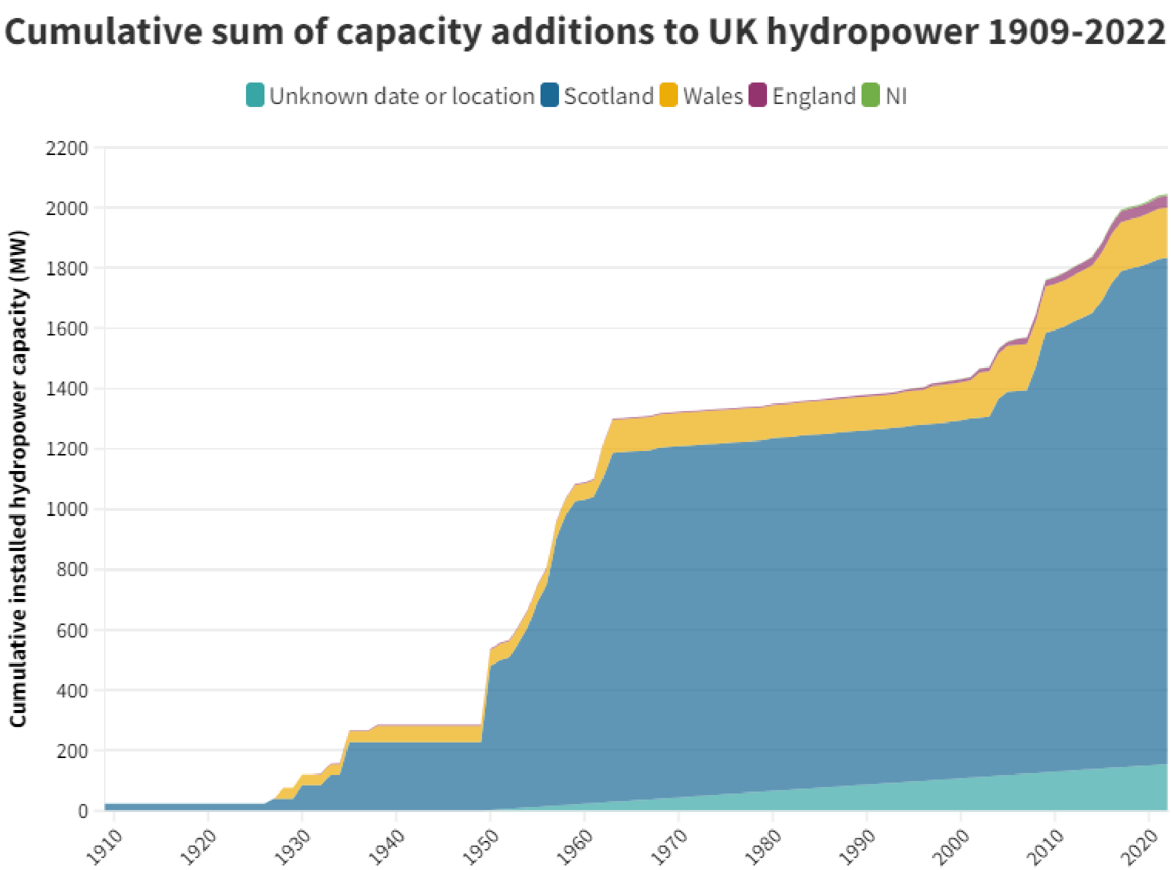

Figure 1 - Cumulative sum of capacity additions broken down by country with additional data spread linearly from 1950 for schemes in the created dataset which did not contain a date or did not contain a location

Code was created in Python code to merge the following datasets into a single file that contained 4107 rows that had duplicate site names:

1. REGO, RO and CCL data (publicly available data)
2. Renewable Energy Planning Database data (publicly available data)
3. Major Power Producers data from BEIS (non-public from direct communication)
4. SepaBNG and SEPA compliance data (publicly available data)
5. Environment Agency data (non-public from direct communication)

[7] https://renewablesandchp.ofgem.gov.uk/Default.aspx

[8] This picked up a handful of hydrogen installations that were subsequently deleted

6. Ofgem Feed in tariff data (non-public data from direct communication (similar to public data, but with the addition of site names))

This combined file then had a manual step of tagging rows of data that were felt to relate to the same hydropower installation (using checks such as capacity, site name, date of installation). As additional data became available at certain points in the project, this was an iterative process. The rapidfuzz natural language processing package for python was investigated at certain points, and although useful, provided enough edge cases to warrant a manual check anyway. It was thus decided to use the manual process given the time constraints of the project and the relatively tractable number of rows that needed checking.

However, the process involving manual steps is not scalable to 10s of 1000s of rows, is not deterministic and it can lead to errors, e.g., for hydropower installations that were upgraded or decommissioned, the original row of data could be left if not checked against a web search or more detailed information from a planning application. Unfortunately, there was not time to do this for more than a handful of cases. Nonetheless, the method and the dataset was felt to be robust enough for the basis of further analysis for the project.

The total capacity installed found from the method was 2045 MW.

Table 2 - Installed capacity in each country of the UK

Scotland	1799 MW
Wales	168 MW
England	47 MW
Northern Ireland	11 MW
Unknown	20 MW
Total	2045 MW

This report's baseline figure of 2045 MW of existing hydropower capacity is almost 10% larger than the latest BEIS figures of 1880 MW for 2021. It is, however, nearly identical to the 2022 edition of National Grid's Future Energy Scenarios baseline value of 2049 MW hydropower capacity for 2021[9].

The effort of pulling these different datasets together to arrive at a view of the installed hydropower capacity of the UK suggests that it would help the wider sector if there was a single source of updated data that at a minimum had a unique site number, x-y coordinates, a capacity value (installed or declared or both) and a site name. The site name could be optional, or indeed differ between datasets, as a unique identifier would be used as a primary key to allow different data to be added for different institutional purposes. For example, environment agencies could link licence numbers to the unique identifier, the valuations office could do so too, BEIS and Ofgem could link and reference details of support mechanisms. Over time, different values of capacity and date of installation could be compared that would improve the overall level of data quality across the sector. Other sectors, notably the wider property sector continue to benefit from a Unique Property Reference Number identifier for similar reasons, i.e., that there is a benefit to having a unique identifier to link other data to.

[9] https://www.nationalgrideso.com/future-energy/future-energy-scenarios#fullsuite

Section 2: Assessment of previous studies into the hydropower potential of the UK

The total hydropower potential of the UK has been previously considered by several studies, both regional and national in scope; three of these studies in particular were useful for comparative values for this report.

The earliest UK hydropower assessment considered in this analysis was the Salford study published in 1989[10]. This exercise consisted of various techniques to produce an estimate for the unexploited hydro resource of the UK between 25 kW (50 kW in remote areas) and 5 MW; sites larger than 5 MW were not considered due to the assumption they would already have been exploited by the public sector regional boards or their future development would fall under the remit of their successor organisations in the private sector. Through a combination of visual inspection of OS maps, site visits and the consultation of engineers and local authorities, it was predicted that there was 322 MW of potential small hydropower generation capacity of which 286 MW was in Scotland, 19 MW in England, 15 MW in Wales and 2 MW in Northern Ireland (from Figure 1 it can be seen this estimate was surpassed by the mid-2010s). However, the methodology in the Salford report for Scotland was not as robust as in other parts of the country, since it did not include any site visits.

Therefore, follow up studies for Scotland were carried out in 1993 by a public-private consortium and in 2001 by Garrad Hassan. The first of these produced a much larger estimate of Scotland's hydropower resource at 1000 MW (reducing to 500 MW when planning restrictions were applied) but the latter limited this to just 270 MW due to lower electricity prices and its impact on the financial viability of projects. Then in 2008, a rigorous analysis was conducted by Nick Forrest, SISTech and Black & Veatch (Niall Duncan is mentioned as a Principal Author/Reviewer)[11]. It was based on a modelling tool called Hydrobot which used digitalised Ordnance Survey mapping and elevation data, and flow data from the National River Flow Archive, in order to model over 36,000 potential sites. Limitations were also applied based on existing hydro, environmental restrictions and heritage designations. Across all of the sites modelled, it was found that in addition to the 1354 MW of existing schemes that there was a practical and technical potential hydropower capacity of 2,593 MW available in Scotland, although just 657 MW of this capacity was deemed financially viable when an 8% discount rate and a revenue of £35 per MWh were applied.

Potential hydropower capacity values (both financially viable and unviable) were also released at a more geographically granular level for the 60 rainfall catchment areas of Scotland considered in the report. Using nine parameters, a sensitivity analysis yielded different values of financially viable hydropower by varying factors such as the electricity revenue and the discount rate (a proxy for the cost of capital).

One key finding from the 2008 Scotland report (and the two that preceded it) is that "market forces have a stronger influence on the national hydropower resource than most of the values and thresholds that are within the Government's control". For example, lowering the discount rate from 8% to 0% increased the capacity of financially viable sites from 657 MW to 1,538 MW. Raising the electricity revenue by £40 per MWh to £75 almost doubled the feasible capacity from 657 MW to 1,206 MW. These figures confirm the potentially obvious view that further hydropower deployment is highly dependent on the economic viability of potential sites in addition to other factors such as the suitability of a site for environmental, planning or grid connection issues.

Dr Niall Duncan published a PhD titled 'Mapping Scotland's Hydropower Resource'[12] in 2014, with values that although broadly supported the Nick Forrest associates 2008 study, also had a lower overall

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[10] http://www.howardrudd.net/files/ETSU-SSH-4063-P1.pdf

[11] https://archive.uea.ac.uk/~e680/energy/energy_links/other_renewables/Scottish_hydropower_2008_0064958.pdf

[12] https://era.ed.ac.uk/handle/1842/9664?show=full

capacity of 440 MW when using a 10% discount rate. Notably, the sites identified from the 1-5+ MW range had a similar overall capacity value, with the smaller schemes between 100 kW and 1 MW having the largest difference in values. Dr Niall Duncan was also an author on the 2015 review paper (Sample et al.[13]) that compared previous work and concluded that 'as of December 2013' there was 1.5 GW of installed hydropower capacity in Scotland (excluding pumped storage) and that estimates of the remaining potential hydropower ranged up to 1000 MW. Of this, 400-500 MW was likely to be financially viable under 8% -10% discount rates and assuming no changes to abstraction licensing and "mostly in the form of small to medium size run-of-river schemes".

For England and Wales, several sub-regional studies have been commissioned since the 1980s. These include the Joule Study[14] of 1995 for the Thames, Severn and Trent catchment areas, the Welsh Study[15] of 2004 and South-East England Study[16] of 2004. In the absence of an updated analysis for the whole of England and Wales, in 2010, the Department for Energy and Climate Change and the Welsh Assembly Government jointly commissioned a resource assessment that was undertaken by IT Power with support from the British Hydropower Association[17]. The study mainly considered sites from the earlier Salford report but updated the design criteria (such as minimum head and power output thresholds) to determine whether a site was viable or not, as well as adding some newly identified locations. Unlike in the Scottish reports, there was less of a detailed financial analysis in the determination of the viability of a scheme. Nevertheless, upper and lower bounds were also estimated for the hydropower potential of Wales and 7 regions of England (based on the Environment Agency's catchment areas). The study analysed approximately 1,700 sites and found the potential hydropower capacity of England to be between 120 and 185 MW, and for Wales between 27 and 63 MW for Wales. These represented significant increases in hydropower potential compared to the Salford study, almost an order of magnitude greater for England (19 MW) and several multiples for Wales (15 MW).

In parallel to the 2010 England and Wales report, data was published by the Environment Agency that details the locations of sites in England and Wales where there is hydropower potential[18]. In this dataset 25,935 barriers and river features (natural and man-made) were analysed. After the application of filters based on environmental sensitivity and power generation potential, 4,195 sites were classified as "win-wins" with a combined capacity of 448 MW (305 MW in England and 143 MW located in Wales). It is notable that these values are around double the capacities estimated by the IT Power study. However, the dataset comes with the strong caveat that its accuracy does not carry a high level of confidence due to the change of waterbody and weir statuses and uncertainty in height measurements due to the use of older RADAR technology being the source of information for a third of sites (the remaining two-thirds have heights based on more accurate LIDAR).

Since 2010, there has been no detailed hydrological assessment of the UK as a whole. The most recent official government estimate for hydropower potential in the UK published by BEIS in 2013 on their website[19] claims between 850 MW and 1550 MW of remaining undeveloped hydropower. Although

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[13] Sample, James & Duncan, Niall & Ferguson, Michael & Cooksley, Susan. (2015). Scotland's hydropower: Current capacity, future potential and the possible impacts of climate change. Renewable and Sustainable Energy Reviews. 52. 111 - 122. 10.1016/j.rser.2015.07.071.

[14] IT Power, Stroom Lijn & University of Kassel. Low-Head Hydropower in Europe. Report for Commission of the European Communities. 1995

[15] Dulas, Energie and WDA. Wales Technology Map: Electricity from renewable energy sources (RES-e)

[16] TV Energy & MWH. Low Head Hydro Power in the South-East of England – A Review of the Resource and Associated Technical, Environmental and Socio-Economic Issues. February 2004

[17] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47950/753-england-wales-hydropower-resource-assess.pdf

[18] https://data.gov.uk/dataset/cda61957-f48b-4b75-b855-a18060302ed1/potential-sites-of-hydropower-opportunity

[19] https://www.gov.uk/guidance/harnessing-hydroelectric-power

BEIS do not detail the original source for these recent studies, it could potentially be an amalgamation of the previously mentioned 2008-10 studies. Alternatively, it could refer to estimates produced by international organisations such as the International Hydropower Association[20] or International Energy Agency[21] which in 2018 and 2021 respectively estimated the UK to have 2.4 GW and 0.9-2.6 GW of additional capacity, although these figures included pumped storage. In addition, National Grid's latest 2022 Future Energy Scenarios predicts up to an extra 464 MW of natural flow hydropower by 2050 in their Consumer Transformation scenario[22]. The other two net zero compatible scenarios saw a growth in the hydropower sector of 157 MW, while the non-net zero compatible scenario shows only a 36 MW increase in hydropower capacity.

Given the range of estimates and forecasted growth rates, it is a recommendation of this report that an appropriate hydrological and techno-economic assessment would be helpful to provide an updated set of values for:

1) the potential of new hydropower installations
2) the impact on hydropower output from changing rainfall patterns due to climate change
3) the potential for increased capacity to existing hydropower installations to capture greater flow rates in winter due to increased rainfall
4) the hydropower potential for low-head and pico-hydro sites

There have been a number of major changes affecting the hydropower sector since the previous reports on potential resource assessments were undertaken, including the dramatic reduction in the price of wind and solar PV generation, and the increase in costs of environmental and other assessments required for hydropower projects. Although not specifically commissioned within the scope of this report, some additional considerations for any future piece of detailed hydrological and techno-economic assessment work are presented in Table 3. Specific examples of technical assumptions which could be considered are: (i) the minimum capacity of remote sites due to advances in pico-hydro and battery storage (e.g., could even be as low as 1 kW), (ii) the minimum head height (perhaps 0.5m might be more suitable) and (iii) the system efficiency. In 2011, Kisliakov et al.[23] reviewed a range of very low head hydropower technologies with wheels and converters described which are able to operate at heads as low as 0.4m. A Norwegian organisation (Zero Emission Resource Organization[24]) has detailed products on the market for schemes operating across the world with ultra-low heads (or even no head at all) and a further TI-UP report published by BEIS identified two commercially available systems, one of which can function at a head 0.5 m[25].

In terms of hydropower system efficiencies, BEIS in 2013 stated "the most modern plants have energy conversion efficiencies of 90% and above"[26]. Despite smaller and micro hydropower schemes typically suffering a slight reduction in efficiency as compared to the most efficient large installations, in 2018 Eurelectric cited information from ANDRITZ Hydro GmbH showing a steady upward trend in turbine

[20] https://hydropower-assets.s3.eu-west-2.amazonaws.com/publications-docs/iha_2018_hydropower_status_report_4.pdf

[21] https://www.iea.org/articles/hydropower-data-explorer

[22] https://www.nationalgrideso.com/future-energy/future-energy-scenarios#fullsuite

[23] Kisliakov, Dimitar & Bozhinova, Snezhana & Muller, Gerald & Hecht, Veronika & Schneider, Silke. (2013). Hydropower converters with head differences below 2·5 m. Proceedings of the ICE - Energy. 166. 107-119. 10.1680/ener.11.00037.

[24] https://zero.no/wp-content/uploads/2016/05/small-scale-water-current-turbines-for-river-applications.pdf

[25] https://assets.publishing.service.gov.uk/media/57a08b3bed915d3cfd000bfa/TI_UP_HD_Oct2009_Micro_Hydro_Low_Head_Turbines.pdf

[26] https://www.gov.uk/guidance/harnessing-hydroelectric-power

efficiency continuing into the 21st century[27]. However, the rate of increase has slowed down, so further substantial improvements are unlikely. Nevertheless, innovation continues to happen in the sector including at a smaller scale of pico and micro hydro including UK based Hallidays Hydro Power[28] and also an example from Japanese electronic equipment manufacturer RICOH that have announced a pico-hydro system suitable for remote locations and agricultural applications[29]. Co-location of hydropower with battery storage[30] will likely present revenue generation opportunities, to allow smaller sites to both be more economically viable, boost their own security of supply and create an output profile more like that of the larger (>20 MW) controlled flow sites (further discussed in section 4).

Finally, electrical network constraints and the role of grid accessibility need to be factored into any future resource assessment to make the model for the locations of feasible schemes as realistic as possible. In the years since the 2008-10 hydropower studies, there have been advancements across the UK's regional distribution network operators in terms of the quality and availability of geospatial electrical system data. This includes the digitalisation of network layouts and network capacity maps, so that previously image-based maps are now digitised and thus becoming more available to run computational analysis on. In addition, greater levels of network characteristics are also becoming more available through the Common Information Models published by the Distribution Network operators, which can include such data as the headroom for additional generation of each primary (e.g., 33 kV) substation.

With this information, the methods developed by the Hydrobot model in the 2008 Scotland report, and the PhD work of Niall Duncan could be refined/expanded and applied to the whole of Great Britain.

The issue of grid constraints at different levels can be a major factor in Scotland in particular, where otherwise viable schemes are simply no longer viable if the major costs of the upgrades are placed on that particular project.

It is expected that the suitability of an area for hydropower will benefit from the increased investment in high voltage networks over the coming decade as well as advances in grid management (such as active network management) and increased competition in connections (to drive down the costs of gaining access to the network).

In addition, the use of storage via post electrical conversion technologies (e.g., batteries) or through pre-electrical conversion via impoundment of the water resource mean that greater control over the timing of the generation can potentially happen. This may also help in terms of managing congestion.

Interestingly, in places where obtaining a grid connection is prohibitively expensive, the scheme could potentially operate with a reduced capacity grid connection if local markets for electricity further develop in future, e.g., for transport and for electrolysis. However, the timing and likelihood of these are highly uncertain at this point, and the ability for additional hydropower generation to continue to benefit the wider UK electrical system would be if they are connected to the grid with a connection that allows them to export when it is most valuable to the rest of the system, such as a winters evening (no solar) with low wind output.

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[27] https://cdn.eurelectric.org/media/3177/hydro-facts_sheets-web-28052018-2018-030-0371-01-e-h-8DD82949.pdf

[28] https://www.hallidayshydropower.com/services/innovate/

[29] https://www.pv-magazine.com/2022/03/25/ricoh-launches-mini-hydropower-system-for-remote-locations-usable-with-solar-plus-storage/

[30] https://www.current-news.co.uk/news/barn-energy-celebrates-success-of-battery-co-location-with-hydropower

Table 3 – A summary of the three major previous resource assessments considered in this study, the assumptions used in each, and comments on whether these could potentially be updated.

Assumption	**Salford (1989)**	**Scotland (2008)**	**England and Wales (2010)**	**Future hydro resource assessment**
Lower power output threshold	25kW or 50kW for remote sites	0kW (but financial viability severely limited the number of <100 kW sites)	0kW or 25kW for remote sites	Could <25kW remote sites be more feasible with advances in storage and off-grid applications (e.g., EV charging)?
Minimum head height	2m (or 3m where there is no weir)	N/A	1m	Could advances in ultra-low-head hydro reduce this?
Financial viability		25 year pay-back period based on 8% discount rate and £80/MWh		Could investors today consider longer payback periods and higher / more dynamic electricity prices?
Taxation		Business rates of £9/kW		How has this changed and what does the future hold?
Financial support		ROCs of £45/MWh (double ROCs considered in sensitivity analysis only)		What was the deployment during FIT and what could be the deployment in future with and without subsidy?
Plant efficiency	80%	Unspecified but turbine efficiency data were provided by Newmills	80% for sites accepted in the Salford report, 75% for those rejected	80% for all sites
Flow rate used to determine power output	Mean annual flow values	1.5x mean annual flow for run-of-river and 2.5x for storage	Mean annual flow values	N/A
Grid connections		Clusters of 10 or more buildings assumed to represent 11kV supply.		Could digitalisation of network data increase the accuracy of network modelling?
Environment agency		SEPA licence threshold of 100 kW and subsistence charge thresholds of 2 & 5 MW		Could advances in turbine technology reduce the needs for licences?
Planning permissions		Three tiers of natural land heritage designations are used to restrict the approved schemes by 20%, 36% and 49%.		Could obligations on local authorities to comply with net zero targets increase the number of schemes accepted?
Other		Railways can charge up to 33% of NPV for schemes crossing rail lines		N/A

Section 3: A comparison of the installed capacity versus previous reports' views of the hydropower potential of the UK

Using details from the 2045 MW of installed capacity from Section 1, which includes sites receiving FiT support from Ofgem, these were compared with the two most recent resource assessment reports for England, Scotland and Wales from Section 2, which were the 2008 Scotland report and the 2010 England and Wales report.

The installed capacity was compared to the predicted amount of viable hydropower in 2008/10. These are presented in the following tables and maps at the most geographically granular areas available for each report; in England and Wales the geographical areas are larger (8 regions in total) whereas for Scotland there were 44 catchment areas that were able to be studied. A future investigation looking to get more granular results for England and Wales (at a river catchment or local authority area basis) could use the Environment Agency dataset from 2010.

In England, there has been progress in some of the areas with greater potential, particularly in the Northwest and Northeast regions. Although, development has been much slower in other parts of South and Central England. Overall, England has only built 9-14% of the potential hydropower capacity predicted by the 2010 study.

- Taking the average of the upper and lower limits, this means that realistically, perhaps another 138 MW could still be built in England.

Wales, on the other hand, has had greater levels of hydropower capacity installed as a percentage of its predicted hydropower resource. Between 22% and 52% of the 2010 deemed potential capacity has been built since the publication of that report. In absolute terms, almost as much hydropower has been installed in Wales (14 MW) during this period as in England (17 MW). The relative success of small-scale hydropower in Wales could be due to the mountainous terrain creating an abundance of high head, high power output sites (which are likely to be more economically attractive than many in England).

- From the datasets studied, it can be estimated another 28 MW of feasible hydropower exists in Wales.

Scotland due to its favourable topography for hydropower hosts both the overwhelming majority of the UK's existing hydropower and its remaining potential. The 2008 Scottish Study predicted a lower limit of 657 MW of hydropower potential of which 33% (216 MW) has been built since the study was published. However, the methodology used in the report was highly sensitive to economic variables; with the most favourable (although unrealistic) discount rates (0%) and revenues (£75 per MWh) applied, it was found Scotland could theoretically install another 2,593 MW. Delving into the Scottish catchment areas reveals a number of interesting findings. Three catchment areas (Dee in Aberdeenshire, Irvin and Ayr, and Spey) have built more than 100% of the predicted financially viable capacity in 2008, while five (Almond Group, Dee in Galloway, Deveron Group, Don in Aberdeenshire and Firth of Forth Group) have built some capacity in areas where the report said there was no economically feasible schemes. Furthermore, a substantial amount of catchment areas (11) have built more than 50% of the lower limit potential capacity and only six have not built anything (like England, these areas had a small overall potential anyway). Thus, the results imply that in Scotland the environment for building new hydropower during the FiT scheme period was favourable, so that development was supported and accelerated during that period.

- As for England and Wales, taking the average of the upper and lower limits from the Scottish resource assessment and subtracting the amount of hydropower connected since 2009[31], yields a reasonable estimate of 1,400 MW capacity still able to be built in Scotland.

Because of the lack of an available detailed resource assessment and data gaps in the commissioning dates of sites in Northern Ireland, the investigation could not be redone for this region.

- However, from the dataset in section 1, it could still be determined that Northern Ireland has a total existing capacity of 11 MW of which at least 4.7 MW has been constructed since 2010.

It is also noteworthy that the FiT scheme did not apply to Northern Ireland, but there was a regionally administered ROC scheme.

The summary of this analysis for England, Scotland and Wales is provided in Figure 2, for the smaller geographical areas in Tables 4 and 5, and Figures 3 and 4, and for each country (including Northern Ireland) in the bullet points below:

- England has built 17.1 MW of hydropower since 2010 and the remaining resource is estimated at 138 MW
- Wales has built 14.0 MW of hydropower since 2010 and the remaining resource is estimated at 28 MW
- Scotland has built 216.2 MW of hydropower since 2009 and the remaining resource is estimated at 1400 MW
- Northern Ireland has built at least 4.7 MW of hydropower since 2010 and the remaining resource is not reported
- From these figures, the total UK hydropower resource is estimated at 1575 MW
- Remaining resource capacity for each country was estimated by the following formula:

$$Remaning\ potential = \frac{(Upper\ limit\ from\ study + lower\ limit\ from\ study)}{2} - Capacity\ built\ since\ study$$

[31] Due to the installation of the large hydropower site Glendoe in 2008, 2009 was used as the baseline year for Scotland.

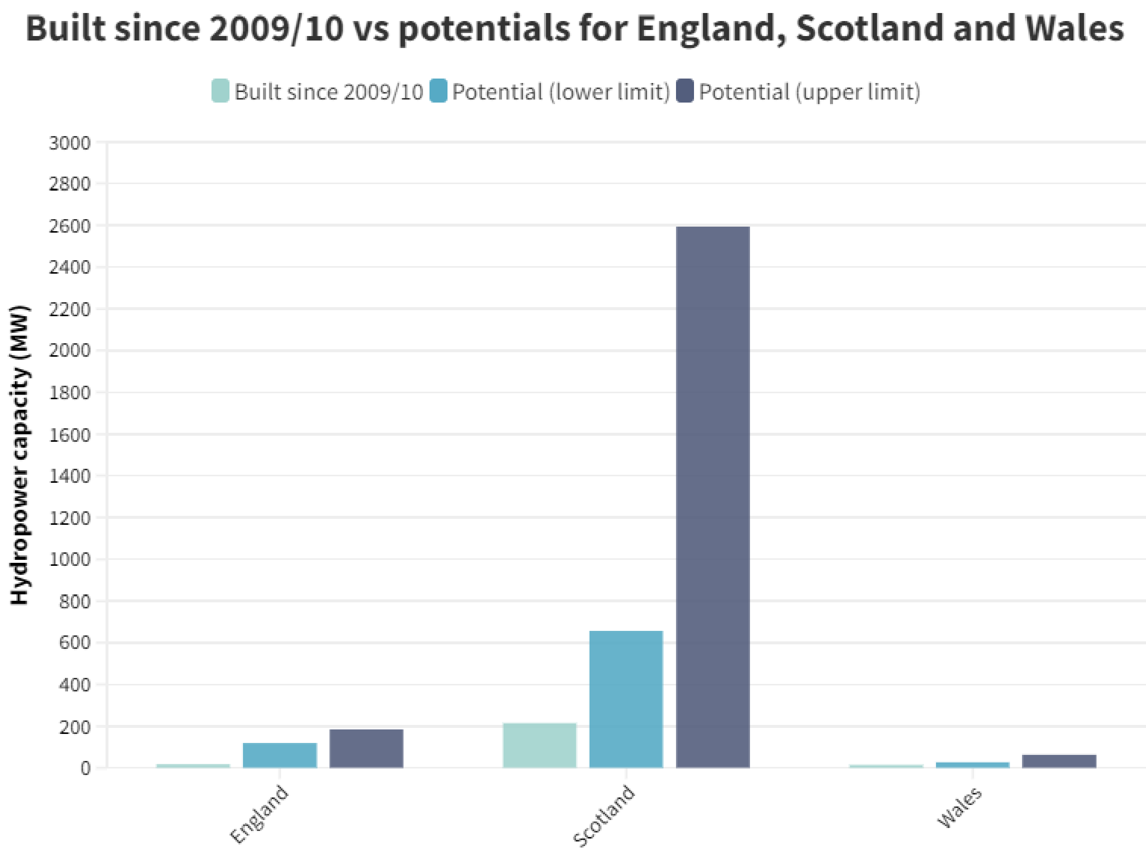

Figure 2 – Chart showing the amount of hydropower built since the resource assessment in England, Scotland and Wales against the upper and lower bounds of the potential capacity.

Table 4 - The amount of hydropower built for each English sub-region since 2010 against the upper and lower bounds of the potential capacity.

Region	Potential lower limit (MW)	Potential upper limit (MW)	Built 2010-2022 (MW)	Built as % of lower limit	Built as % of upper limit
Anglian	4.92	13.37	0.00	0%	0%
Midlands	18.00	32.40	2.19	12%	7%
Northeast England	27.33	39.81	5.00	18%	13%
Northwest England	32.00	37.70	7.07	22%	19%
Southwest England	20.00	29.40	1.85	9%	6%
Southern England	1.10	2.60	0.00	0%	0%
Thames	16.20	30.12	0.96	6%	3%
Wales	**26.73**	**63.00**	**13.98**	**52%**	**22%**
England (total)	**119.55**	**185.40**	**17.06**	**14%**	**9%**

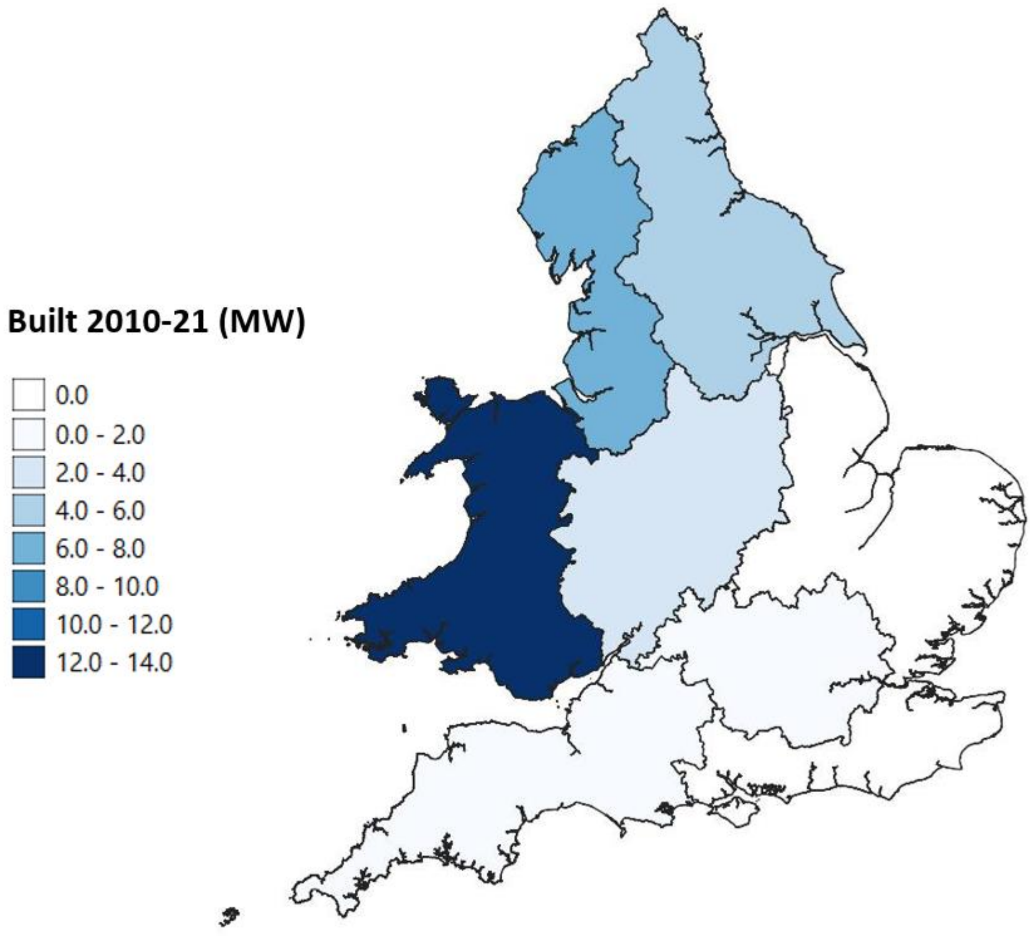

Figure 3 – Choropleth to show the regional variation in hydropower built from 2010-21 in England and Wales

Table 5 - The amount of hydropower built for each Scottish catchment area since 2009/10 against the upper and lower bounds of the potential capacity.

Catchment area	***Cat. ID***	***Potential lower limit (MW)***	***Potential upper limit (MW)***	***Built 2009-2022 (MW)***	***Built as % of lower limit***	***Built as % of upper limit***
Add and Kintyre Groups	*88 & 104*	*14.8*	93.4	4.3	29%	5%
Almond Group	*19*	*0.0*	9.9	0.6	-	6%
Annan	*78*	*1.0*	24.2	0.5	47%	2%
Awe and Etive	*89*	*60.5*	186.0	19.6	32%	11%
Beauly	*5*	*38.7*	98.0	4.9	13%	5%
Clyde	*84*	*1.2*	56.5	0.9	78%	2%
Conon Group	*4*	*18.9*	93.9	12.0	64%	13%
Cree Group	*81*	*2.7*	40.6	0.2	6%	0%
Dee (Aberdeenshire)	*12*	*1.0*	33.0	2.1	>100%	6%
Dee (Galloway)	*80*	*0.0*	32.0	0.9	-	3%
Deveron Group	*9*	*0.0*	10.5	0.1	-	1%
Don (Aberdeenshire)	*11*	*0.0*	24.9	0.2	-	1%
Doon Group	*82*	*3.1*	31.4	0.3	11%	1%
Earn	*16*	*14.9*	44.1	2.2	15%	5%
Esk (Dumfriesshire)	*77*	*0.0*	21.2	0.0	0%	0%
Esk Group	*13*	*1.2*	35.5	0.8	63%	2%
Findhorn Group	*7*	*1.2*	40.9	0.1	12%	0%
Firth of Clyde Group	*86*	*22.6*	50.6	4.3	19%	8%
Firth of Forth Group	*17*	0.0	10.7	0.8	-	8%
Firth of Tay	*14*	0.0	5.1	0.0	0%	0%
Forth	*18*	11.2	48.5	7.0	62%	14%
Fyne Group	*87*	41.7	73.4	4.7	11%	6%
Helmsdale Group	*2*	1.5	38.4	0.8	56%	2%
Inner Hebrides	*105*	20.6	107.7	2.5	12%	2%
Irvine and Ayr	*83*	1.5	27.6	3.3	>100%	12%
Laxford Group	*95*	50.4	126.0	10.5	21%	8%
Leven (Dumbartonshire)	*85*	10.5	37.0	7.4	71%	20%
Loch Alsh Group	*93*	59.8	164.7	9.6	16%	6%
Loch Linnhe Group	*90*	44.0	103.9	14.6	33%	14%
Loch Maree group	*94*	32.2	76.0	9.8	30%	13%
Loch Shiel Group	*92*	40.7	90.5	15.4	38%	17%
Lochy (Invernesshire)	*91*	30.7	97.8	20.4	67%	21%
Naver group	*96*	7.6	58.3	0.1	1%	0%
Ness	*6*	26.9	119.3	20.5	76%	17%
Nith	*79*	0.4	38.7	0.3	79%	1%
Outer Hebrides	*106*	1.1	29.0	0.2	18%	1%
Shin Group	*3*	7.8	60.7	5.5	70%	9%
Spey	*8*	0.6	46.4	0.9	>100%	2%
Tay	*15*	84.8	221.8	27.3	32%	12%
Thurso Group	*97*	0.0	9.5	0.0	0%	0%
Tweed	*21*	0.6	58.3	0.4	61%	1%
Tyne (Lothian)	*20*	0.0	2.6	0.0	0%	0%
Wick Group	*1*	0.2	5.8	0.0	0%	0%
Ythan Group	*10*	0.0	1.9	0.0	0%	0%
Scotland (total)	-	**656.6**	**2593.2**	**216.2**	**33%**	**8%**

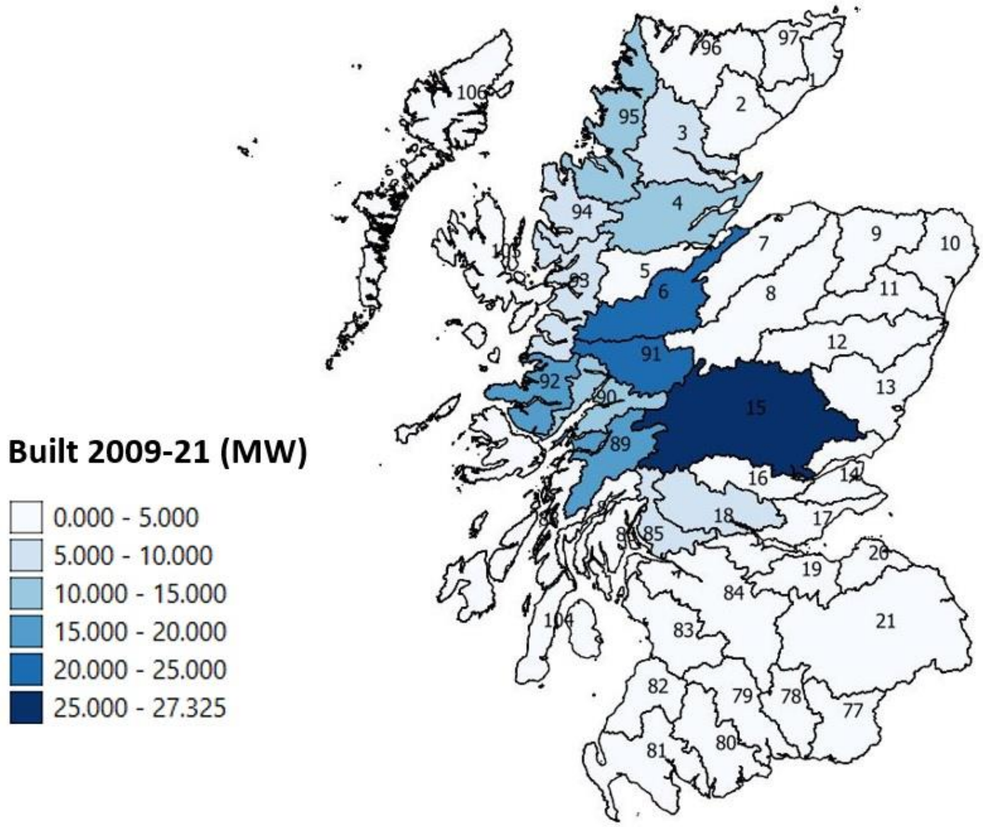

Figure 4 - Choropleth to show the regional variation in hydropower built from 2010-21 in Scotland.

FiT rate analysis

Finally, in this section, when considering the economic drivers for the deployment rates of hydropower, the levels of FiT support changed at different times across the scheme's existence. These were analysed to provide insight into how this affected the levels of deployment on an annual basis. Firstly, the inflation adjusted generation FiT rates were downloaded from a dataset published by Ofgem[32] and parsed into a single chart shown in Figure 5.

These rates could then be compared with the dataset on FiT recipients provided by Ofgem which shows that the annual deployment of hydropower (Figure 6) broadly tracks with the FiT rate (albeit with a 1-2 year lag, since sites may pre-accredit for the FiT payments offered at the time, in advance of their actual commissioning). A small number of pre-2010 sites were eligible for FiT, so applied upon the scheme's introduction, and in its first few years until 2014, a steady 10-20 MW of capacity was built each year. The annual capacity installed then increased markedly to a peak of 58.3 MW in 2016. The reason for this is likely that many sites were pre-accredited in 2014-15 in anticipation of the upcoming 'cliff-edge' reduction in FiT rate.

[32] https://www.ofgem.gov.uk/publications/feed-tariff-fit-tariff-table-1-april-2022

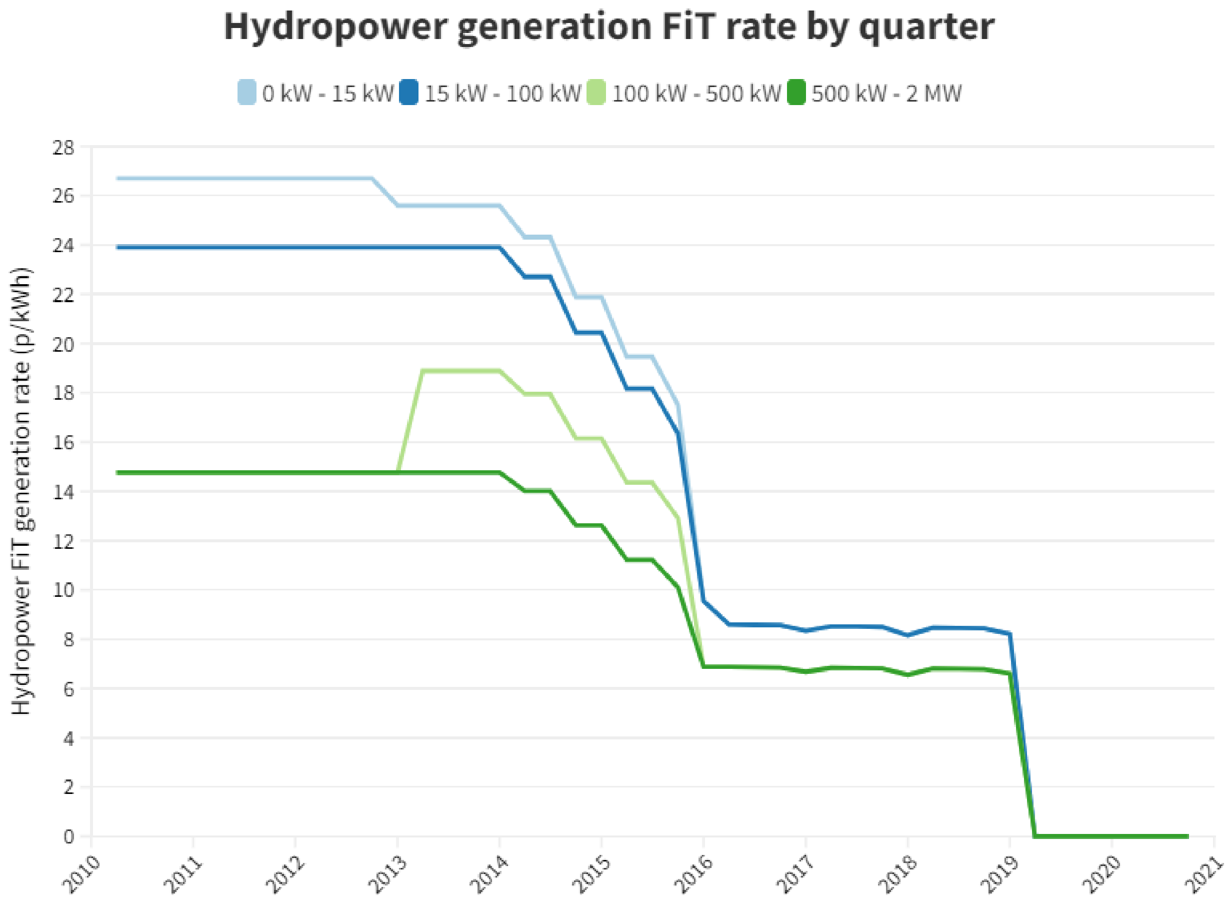

Figure 5 – Variation in the FiT rate for hydropower installations of different sizes from 2010-19

The introduction of a separate, more generous rate for 100-500 kW schemes could also have spurred growth in this capacity range of the sector over the same period. Following the 2015-2016 reduction in tariff, new installs plummeted to under 5 MW in 2018, although a slight rise was recorded each year until 2021 which is perhaps a less pronounced version of the previous phenomenon, i.e., many sites pre-accredited before the removal of all offers of generation tariffs to new applicants in 2019. Due to the COVID-19 pandemic, further extensions were granted for pre-accredited sites, so a handful of FiT schemes will potentially still be built in 2022[33].

FiT payments analysis

FiT generation rates were combined with the Ofgem FiT rate dataset to calculate the estimated level of annual generation payments in each quarter. Each site's capacity and Tariff code was used to determine its tariff band and an estimated universal load factor of 35.5%, taken from the 12-year average for hydropower in BEIS' Energy Trends[34]).

These calculations showed that by 2021, annual generation FiT payments for hydropower had reached £117 million (cf. Figure 7). Summing over the 12 years since 2010, it is estimated that £877 million has been transferred through energy suppliers (mandated by BEIS) that has provided an approximately additional 250 MW hydropower capacity to be developed, that generates an estimated 0.8 TWh per year. Note that this figure does not include the export component of the FiT as the data is unavailable to include in the calculations. It would be interesting for a future piece of work to consider how this

[33] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/915325/fit-extension-govt-response.pdf

[34] https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

compares with other renewable technologies deployed throughout the FiT scheme era and obtain more accurate data for the export rates.

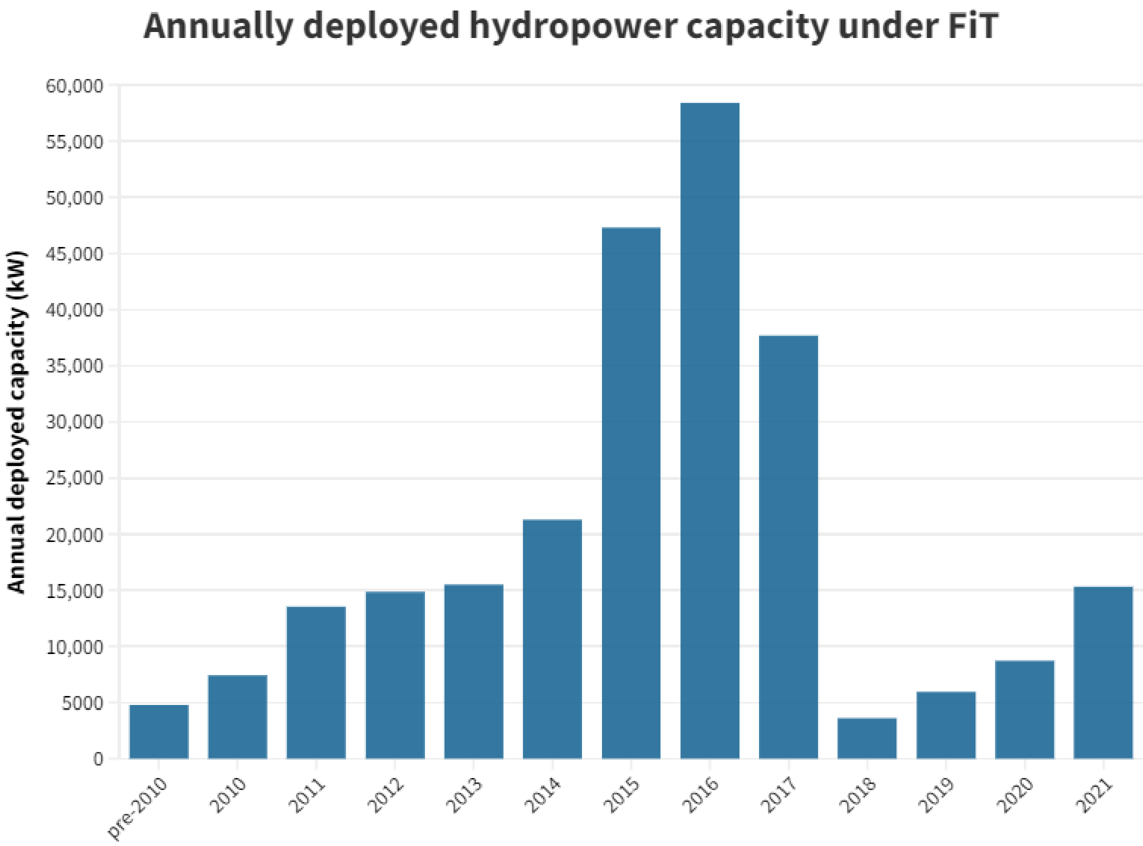

Figure 6 – Annual deployment of hydropower installations under the FiT regime.

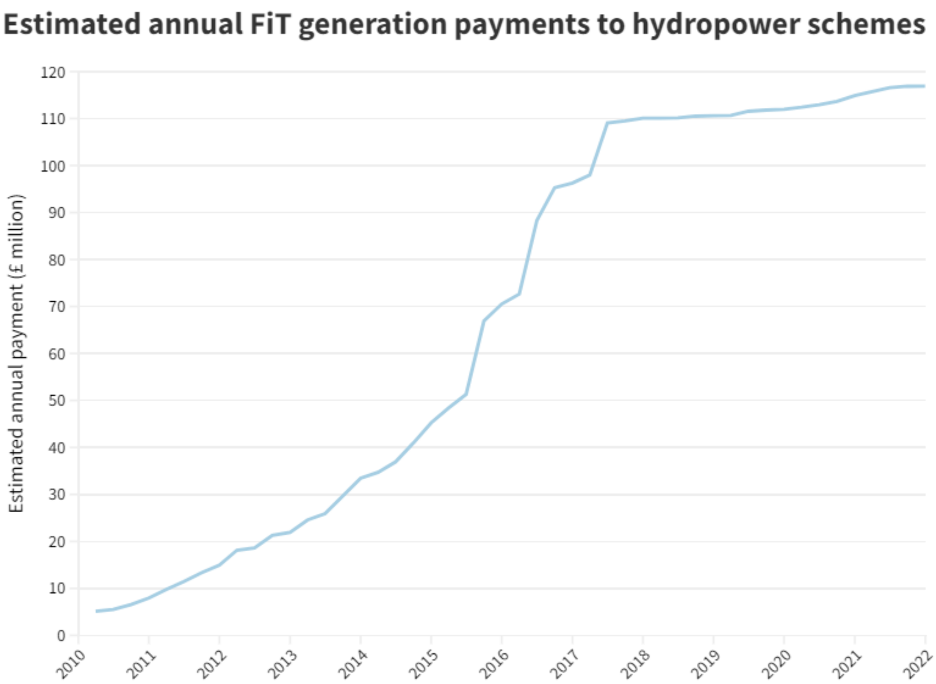

Figure 7 – Estimated annual FiT payments for accredited hydropower schemes.

FiT installed scheme size distribution

The distribution of the capacity of FiT installed schemes is plotted in Figure 8 to identify whether developments have scaled their installed capacity to a certain size to fall within a desired FiT band. This would be indicated by flatter sections of the curve that is plotted.

Looking at the chart, it supports the claim that hydropower schemes were undersized to meet the criteria of a more generous FiT support band; when ranked by their capacity size it was found that many schemes clustered around certain values; approximately 30, 80 and 150 schemes were all sized at or just below 2 MW, 500 kW and 100 kW respectively. These were boundaries at which the FiT generation rate tapered. If the graph followed a more typical exponential decay distribution, it would be expected that several more MW of capacity could have been constructed.

It is a challenge for policy makers to manage these types of consequences from the design of support schemes, but the evidence here suggests it does have at least some impact. Any future funding scheme that seeks to increase hydropower generation should try to mitigate these types of effects to encourage the maximum amount of hydropower that a site could develop, rather than it being undersized to meet other criteria.

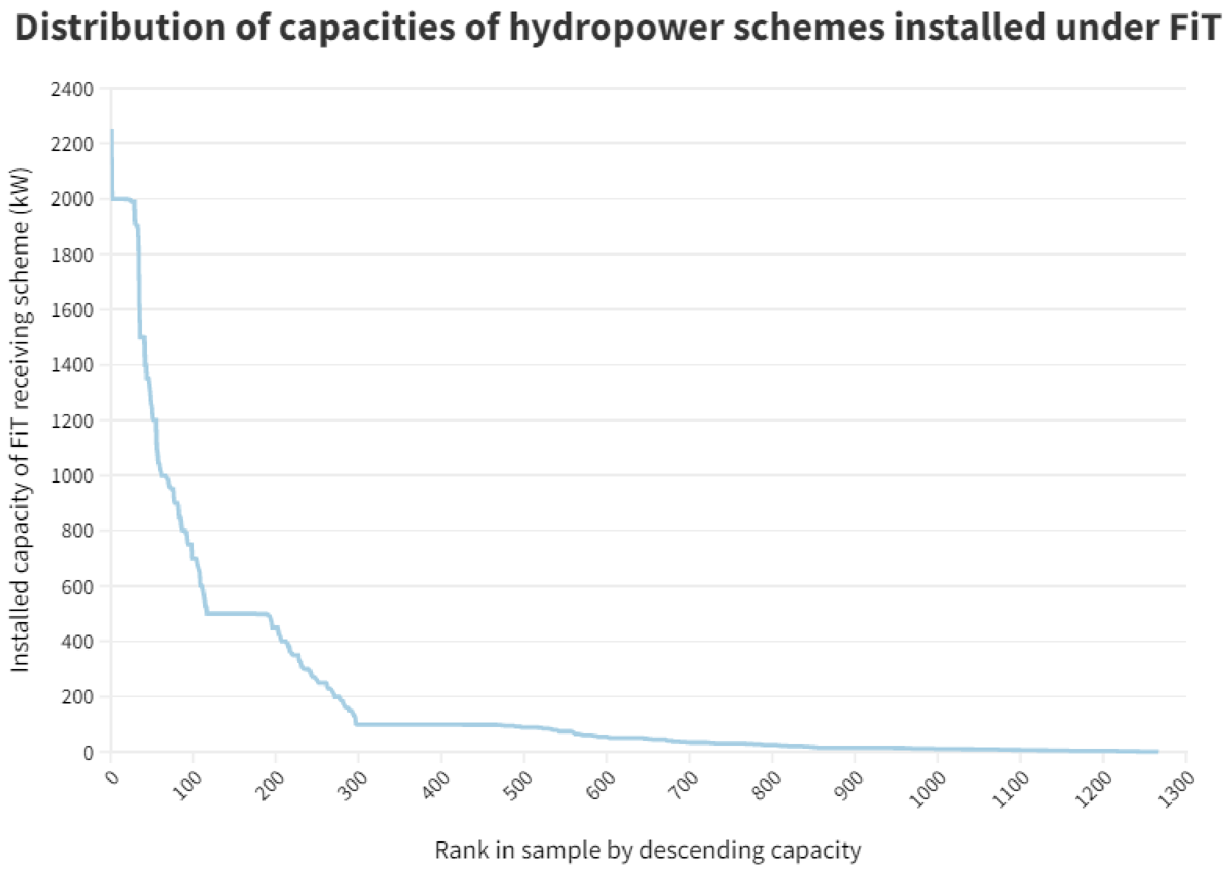

Figure 8 – Distribution of hydropower schemes installed under FiT when ranked by their capacity. Note that the straight lines around 2 MW, 500 kW and 100 kW, indicate a significant number of schemes may have been undersized to fall within a more generous tariff band.

Section 4: How can hydropower continue to decarbonise the UK's energy system?

This section considers the output from hydropower generation in the UK and how it has historically and in future could continue to benefit the UK's transition to net-zero.

Historical estimate of hydropower's impact on UK electrical sector emissions

To help consider this, it is useful to look at the benefit that hydropower generation has already had in terms of decarbonisation over a longer-term view covering the last 100 years.

To calculate the tonnage of carbon equivalent emissions that hydropower generation has already saved the UK, three main data values are required:

1. the amount of hydropower generation in kWh per year
2. the average carbon equivalent intensity per kWh of the electrical generation mix over a year
3. the average carbon equivalent intensity per kWh of hydropower generation

With these data for each year, and assuming that each kWh of hydropower displaces a kWh of generation at an average carbon equivalent intensity, it is a straightforward calculation to arrive at an approximation of the tonnes of carbon equivalent that was saved.

In equation terms it is for each year under consideration: (the average carbon equivalent intensity of the electrical generation mix per kWh minus the average carbon equivalent intensity of hydropower generation per kWh) multiplied by the amount of generation hydropower in kWh

Historical hydropower generation data

The three datasets from the Department of Business, Energy and Industrial Strategy that have values for hydropower generation are:

- The 'Historical electricity data: 1920 to 2020' spreadsheet[35] with annual values for 'Hydro Natural Flow' from 1920 to 2020
- The 'Digest of United Kingdom Energy Statistics (DUKES) 2021: annexes E to J and long-term trends dataset' spreadsheet[36] on the worksheet tab 5.1.3 for 'Electricity generated and supplied' with annual values for 'Hydro natural flow' from 1970 to 2020. This is described as 'Electricity supplied (gross)'.
- The Energy Trends 'Fuel used in electricity generation and electricity supplied (ET 5.1 - quarterly)' spreadsheet[37] with annual and quarterly values for Hydro (natural flow) from 1998 to 2021. This is split into 'Major Power Producers' and 'Other Generators'.

When comparing the values from these three datasets, it seems that the values in the 'Historical electricity data: 1920 to 2020' and the 'Digest of United Kingdom Energy Statistics (DUKES) 2021: annexes E to J and long-term trends dataset' are for Major Power Producers only, and match with the values in Table 5c: electricity supplied by fuel 1998 to 2021 (TWh) from the Energy Trends 'Fuel used in electricity generation and electricity supplied (ET 5.1 - quarterly)' spreadsheet. From the Energy Trends

[35] Historical electricity data: 1920 to 2020 https://www.gov.uk/government/statistical-data-sets/historical-electricity-data

[36] Digest of United Kingdom Energy Statistics (DUKES) 2021: annexes E to J and long-term trends dataset' spreadsheet on the worksheet tab 5.1.3 for 'Electricity generated and supplied' https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1025456/DUKES_2021_long_term_trends_dataset.xlsx

[37] Energy Trends 'Fuel used in electricity generation and electricity supplied (ET 5.1 - quarterly)' https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1086790/ET_5.1_JUN_22.xlsx

Table 5c it is clear that there are additional generation from 'Other generators' which has increased since the records began in 1998.

As this additional generation for hydro is missing in the other datasets, it was recreated by multiplying by a certain factor from 1970 to 1998. Prior to 1970, it was assumed there were no 'Other generators' for hydro. From 1970 to 1998, the multiplication factor was a simple linear increase from 1 in 1970, to 1.21 in 1998, which was the ratio for (Major Power Producers output + Other generators output) / Major Power Producers. This created a synthetic dataset for hydropower generation from 1920 to 1998 and used the reported values from 1998 to 2020 for the total of Major Power Producers and Other generators.

Historical average electrical grid intensity data

The data for average UK carbon equivalent intensity per kWh was taken from 'Table 8: Base electricity generation emissions factors (including imported electricity)' in the '2021 Government Greenhouse Gas Conversion Factors for Company Reporting' document[38]. The values in the 'Total' column for the section 'For electricity GENERATED (supplied to the grid, plus imports)' was used. The Emission Factor values were in units of $kgCO_2eq$ per kWh and had annual average values from 1990 (0.68697) to 2020 (0.23314)[39].

Emission values prior to 1990 were simply taken as the 1990 value, as it was assumed that these would be on the conservative side, as years prior to 1990 had a reducing amount of nuclear (first reported in 1956) and the remaining electrical generation would be coal or oil, which on average would likely be less efficient than equivalent plants producing in 1990, and thus would lead to a greater annual electrical grid intensity.

Hydropower emissions intensity data

The emissions intensity data was taken from the Parliamentary Office for Science and Technology Note 383 titled 'Carbon Footprint of Electricity Generation' [40]. This had a range of values from 2 to 13 gCO_2eq per kWh that was for run-of-river; the values for reservoir-based emissions would be higher but are uncertain. Therefore, the run-of-river value of 13 gCO_2eq per kWh was taken for the analysis, but a value of 26 gCO_2eq per kWh was also used to check the sensitivity to the value.

[38] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1049346/2021-ghg-conversion-factors-methodology.pdf

[39] The 2020 value was taken from Conversion factors 2020: condensed set (for most users) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/891105/Conversion_Factors_2020_-_Condensed_set__for_most_users_.xlsx

[40] https://www.parliament.uk/globalassets/documents/post/postpn_383-carbon-footprint-electricity-generation-references.pdf

Using the values and methodology described, hydropower generation has saved the UK the amounts shown in Table 6

Looking at the CO_2 benefit of hydropower, taking a long-term view, our analysis estimates that since 1920 hydropower generation has saved the need to generate nearly 300 TWh of electrical energy from other fuel types, thus saving around 160 million tonnes of CO_2 equivalent emissions; for comparison the UK territorial emissions were nearly 450 million tonnes of CO_2 equivalent[41] in 2019). Hydropower is the UK's longest running renewable electrical fuel-type, and similar to other renewables is limited by the resource itself in terms of its technical, financial and, importantly, its environmental impact.

Table 6 - Cumulative and annual emissions savings by UK hydropower generation

Emissions intensity of hydropower generation	Cumulative emissions saved from 1920 to 2020 in million tonnes of CO_2eq	Annual saving in 2019 in million tonnes of CO_2eq	Annual saving in 2020 in million tonnes of CO_2eq
13 gCO_2eq/kWh	160.5 MT of CO_2eq	1.1 MT of CO_2eq	1.0 MT of CO_2eq
26 gCO_2eq/kWh	156.7 MT of CO_2eq	1.5 MT of CO_2eq	1.4 MT of CO_2eq

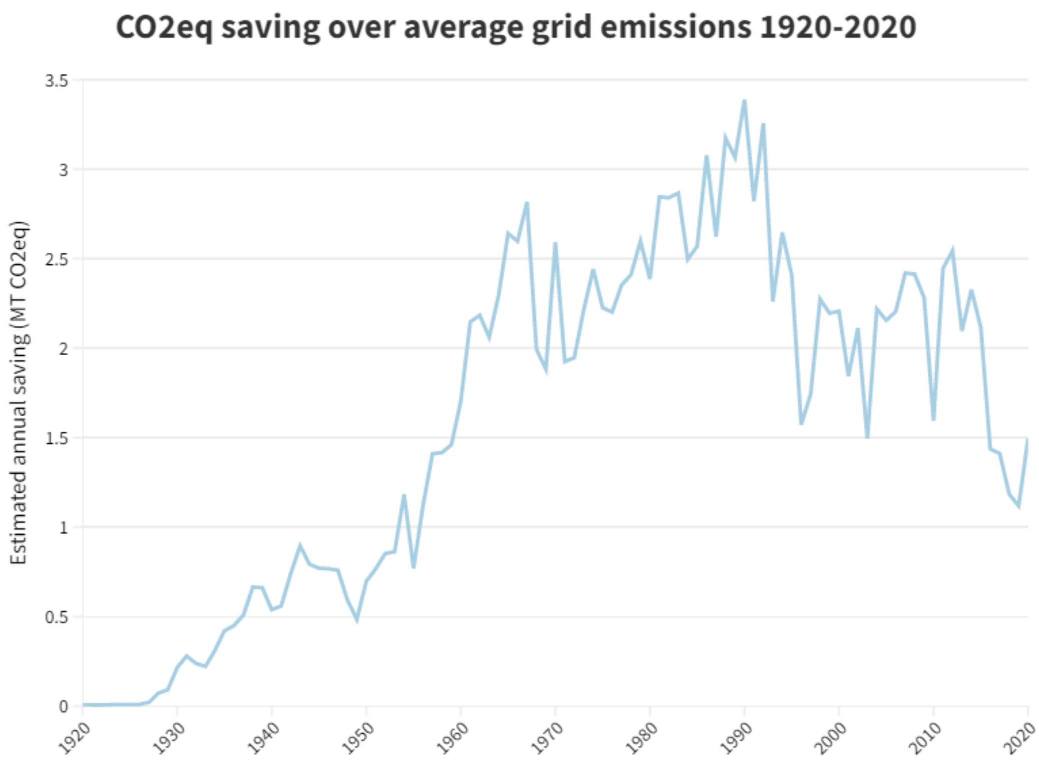

Figure 9 - CO_2eq saving over average grid emissions from 1920 to 2020

Discussion on CO_2eq savings

There are a number of uncertainties inherent in the analysis such as the average electrical carbon equivalent emissions intensity for years prior to 1990 and the value for hydropower generation (particularly around Land Use, Land Use Change and Forestry and construction of reservoir dams and tunnels). Another uncertainty is based on the likelihood that the electrical generation displaced by hydro

41 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf

would not be at an average intensity, but at the rate of the marginal plant that would have to change its production to cover for the loss of or lack of hydro.

This is a complex research area that has become more challenging with a greater diversity of fuel types (including renewables), interconnectors and demand shifting. There is also an uncertainty in using national level data, whereas the marginal fuel type is also determined by location in relation to network constraints and the overall levels of electrical system inertia and thus has a more regional impact.

Nonetheless, even with those uncertainties, it seems a valid assumption that hydropower generation has contributed to the reduction in the UKs overall emissions for a century, by offsetting the need for greater levels of fossil fuel generation (mainly coal) that would otherwise have been required. The annual emissions saved will continue to reduce when the difference in emissions intensities between the average electrical grid value and hydropower generation narrows as the UK's electrical generation portfolio continues to decarbonise.

Benefit of long-term generation

The x-axes in Figure 9 show 100 years of data. This shows a key differentiator of hydropower in terms of its design life not only from other renewables, but also of thermal plant such as fossil-fuels and surpassing nuclear in terms of its potential longevity. Feedback from the sector has consistently pointed out the design life of hydro installations is far greater than any other type of renewable generation. An expectation is that with the correct initial design and ongoing maintenance that hydropower installations can continue to generate for timeframes well in excess of 50 years. However, there is also a feeling that current market signals are characterised by a lack of long-term project support and in 2022 in particular the increase in short-term higher wholesale electricity prices. This situation in turn creates a preference towards smaller extension or enhancement projects with shorter pay back periods and away from larger new build projects.

A factor for regulators in the shaping of energy policy is the levelised cost of electricity, which allows different technology types to be compared using this metric. A report from BEIS on how the levelised costs of electricity are calculated is 'Electricity generation costs 2020'[42]. This takes the net present value of future costs and divides them by the net present value of revenue derived from future energy generation. For long lived assets such as hydro with high upfront capital costs, this method of calculation would seem to disproportionately disadvantage the eventual value of the levelised cost of electricity, particularly if the value of that electricity is considered to be of a constant unit price. For example, for a 10 MW scheme with an annual average load factor of 40%, this would equate to a net present value of energy generated of 10 x 8760 x 0.4 = 35 GWh in the first year of operation. Using the BEIS levelised cost equation, with a discount rate of 8%, the denominator would calculate the hydro installation's net present value of energy generated in year 20 as 7.5 GWh, and by year 50, this would have dropped to 0.75 GWh. The equation is an accepted way of calculating the levelised cost of electricity, but perhaps there are additional ways to consider the value of electricity generation with a long-time horizon into the future.

Hydropower generation since 1998 – different datasets

The time-series data in this section are from the Energy Trends publication[43] 5.1 'Fuel used in electrical generation and electricity supplied (ET 5.1 – quarterly)' that as introduced in the previous section has generation values for Major Power Producers and Other Generators on an annual and quarterly basis

[42] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/911817/electricity-generation-cost-report-2020.pdf

[43] Energy Trends 'Fuel used in electricity generation and electricity supplied (ET 5.1 - quarterly)' https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1086790/ET_5.1_JUN_22.xlsx

starting from 1998. Another source of data is from the 'Generation by Fuel Type – Historic HH'[44] from Elexon's Portal, this has data for transmission connected generation and is reported at a half-hourly level. The Elexon data starts in November 2008.

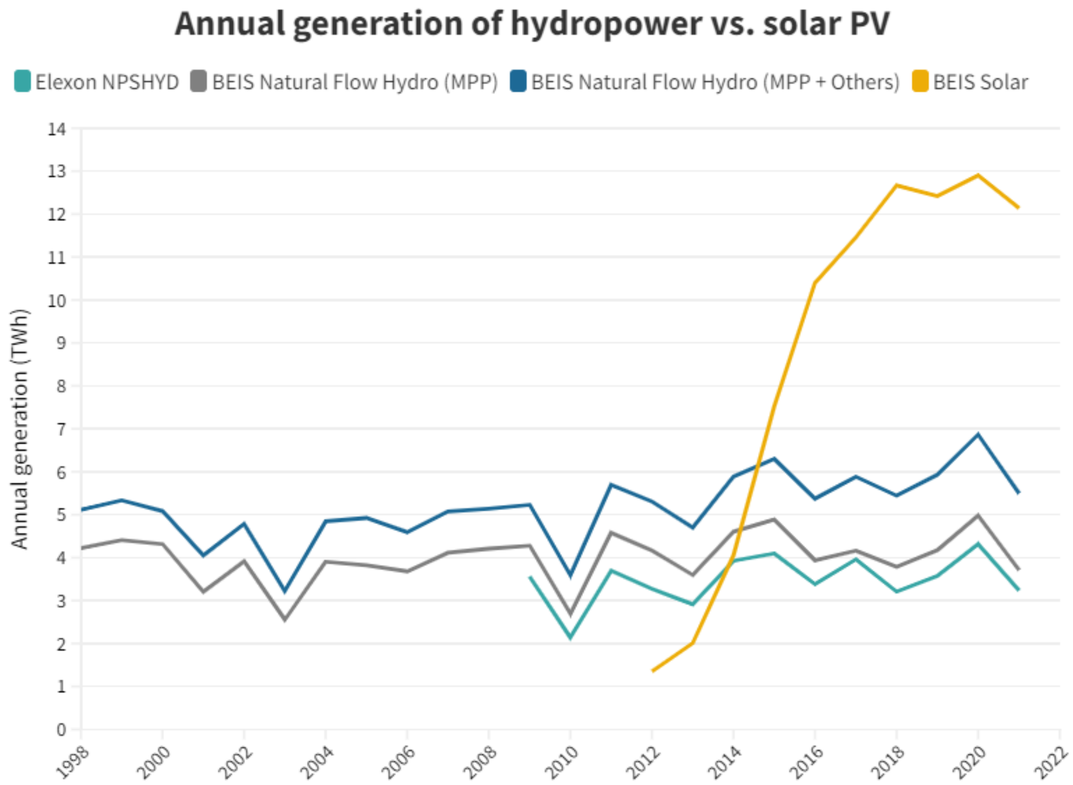

Figure 10 - Annual generation from solar and hydro (from different datasets) 1998-2021 (data from Energy Trends Table 5.1c, and Elexon)

Figure 10 shows three timeseries plots for hydropower generation against a single plot for solar. The three hydro timeseries are from highest to lowest

1. the total of the BEIS data for hydro natural flow from Major Power Producers + Other Generators
2. BEIS data, but this time just for Major Power Producers alone
3. Half-hourly power output data from Elexon non-pumped storage hydro (NPSHYD) aggregated to a quarterly level

Comparing the quarterly data from 2008-2022 Q1, the reported generation from BEIS from Major Power Producers + Other Generators is on average 58% higher than the equivalent half-hourly data from Elexon. The BEIS Major Power Producers only (without the Other Generators added) is still above the equivalent Elexon values.

Timing of hydropower generation in the UK

To compare hydropower generation on a more detailed than quarterly basis, the Elexon data are utilised as they are half-hourly and provide the detail required in terms of timespans. However, as this timeseries data is always less than the equivalent quarterly generation values from BEIS for the total of Major Power Producers and Other Generators, the half-hourly Elexon values are multiplied by 58% to account for the 'missing' hydropower generation. This has uncertainty in terms of when the missing hydropower generation actually happens, as it is likely to be skewed to particular times of day rather

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44 www.elexonportal.co.uk/fuelhh

than a simple % increase across each quarter. However, under the weekly analysis shown in Figure 11 , or daily or monthly values this is felt to be less of an issue.

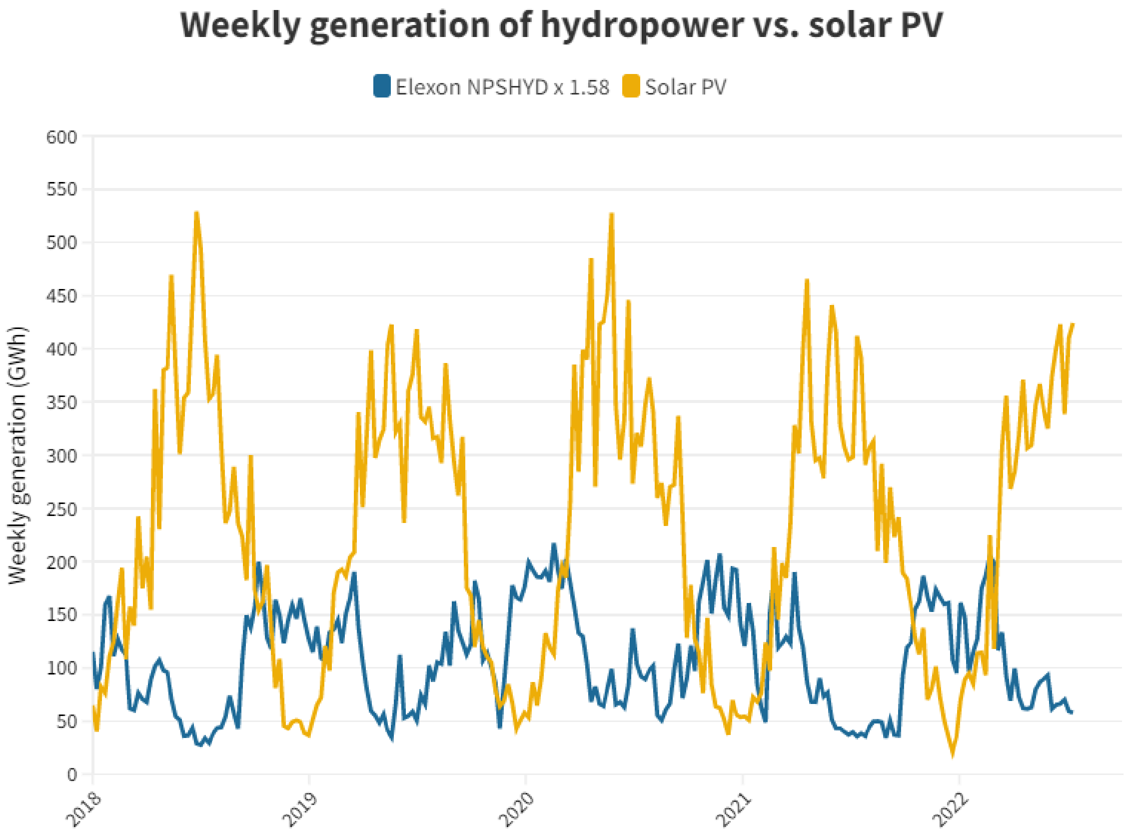

Figure 11 -Weekly energy output from Elexon hydropower generation data multiplied by 1.58 and solar generation form National Grid[45]

Figure 11 shows that as expected, hydropower generation is seasonally inversely correlated with solar, so that when solar generation is lower in the winter, the output from hydropower is higher, and vice versa. However, it should be recognised that the majority of hydropower generation is located in Scotland that has a lower amount of solar generation than England.

[45] Electrical half hourly raw and cleaned datasets for Great Britain from 2008-11-05 https://doi.org/10.5281/zenodo.3884858

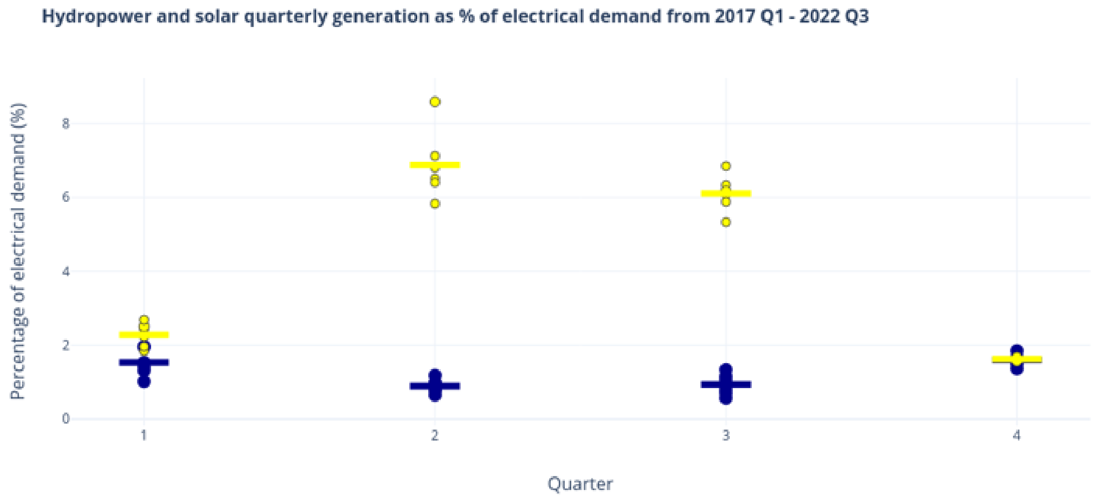

Figure 12 – Hydropower (blue) and solar (yellow) generation as a % of quarterly electrical supply 2017 – 2022 (data from Energy Trends Table 5.1c). The circles are the values for each quarter and the bars are the average over all of the same quarters within the time period.

Figure 12 shows the quarterly data from 2017-2022 Q1 from the Energy Trends dataset from solar and the total value for hydropower generation from Major Power Producers + Other generators. The value is expressed in % terms as a fraction of the overall generation supply for that quarter. The data shows that the quarterly output of solar and hydro in Q1 is broadly similar at between 1.5 and 3% (but mostly around 2%), and that hydropower generation (at about 2.4%) is higher than solar in Q4. Solar output is much higher than hydropower in Q2 and Q3 with solar being around 5.5 to 6.6% of total generation (the 8% value for solar was in Q2 2020 when the first COVID-19 lockdown had reduced the overall electrical demand).

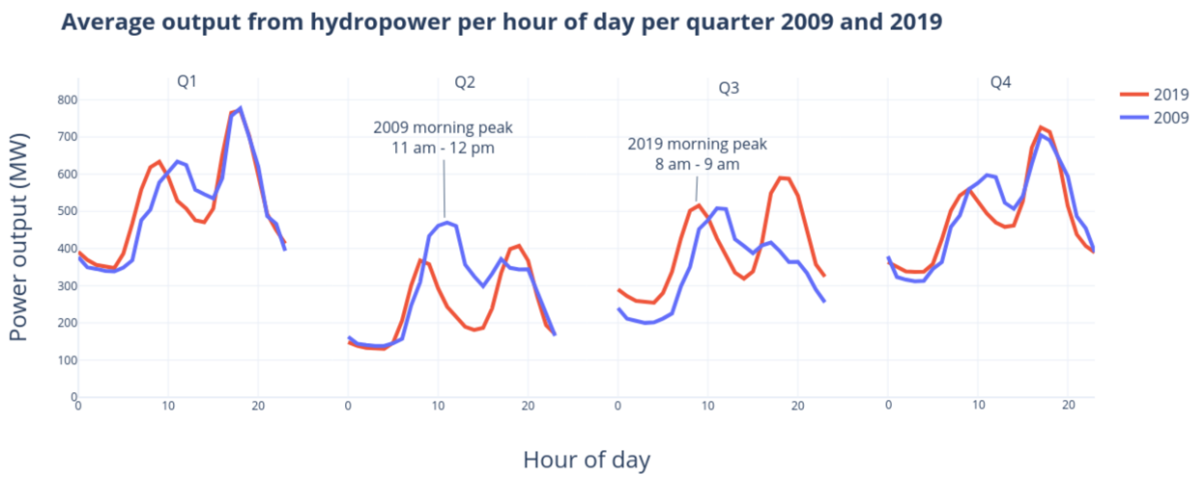

Figure 13 - Hourly average of generation for hydropower from Elexon values (not multplied by factor of 1.58)

Figure 13 shows a number of interesting features:

1. The generation profile over a day is not flat but has a shape that broadly reflects the overall electrical demand for Great Britain
2. There is generation overnight from 7pm to 7am at an average level about 60 to 70% of the average of the 7am to 7pm daytime value
3. Earlier years of data had a morning peak centred around 11-12am, whereas in recent years this has shifted 2-3 hours earlier to 8-9am.

The generation profile for hydropower is found to be broadly reflective of the overall electrical demand. This indicates a controlled release of the hydro resource to match the changing electrical demand, rather than the hydro resource merely being available in greater amounts at peak demand times of day, or lower amounts at lower demand times of day. This is likely to be reflective of the larger generation plants that are part of a fleet of electrical generators under an active trading management seeking out opportunities for greater revenues, or potentially part of contractual agreements to generate more at certain times of day. The source of the sub-daily generation data (the Elexon data) is limited to larger hydropower generation sites that are large enough themselves to warrant half-hourly reporting, or potentially aggregated with other generation and badged as being 'hydro' under reporting conventions.

Whatever the process underpinning the change in output, it is clear from these data that this already happens, suggesting not only an active management, but also that it can happen, i.e., there is some form of 'storage' that allows generation to be ramped up and down. This is likely to be water impoundment of various scales and types such as dams. Indeed, many of the larger and older hydro schemes in Scotland have impoundment, and without drilling further into the data it is assumed that it is the output from these schemes that are the main fractions of the Elexon data, and thus the basis for the average generation profile over the day.

An interesting question arises on how reflective the profile of larger generators with impoundment is of smaller generation, particularly those with limited or no impoundment that are likely to generate simply when the water flow is available. For smaller hydropower and run-of river schemes without impoundment, the overnight and within day average generation values would be expected to be closer as they are not expected to have anywhere near as much of managed profile for their output.

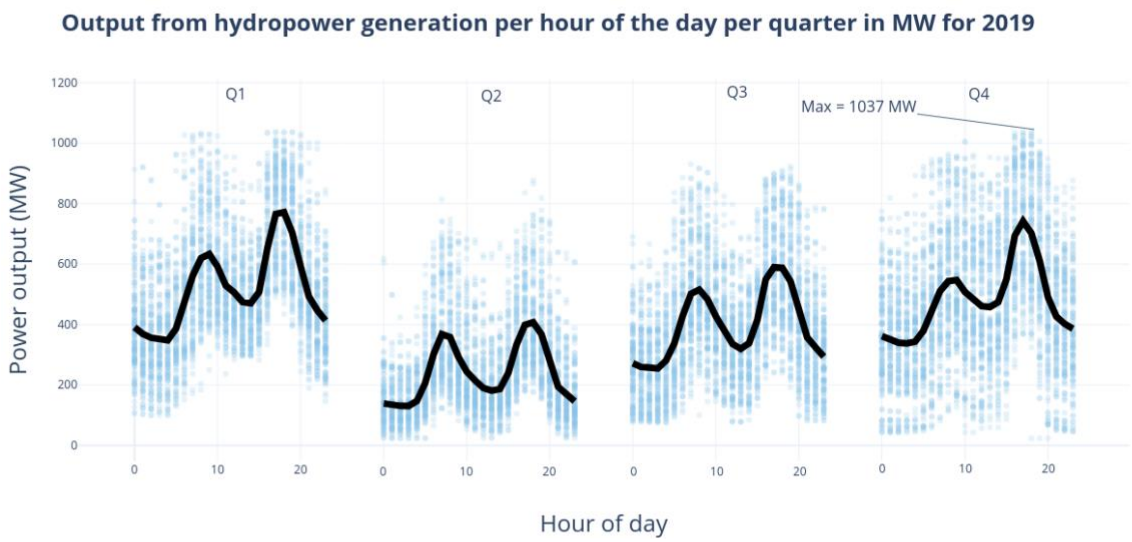

Figure 14 - Spread of generation per hour per quarter for 2019

Figure 14 shows the spread and density of values of generation for every half-hour in 2019; the black line is the average value of generation for each hour per quarter. Over the heating season period (Q1 and Q4) the overnight output reported by Elexon has an average of about 350 MW, which is a helpful addition to the low-carbon portfolio now and in future. It is particularly helpful as solar generation would not be generating overnight and would thus need some form of electrical storage to output at that time. However, Figure 14 shows that hydropower also has low output periods, but it is not known if these are indicative of a lack of an underlying resource at these times (perhaps due to necessary mitigation flows), or a managed shifting of output to times of higher prices. Onshore wind has some similarities with hydro in terms of seasonal output, and the average overnight output being above zero too.

Hydropower generation as a fraction of the UK's 2050 net-zero energy systems

If there is no additional hydropower capacity built in future, and therefore its output remains broadly at the same level as recent years, its contribution would decrease as a % fraction of the overall electrical supply. This is due to the necessary increase in overall electrical supply to satisfy the electrification of various fractions of heating and transport demand. For example, under National Grid's Future Energy Scenarios 2022[46], the annual electrical demand in 2050 under different scenarios is estimated to be between 566 TWh and 716 TWh, up from almost 300 TWh in 2021. This suggests an approximate doubling of electrical supply in 2050, meaning hydropower's existing output would drop from about 1.8% to nearly 1%.

So, for hydropower to remain about 1.5% of the UK's electrical system output over the longer-term, it would require a significant and sustained increase in its capacity of approximately 50%, equivalent to a 1000 MW of capacity increase over the existing installed capacity of circa 2 GW.

In a low-carbon generation future based more and more on wind and solar, it is increasingly clear that there is value brought from different generation types with different resource characteristics. Security of supply is enhanced by having generation that has different resource characteristics. It is not only the annual output that matters, but when the generation happens throughout a day and year, and importantly how controllable and reliable this might be. Figure 14 shows that hydro currently flexes its output, so, demonstrably there is a significant element of hydropower that already can be controlled to flex its output both up and down. In addition, the ability of hydropower to generate when other low-carbon sources may simply not be able to (without some form of storage) provides an increasingly attractive benefit of hydropower's intrinsic characteristics during the winter season when electrical heating will disproportionately increase overall electrical demand. The BEIS publication on the Benefits of long-duration electricity storage[47] details the critical need for seasonal storage in a net-zero electrical system, a service that has historically been provided by fossil-fuels. However, in a net-zero electrical system without the benefit of fossil-fuels a seasonal match to the electrical system demand will be helpful. Wind has this seasonal match, whereas solar is negatively matched seasonally to the increased electrical demand over winter. At a high level of assessment, the output from hydropower is 1 TWh to 1.5 TWh greater in quarters 1 and 4 than it is in quarters 2 and 3. How much of that intrinsic benefit of greater output in winter than in the summer could accrue to hydropower in future market frameworks is an interesting and open question.

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[46] https://www.nationalgrideso.com/document/263876/download

[47] https://www.gov.uk/government/publications/benefits-of-long-duration-electricity-storage

Section 5: BHA survey

The BHA has circa 300 members, of which circa 125 own and operate hydropower schemes or intend to develop them as part of their business. This membership represents a substantial share of the hydropower market in the UK. Engaging with the sector was seen as an essential way to gain insight into the state of the sector, identifying schemes which were potentially undersized with regard to their power output, challenges faced by developers when new schemes are investigated and the appetite for future development under hypothetical guaranteed funding arrangements. Therefore, conducting a survey was deemed a suitable method to provide quantitative data to assess these areas of interest in terms of the UK's future hydro potential to help to balance the analysis from predicted capacity from previous reports.

The survey was designed to strike a balance between containing sufficient detail to allow meaningful insights to be gained, but also presented in a straightforward and concise manner to ensure a reasonable response rate (it was aimed for the completion of the survey to take approximately 10 minutes).

It was created as an anonymous survey so that the answers would not be identifiable to specific individuals or companies, which was felt to allow for more open and candid responses. To mitigate the chance of disclosing respondents' identities when presenting the results, responses are either grouped into bins or trend lines are applied when linking two variables in a scatter chart. The survey consisted of 12 questions split into three sections with request for information on:

1) the respondent's existing hydro schemes
2) schemes with relevant consents but not yet built
3) future schemes which have not yet sought any consents

The full questionnaire is contained within Appendix C

Part 1 of the survey: respondent's existing hydro schemes

The survey link was emailed to BHA members and open for 12 days in June 2022; of members contacted, 49 responses were received, which is a response rate of approximately 15%. These responding members constitute a collective portfolio of 436 hydro schemes with a combined capacity of 1,403,000 kW and annual output of 4,899,000 MWh, although one large capacity organisation did not provide a generation value.

This represents a significant share of the sector since these figures (using data from Section 1) correspond to 26% of the number of schemes and 69% of the total installed capacity in the UK. Since the capacity dataset created in Section 1 did not consider annual generation output, using data from BEIS[48], it is estimated that the survey respondents covered about 70% of annual generation output.

Importantly, the survey respondents were felt to be representative of a diversely sized range of organisations; 6 responding parties had no existing hydro schemes, 16 operated only one generation facility, around half of the respondents operate between 2 and 20 schemes and 7 operate more than 20. A more detailed breakdown of these intervals and bandings for portfolio capacities and generation outputs are given in Figures 15, 16 and 17. It should be noted that 2 of the 43 respondents with generating schemes did not provide annual generation output figures (one of these was the respondent with the second largest total installed capacity, so the annual output of 4,899,000 MWh is likely a significant underestimate).

[48] https://www.gov.uk/government/statistics/regional-renewable-statistics

Figure 15 – Chart to show the distribution of the number of schemes operated by survey participants.

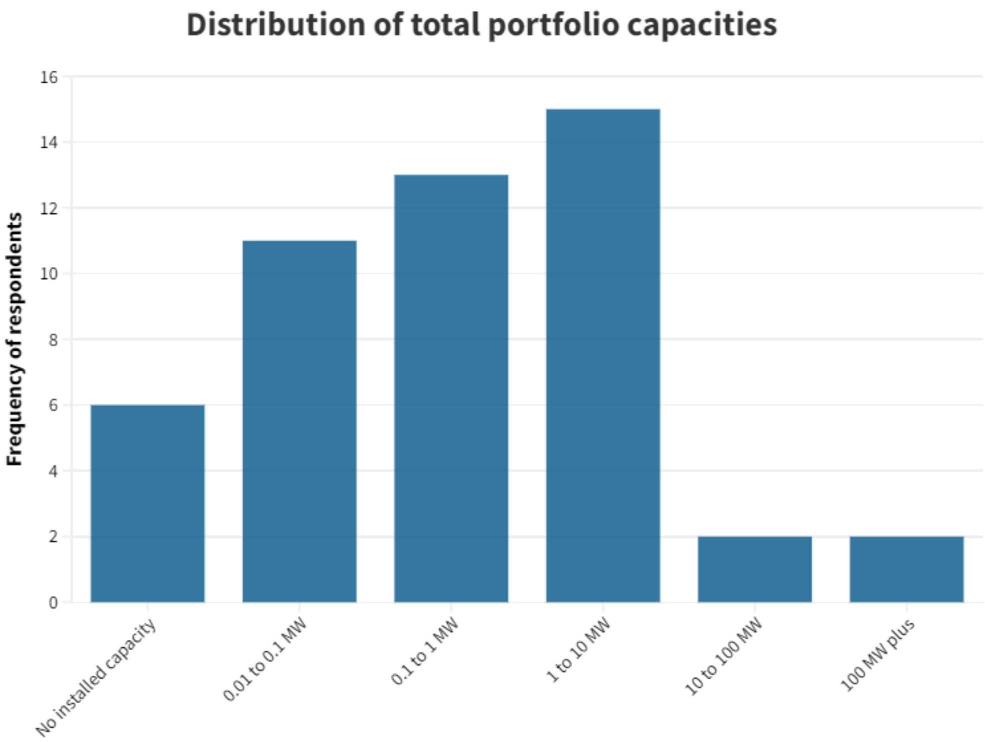


Figure 16 - Chart to show the distribution of total hydropower portfolio capacities operated by survey participants.

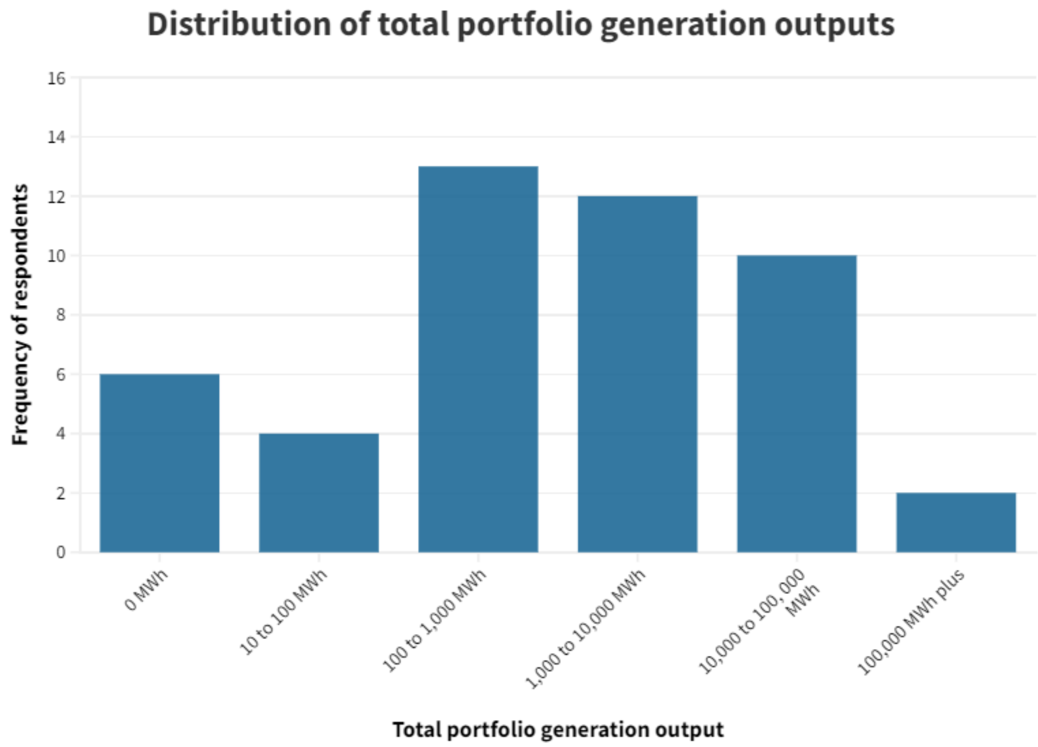


Figure 17 - Chart to show the distribution of total hydropower portfolio power outputs operated by survey participants.

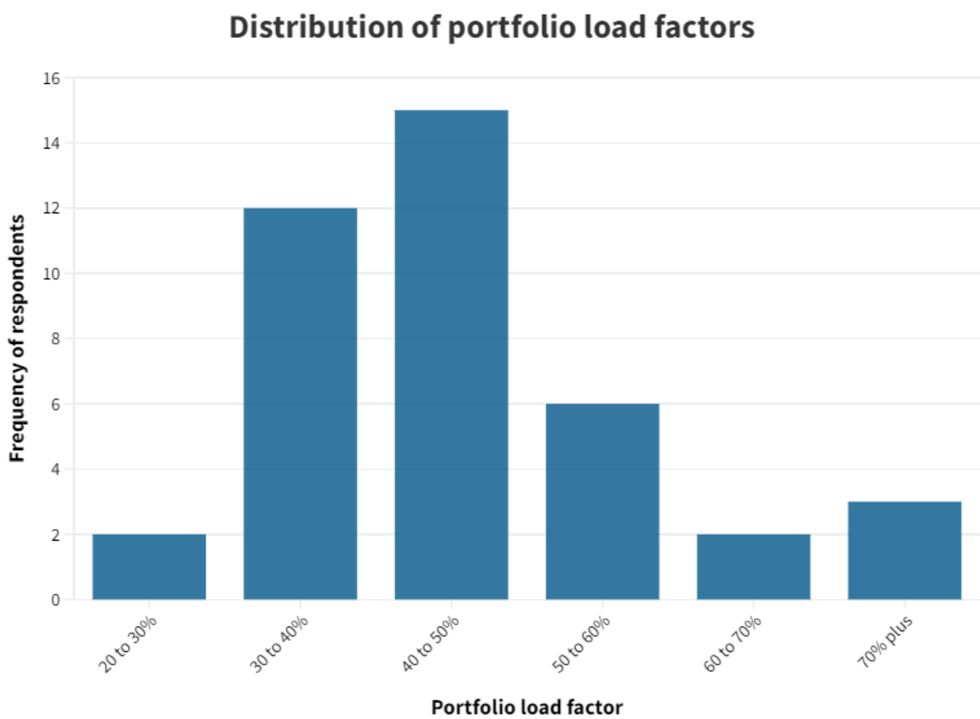


Figure 18 - Chart to show the distribution of net hydropower portfolio load factors operated by survey participants.

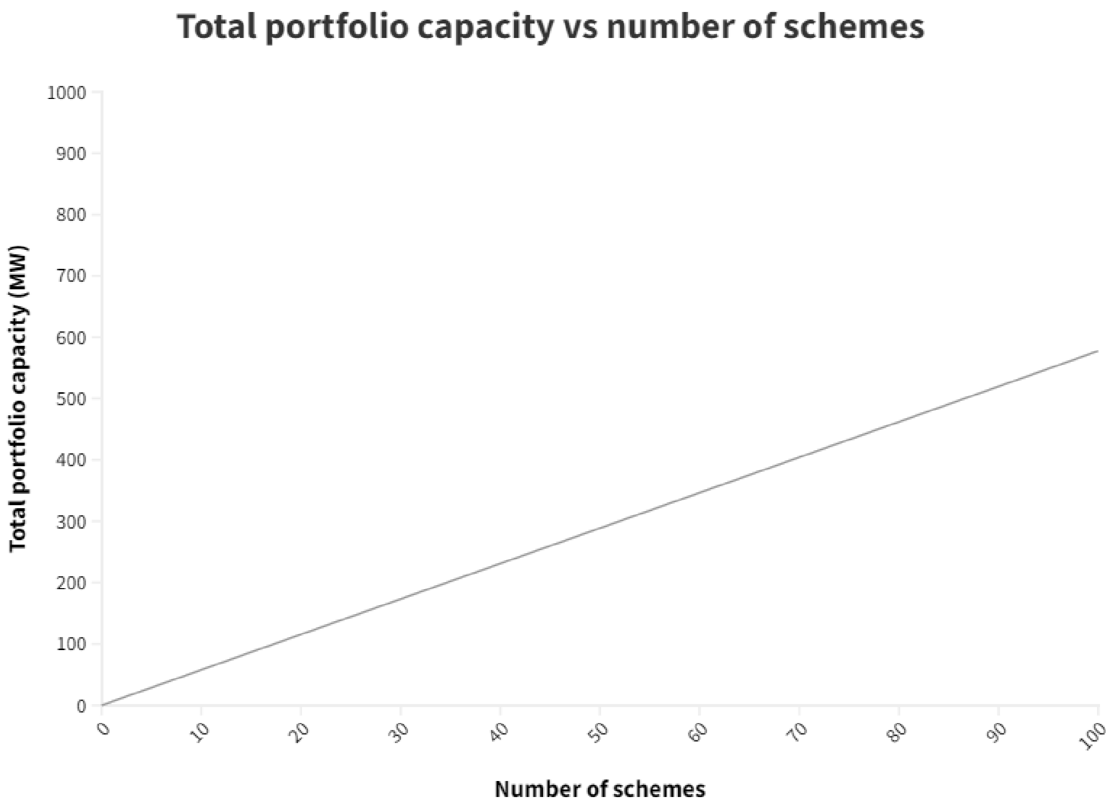


Figure 19 – Chart to show a trend line between the total portfolio capacity and number of schemes operated.

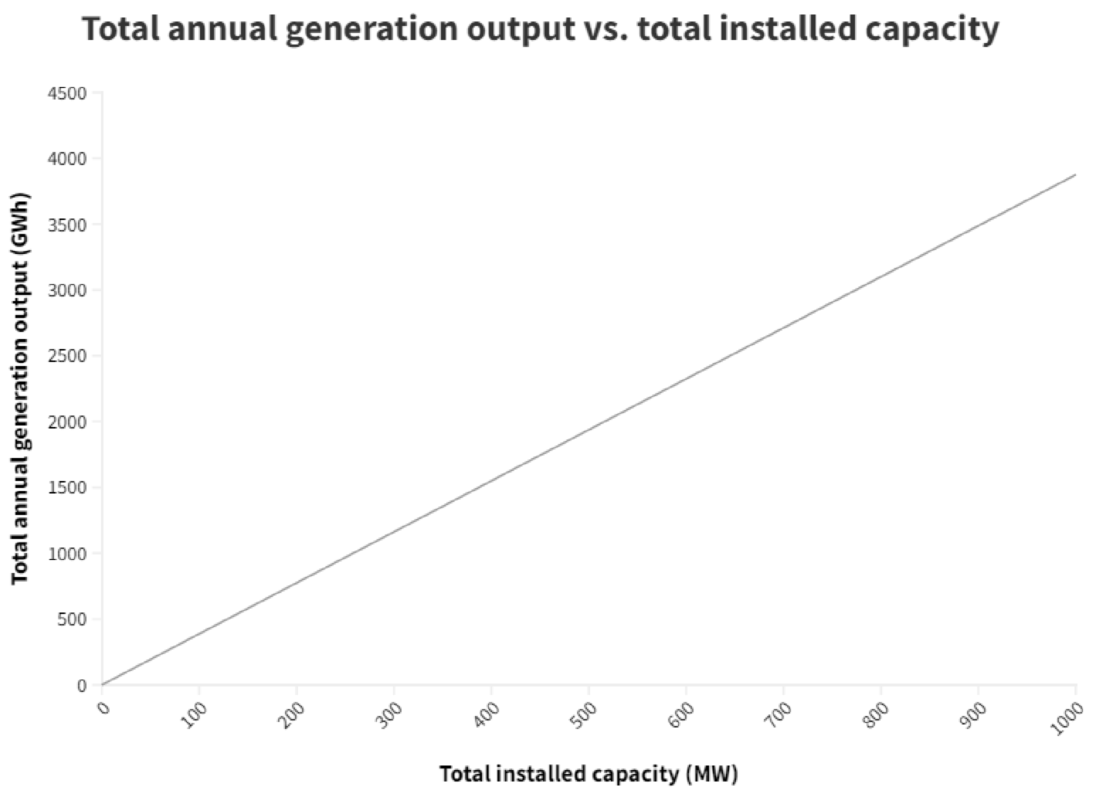


Figure 20 - Chart to show a trend line between the total portfolio power output and total portfolio capacity.

Net load factors could also be calculated for each respondent's portfolio of schemes based on the ratio of the annual generation of each collection of sites to the total theoretical output of each portfolio (equal to the capacity multiplied by 8760 hours for a non-leap year and converted to MWh). The distribution of these calculated load factors is shown in Figure 18. It should also be noted one further site was omitted from this analysis as they reported a generation, greater than the theoretically possible maximum (it was a small site and only a typical yearly answer was asked, so this could be due to rounding up to the next 100,000 kWh interval).

Finally, to show a deeper insight into the characteristics of the portfolios of responding organisations, respondents without operating sites were removed and two trend lines (Figure 19 and Figure 20) were produced to show the relationship between (a) the number of sites and total installed capacities and (b) the total installed capacities and the total generation output. As expected, there is a strong positive correlation between the capacity of the portfolio and the power output (larger sites will generate more), but there is a less clear relationship between portfolio capacity and number of schemes owing to the diversity of up to two orders of magnitude in portfolio capacity at lower numbers of schemes.

The final question on existing schemes asked respondents to identify if they were aware of any of their existing sites which could have their capacity expanded. The motivation for this question stemmed from anecdotal evidence within the sector of schemes being undersized to fall within a type of constraint e.g., to receive a certain FIT payment as evidenced by the distribution of site capacities in Section 1 and shown in Figure 8. Other reasons of under sizing capacity could be due to the limited grid connection or other applied for consent. For historic schemes, there is a view that upgrades could in certain cases increase the nameplate capacity of turbines due to efficiency improvements in the sector through more modern equipment. This question received a binary reply from all 49 respondents with 23 saying 'Yes' (they are aware of such sites that could be expanded in their capacity) and 26 saying 'No' (that they aren't aware of such sites).

Of those organisations which said they had at least one scheme which could be expanded, the distribution in terms of site numbers and potential additional capacities across all sites was as follows.

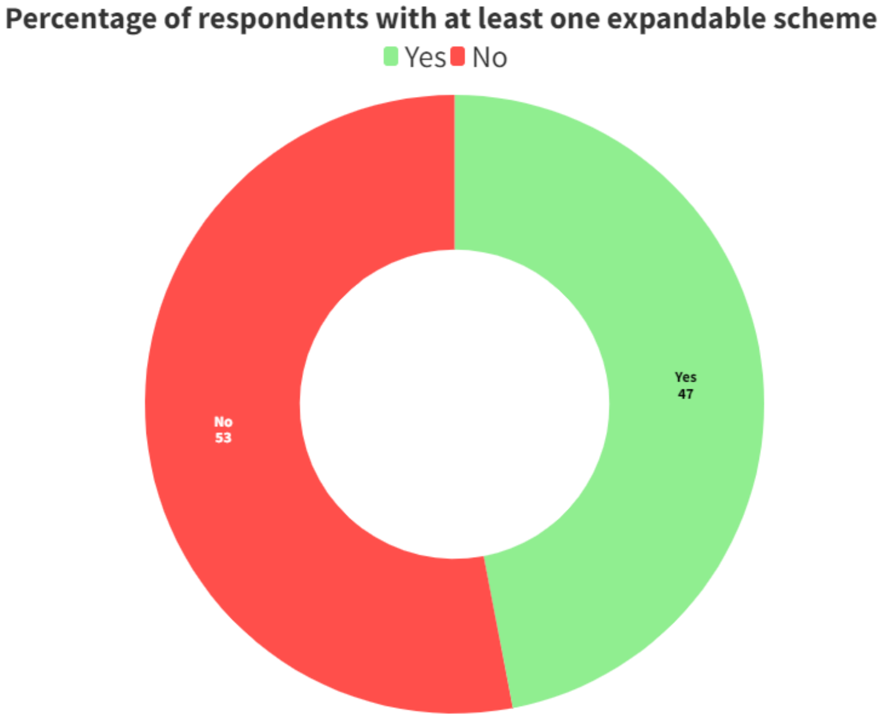


Figure 21 – The yes/no percentage split of respondents who said they could expand at least one hydropower scheme.

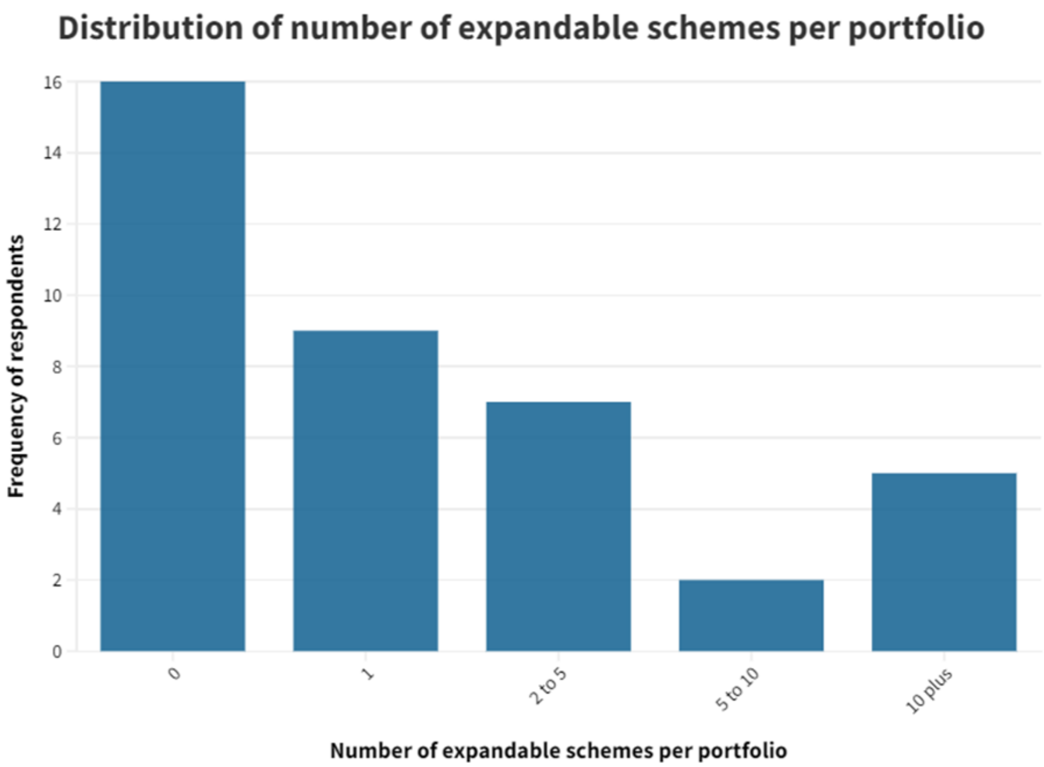


Figure 22 – Chart to show the distribution of the number of expandable schemes per portfolio.

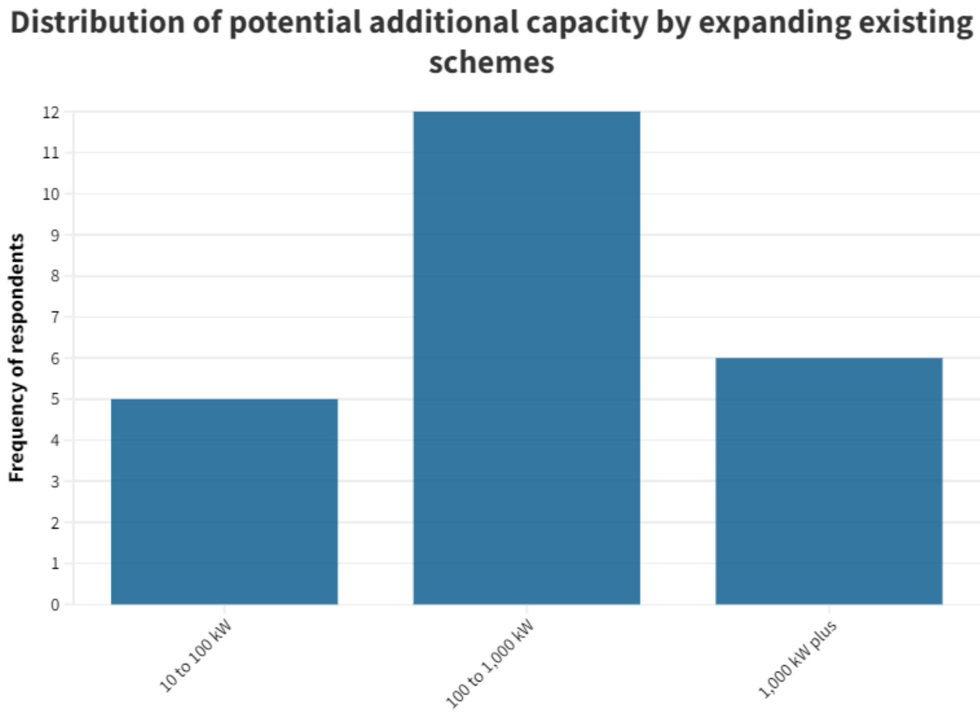


Figure 23 - Chart to show the distribution of potential additional capacity of expandable schemes by respondent.

From this data it can be seen that there are 124 schemes identified by survey respondents which could be expanded (just over a quarter of all schemes covered) with a total potential additional capacity of nearly 48 MW. From this value, it can be determined that the average existing scheme can be expanded by 0.11 MW. Extrapolating this value for all 1657 generating schemes in the UK yields a potential additional hydro capacity of 181 MW through the expansion or upgrading of existing schemes, however, this extrapolated value is highly uncertain for a number of reasons.

Part 2 of the survey: schemes with relevant consents but not yet built

The next section of the questionnaire asked participants if their organisation had any schemes for which required consents (such as planning permission and devolved environment agency licences) had been successfully applied for but, for whatever reason, the scheme had not been developed to the point where it was operational. Of the 49 respondents, 8 replied ‘Yes’ (that they were in such a situation), 40 ‘No’ (that they were not) and 1 did not respond to this question.

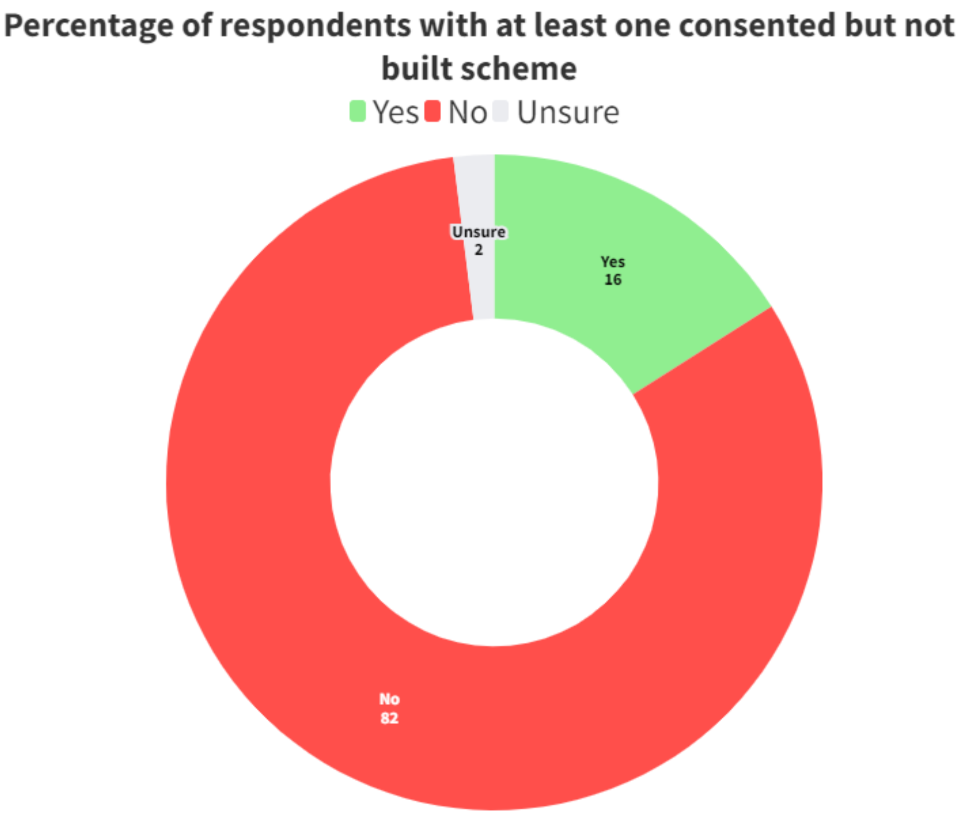


Figure 24 – The yes/no/unsure percentage split of respondents who said they had at least one scheme which has all or most of the necessary consents (e.g., planning permission, grid connection and environment licences) but has not progressed to a stage of being constructed.

Delving further into these responses reveals that a total of 41 hydro schemes with a total capacity of 18.8 MW were applied for but not yet built. The following Figure 25 and Figure 26 show the breakdown of these for each respondent.

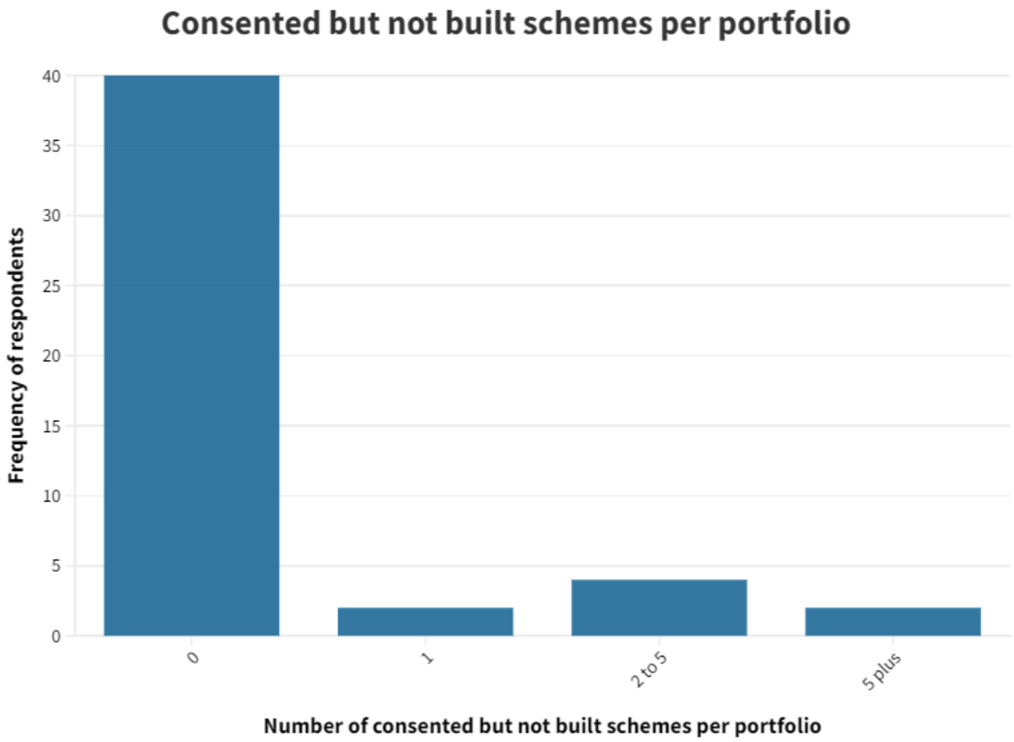


Figure 25 - Chart to show the distribution of the number of schemes with consents but not yet built per respondent portfolio.

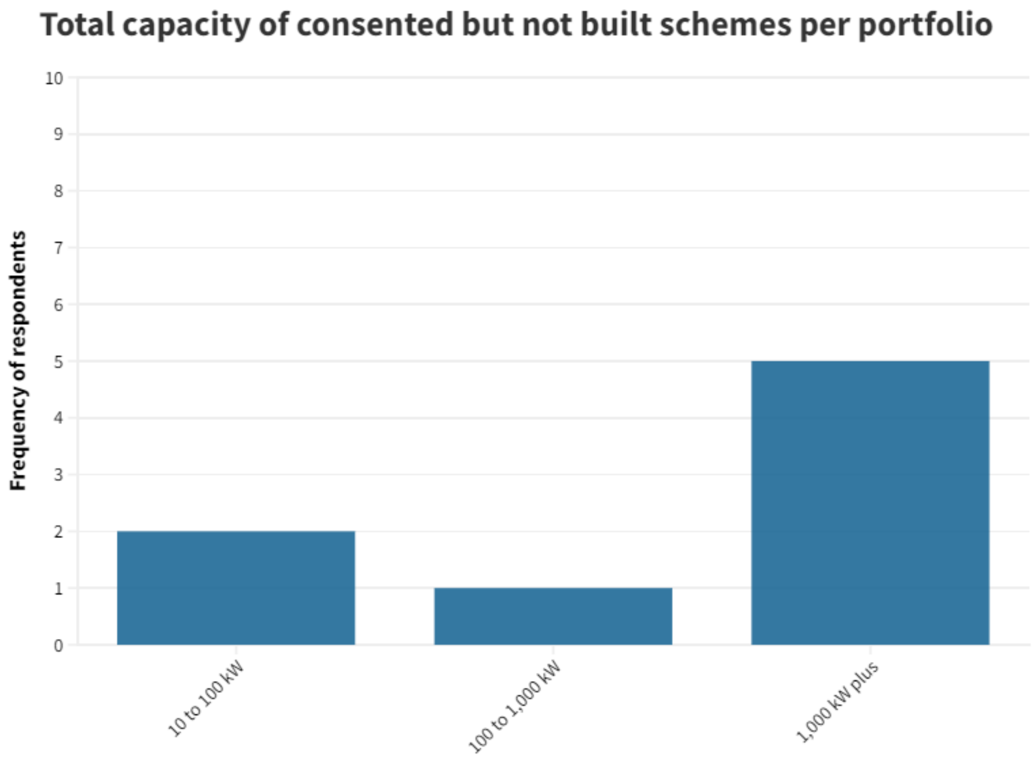


Figure 26 - Chart to show the distribution of the total capacities of schemes with consents but not yet built per respondent portfolio.

Following the same assumptions as in the previous estimate for expandable existing schemes, there could potentially be an additional 71 MW which is at the phase of having the necessary permissions but has not yet been constructed. A future task could be to compare this figure with the environment agency and renewable energy planning database datasets, to validate the accuracy of the estimation.

The next sub-question revealed that out of all of these potential schemes, only 1 out of 41 (a 60 kW scheme) would be operational in the next 5 years. This means that the remaining 40 schemes would not be built within this period that would seem to be a stark indication the poor investment environment facing the sector. Respondents were then given an optional free text box to explain why the scheme or schemes are unlikely to come into fruition.

In analysing these free text comments, there was a common theme in that almost all organisations mentioned the lack of ongoing financial certainty as a barrier to the viability of the project. One response was simply "Lack of financial support, i.e., feed in tariff". Others gave similar responses but with additional nuance or reasons such as expiration of environment agency consent, COVID-19 related delays in the sourcing of electronic parts, bank loans being dependant on a certain return rate (which was not achievable without FIT), inability to obtain a grid connection and uncertainty over future electricity prices and taxation arrangements.

Part 3 of the survey: future schemes which have not yet sought any consents

The final section of the questionnaire asked participants on future schemes, defined as sites for potential generation which may have only undergone a basic level of resource assessment or a detailed feasibility study, but in either case no licences or permissions had been formally applied for. The questions were designed to supplement existing studies on the potential of natural flow hydro and gauge the ability / appetite of the sector to meet demand if a more pro-active policy environment was fostered.

In the absence of an updated detailed hydrological and techno-economic assessment for the UK, it was felt this method of expert knowledge was a useful way of obtaining insights to supplement the previous resource assessments.

The survey asked if respondents had any strong knowledge of the undeveloped hydropower potential in a given geographical area. They were prompted to give an answer in terms of local authority areas (for consistency and ease of comparison with statistics published by BEIS).

Of the 49 participating organisations, 26 gave an answer indicating that they had knowledge of the hydropower potential of at least one local authority sized area. The question attracted a diverse range of responses both in terms of location and size, and helpfully, there was representation in the answers of all four constituent countries of the UK. 2 responses claimed to have a knowledge of the entire UK (one identifying from their mapping work, 10s of thousands of schemes across every local authority, which were assumed to include pico and micro-hydro), while 3 responses stated they had detailed information on the potential for hydro across all of Scotland, England and Northern Ireland, respectively.

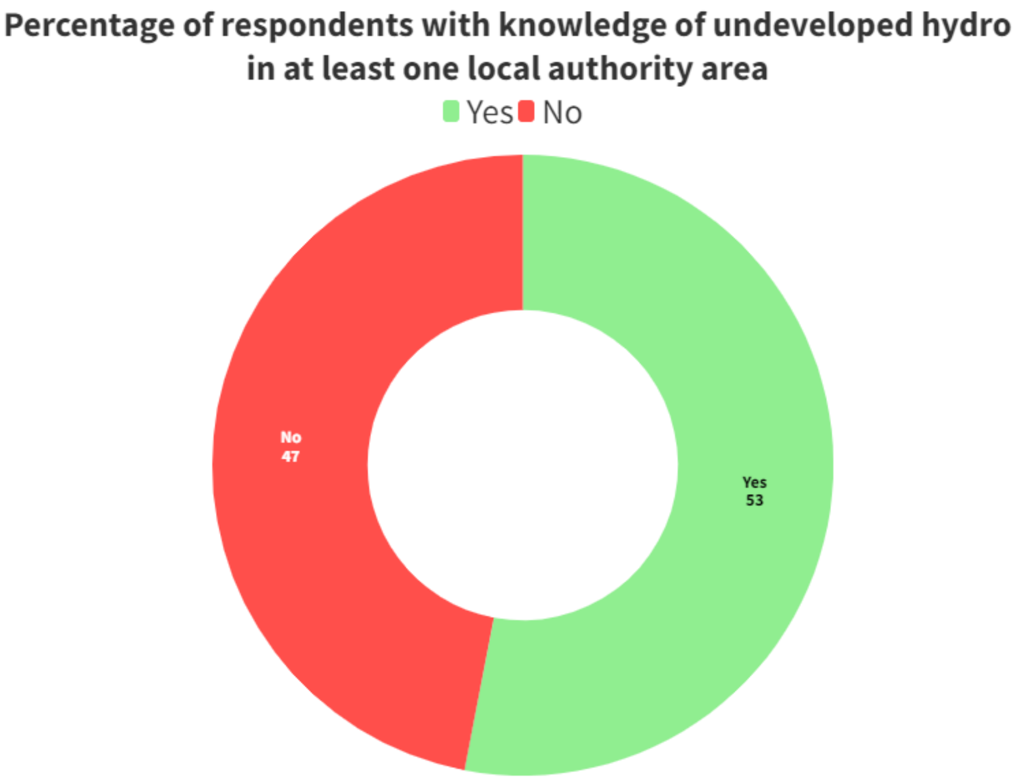


Figure 27 - The yes/no percentage split of respondents who said they had detailed knowledge of the potential for undeveloped hydropower in at least one local authority area.

Local authority areas (or alternative geographic descriptions) to feature in more than one reply were: Highland (or the Highlands or Lochaber or West Ross), Argyll and Bute (or Argyll), Perth and Kinross (or

Perthshire), Dumfries and Galloway, Gwynedd (or Snowdonia), Powys and Northamptonshire (or West Northamptonshire). The remaining local authorities and broader geographic areas mentioned only once included: Amber Valley, Blaenau Gwent, Carmarthenshire, Carlisle, Central Scotland Region, County Derry, Denbighshire, Derby, Derbyshire Dales, East Ayrshire, Greater Manchester, Lake District National Park, North Lanarkshire, Stirlingshire, South Hams, Teignbridge and West Devon.

Figure 28 - Map to show areas of the UK where survey respondents claimed to have detailed knowledge of the undeveloped hydropower potential.

These areas are mapped in Figure 28. It is also noteworthy that one respondent used the free text in this question to add an additional comment: "Local Planning Authorities have a poor knowledge of hydro potential in our experience." If this opinion is echoed across the sector, then a recommendation could be an effort to help increase the capacity for local authorities to better understand the hydropower potential of their area and greater knowledge sharing at a local level between relevant organisations including BHA members, community energy groups, government departments and

Distribution Network Operators. Some examples of local authorities with reasonable hydropower potential and providing publicly available data by publishing detailed maps of existing and proposed schemes are Highland[49], Perth and Kinross[50] and Argyll and Bute[51]. The production of similar resources for all councils with hydro potential and combining the separate maps into a national map to be compared with other data sources (e.g., statistics published by BEIS or this report) could be a valuable effort and helpful for the sector overall, particularly if tied together with a unique hydropower site reference number.

After identifying geographic areas, the survey question then asked respondents to estimate a potential capacity in kW of untapped hydro schemes within the chosen area. The available responses were given in 6 bands from: < 1,000 kW, 1,000 – 5,000 kW, 5,000 – 20,000 kW, 20,000 – 100,000 kW, 100,000 – 500,000 kW and > 500,000 kW. The answers received are shown in Figure 29. Interestingly 3 respondents who did not answer still gave an estimate of the potential, perhaps as this related to a specific potential scheme or set of schemes they had identified but did not want to tie to a geographical area.

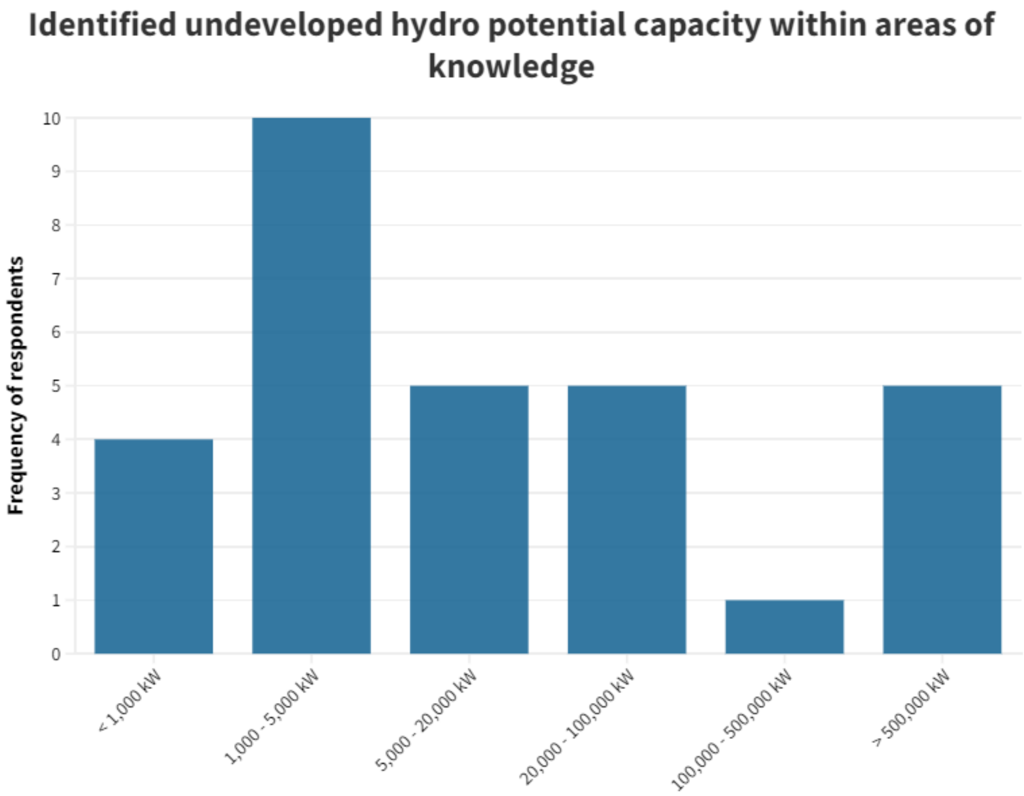


Figure 29 - Chart to show the distribution of the respondents' views on the potential undeveloped hydropower potential in the area of identified knowledge. This could vary from one local authority to the whole of England, Scotland or even the UK.

Tying geographical areas to the potential hydropower capacities from the raw survey results was found to be a non-trivial task and fraught with uncertainty, since the different geographical areas of knowledge given do not follow a one-to-one mapping between members and their different specialisms (e.g., in project installation sizes) and levels of expertise in resource assessment may lead to different approximations. For example, for the two respondents who named Lochaber as a geographical area for which they had knowledge, one estimated 1,000 – 5,000 kW of undeveloped capacity, while the other

[49] https://www.highland.gov.uk/info/198/planning_-_long_term_and_area_policies/152/renewable_energy/5

[50] https://www.pkc.gov.uk/article/18662/Small-scale-hydro-schemes-map

[51]https://argyll-bute.maps.arcgis.com/apps/webappviewer/index.html?id=fa5f97accaf34ab7a1af1d280eb04568

predicted 20,000 – 100,000 kW. Hence, although useful as an indication of geographic areas where respondents thought there was some hydropower potential, the uncertainty evidenced by the variation in values was felt to be too great to provide a quantified value to be generated for those areas.

For a hydropower scheme to be built, its net present value needs to be positive, i.e., it is not enough for a scheme to be technically feasible and able to meet consent criteria, but it must also be financially viable. Therefore, in addition to the first question on the untapped hydropower potential, another subset of questions dealt with the amount of additional hydropower capacity respondents could build by 2030 under 3 funding scenarios, where schemes are guaranteed a return of £120, £140 or £160 per MWh respectively.

This question was felt to assess the appetite of the sector under different financial conditions and provide, even at a high level, an insight of the price elasticity of hydropower development.

As with the geographic based potential questions, the answers to this question suggest that it was not always a straightforward response for respondents to provide. The results should therefore be treated with some degree of caution. 36 of the 48 respondents provided answers that are shown form the basis of the Figure 30, and Figure 31.

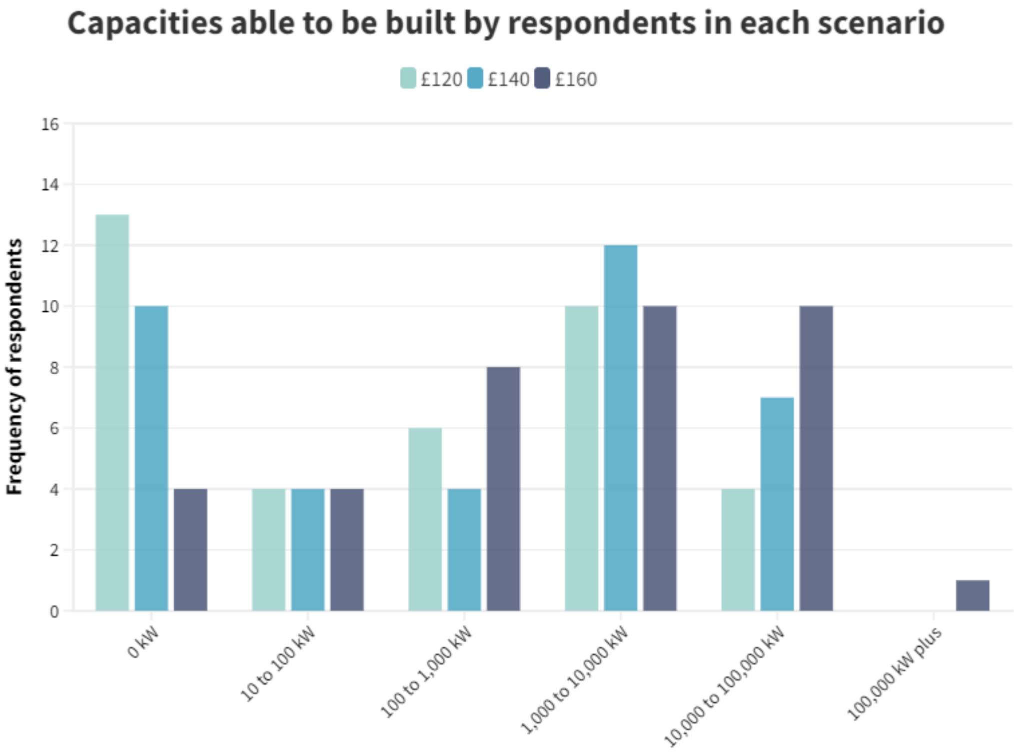


Figure 30 – Total capacities that the respondents would be able to build by 2030 under different guaranteed rates per MWh (£120, £140 and £160).

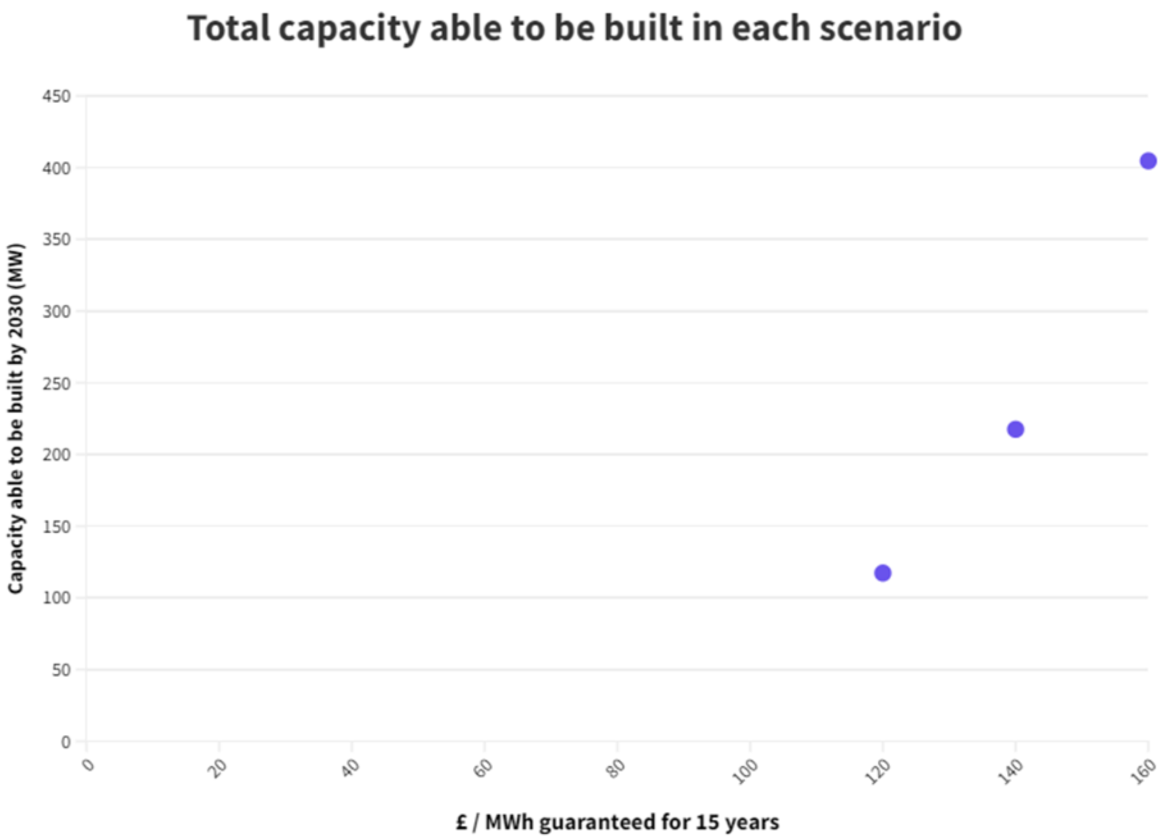


Figure 31 – The total capacity across all respondents that would be able to be built by 2030 under different guaranteed rates per MWh (£120, £140 and £160).

Table 7 - Total capacity able to be built under different guaranteed rates per MWh

Guaranteed 15-year price	***Total deployment by 2030***
£120 per MWh	117.3 MW
£140 per MWh	217.5 MW
£160 per MWh	404.7 MW

The responses of these questions led to one of the key insights of the survey, that under the most generous funding regime, the respondents felt they could build over 400 MW of new hydro schemes by 2030 (in 8 years). From the answers, it can also be seen there is a significant increase between each level of guaranteed price per MWh over a 15-year period; within the range considered, an approximate doubling of capacity for each additional £20 per MWh.

From the above Figure 31, it can be seen that portfolio percentage capacity growth tracks the guaranteed electricity revenue. The data behind this chart can also be extrapolated to yield an estimate of the potential growth of the entire sector to 2030. This was done by comparing the answer to this question (how much capacity the survey participant could build under different funding scenarios) to the earlier question on their existing portfolio capacity. Neglecting respondents without any presently operational hydropower schemes, a percentage was calculated based on the ratio of what could be built under each funding scenario to the existing portfolio capacity. The median of these percentage values (across all respondents with percentage growths of their portfolios calculated) were then noted under each scenario and shown in Table 8 below.

Finally, when compared with the 2.045 GW of existing capacity and applying these calculated percentages as representative of the whole sector, it can be estimated that under these scenarios (from least generous to most generous) the UK would have 470 MW, 1430 MW and 2900 MW of potential additional hydro capacity. When compared to the 2008 Scotland report, there is a strong agreement with the finding that financial barriers being subject to market forces rather than other policies within the government's control or technical limiting factors are the main reason for curtailing further deployment of hydropower in the UK. Parallels could also be drawn between the non-linear growth rate of the deployment capacity in this survey, and sections of the curve in the 2008 Scotland report (adjusting the lifetime cost for energy price inflation).

Table 8 – Based on the extrapolation of the survey results, the additional capacity of the sector was estimated for each of the guaranteed funding scenarios.

Guaranteed 15-year price	***Percentage capacity growth of sector***	***Additional capacity***
£120 / MWh	23%	470 MW
£140 / MWh	70%	1430 MW
£160 / MWh	142%	2900 MW

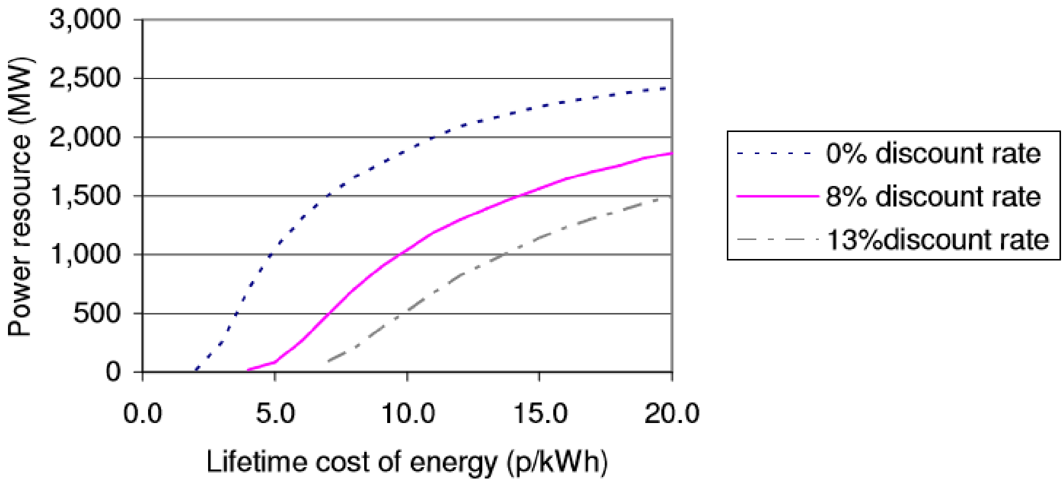


Figure 32 – Figure taken from the 2008 Scotland report[52] for comparison. There is agreement between that report and these findings, in that there is still a strong relationship between the available hydropower resource and the prices paid for energy generated to provide enough revenue for more schemes to be financially viable.

For the final part of the survey, participants were asked to rank perceived barriers to future hydropower deployment. Eight factors were to be scored from 1-5, a score of 1 meaning the issue was not perceived to be a barrier and a score of 5 meaning it was a major obstacle to the development of future or planned hydropower schemes. It can be seen from the average scores received for each factor that the barriers can be divided into two classes; stronger barriers with an average score of 3.5 to 4 and weaker barriers with an average score of 1.5 to 3.

The most commonly perceived obstacles to new schemes (by descending average score) are:

- insufficient ongoing financial certainty
- obtaining required environment licences
- obtaining a grid connection
- obtaining planning permission

Conversely, the lowest scoring factors (by descending average score) are:

- obtaining initial capital finance
- land ownership issues
- opposition from local communities
- lack of information to assess feasibility

52 https://archive.uea.ac.uk/~e680/energy/energy_links/other_renewables/Scottish_hydropower_2008_0064958.pdf

Table 9 – The average score received for each perceived barrier to further deployment of hydropower.

Barrier to hydropower deployment	Average score (5 = major barrier, 1 = no barrier)
Insufficient ongoing financial certainty	3.9
Obtaining required environment licences	3.8
Obtaining a grid connection	3.7
Obtaining planning permission	3.6
Obtaining initial capital finance	2.7
Land ownership issues	2.3
Opposition from local communities	2.2
Lack of information to assess feasibility	1.9

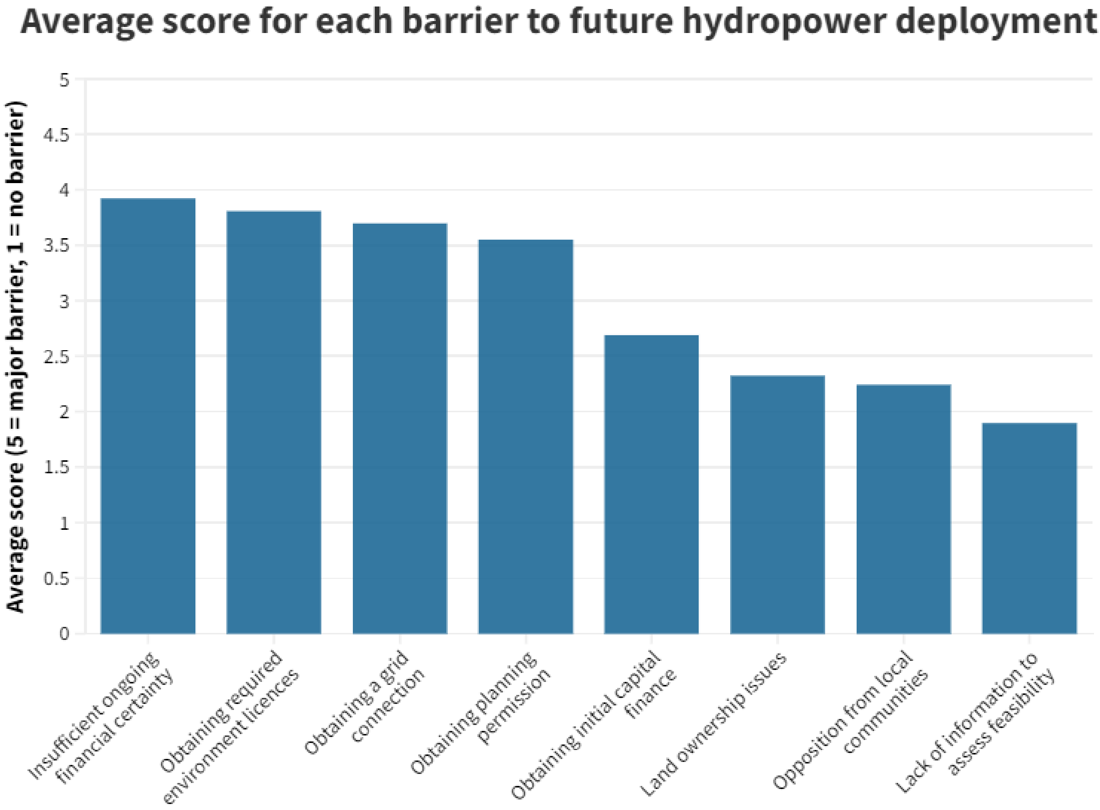


Figure 33 – Chart to the average score received for each perceived barrier to further hydropower deployment.

These results yield two interesting observations. Firstly, that obtaining initial capital finance is less of a perceived barrier to developers than the variability of revenue across the lifetime of a scheme. In a subsidy-free environment, revenue can fluctuate based on the price of electricity either through export or PPAs (which will become increasingly dynamic even for smaller generators as the electrical generation becomes more renewable), and any changes in taxation policy (e.g., business rates) affecting the cost base of generators. Financial certainty was improved by the FiT scheme from 2010-2021 which saw differing annual amounts of hydropower added to the system throughout this period. In the optional free text section, which accompanied this section of the survey, one respondent summed up the situation in their opinion by stating: "[The lack of] a stable funding mechanism has devastated the development of new hydro schemes since ~2018. We developed over 50 new sites in the prior 10 years and only 1 since." A further participant said that the cliff edges of FiT rates hampered the growth of expertise and specialists in the sector as many have now moved to other sectors. They felt that "a consistent subsidy builds an industry, an inconsistent subsidy does not."

This implies that any potential support scheme which seeks to maximise the amount of additional hydropower constructed should target assistance through an ongoing support rather than upfront grant basis, in a similar, though not necessarily identical, mechanism to FiT.

A criticism of the FiT scheme (and also the Renewable Heat Incentive) particularly for a domestic developer is that it did not directly address the issue of a lack of initial capital, which is likely to be more prevalent for small scale technologies being installed at the household level particularly in low-income neighbourhoods. However, hydropower is historically more of a non-domestic scale technology, so the same argument might not apply to commercial developers which need to have access to capital as part of their business. Nevertheless, examples of where up-front grants might provide targeted support is for new entrants (particularly community schemes) or micro-scale schemes to power a single home or small business premises.

Secondly, the results show that gaining consents from different organisations is not straightforward and changes of approach can often have a negative impact on the growth of hydropower in the UK. The three organisations from whom consents must be sought are under three different institutional structures:

1. local government (in the case of planning authorities)
2. nationally devolved governments (in the case of environmental agencies)
3. private companies (in the case of the DNOs) for electrical grid connections

Therefore, a common and constructive approach to hydropower between each authority would seem to benefit the sector. This was highlighted in the free text section from one respondent where they replied: "Planners, consultees and other authorities should take a problem-solving approach to when considering a scheme, working with developers to mitigate concerns". This supports the case for a more joined up approach to supporting hydropower development. Another respondent replied: "There appears to be a real lack of support from regulators with regards to making projects work. This is highlighted by the recent rise in the cost of environmental licences." This specific issue featured in many replies, highlighting sector concerns around the recent (April 2022) increase in Environment Agency licence fees from £1500 to up to £13,392, which disproportionately affects the viability of smaller sites (< 50 kW)[53].

There were views that the balance between the development of hydropower and the protection of the environment was disproportionately limiting its development in certain cases. One respondent described their process in obtaining an abstraction licence as "nightmarish" and another goes even further to state: "The environmentalist lobby (against hydropower) have had a disproportionately strong influence on the Environment Agency and other government agencies."

[53] https://www.waterpowermagazine.com/opinion/opinionnail-in-the-coffin-9677334/

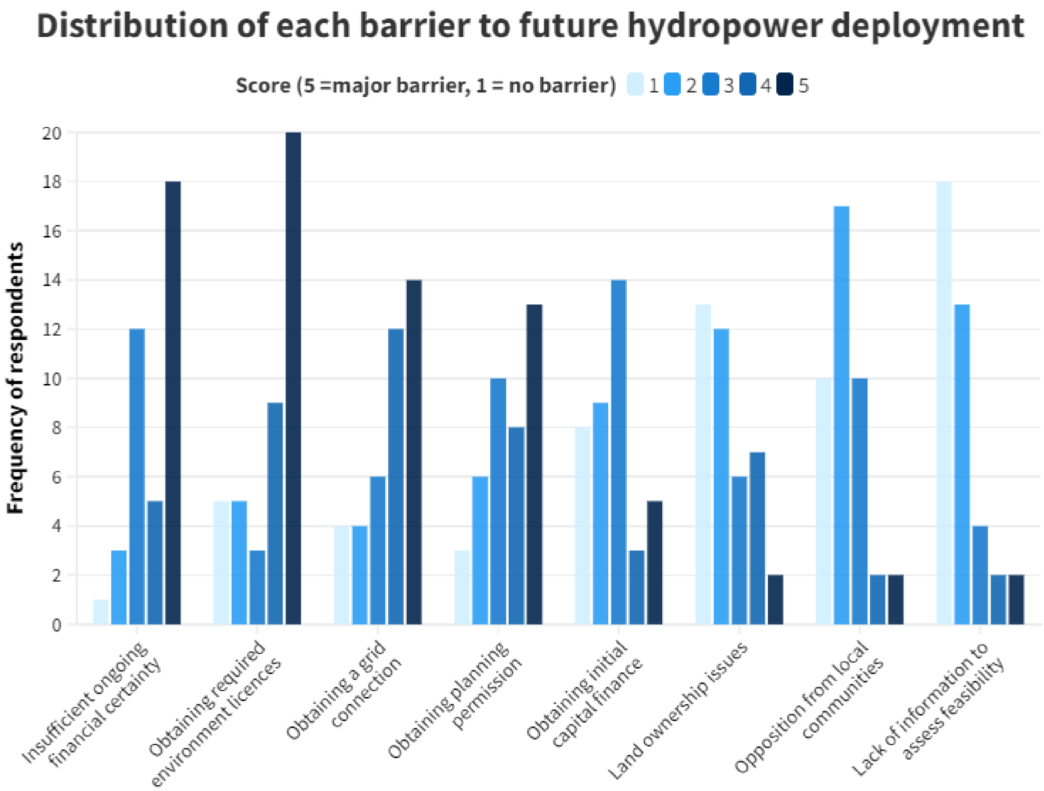


Figure 34 – Chart to show the distribution of scores received for each barrier to further hydropower deployment.

Analysing the results in more detail, the barriers can be shown by their score distribution rather than their average. This chart shows that some factors demonstrate more of a skew than others. For example, the barrier 'obtaining required environment licences' had more answers rated 5, 2 and 1 than 'ongoing financial uncertainty'. This means that with similar average scores, the financial barriers would seem to be more constant across the respondents' varying attributes (i.e., geography or organisation size) than environmental consents.

The responses were split into the averages by the devolved nation in which the respondent is located (based on their answer in the previous section of questions to see if they had any knowledge of a specific geographical area). Here it can be clearly seen that the Environment Agency in England scores much higher as a barrier to hydropower than its counterparts in Wales, Scotland and Northern Ireland. Conversely, obtaining a grid connection appears to be less of a barrier in England than the other nations.

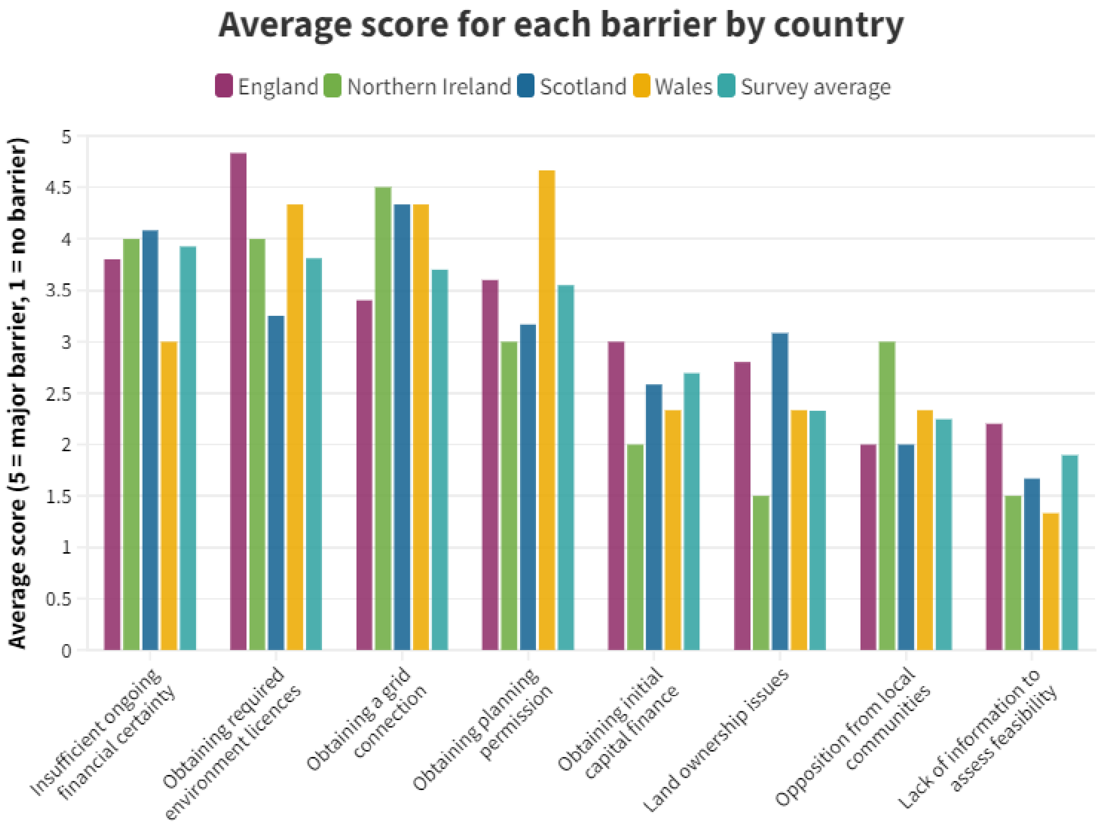


Figure 35 - Chart to show the average score received for each barrier to further hydropower deployment in different countries of the UK.

Although the EA received the most comments suggesting their policies were a perceived barrier to further hydropower development, DNOs were also criticised for "regularly applying unrealistic assumptions to their assessments" and for being slow to upgrade their networks, with one comment (referring to 132 kV reinforcement works in Scotland) stating "essential grid upgrade works need to be fast tracked. It cannot take 8+ years for a required upgrade to get approval." Other issues not explicitly covered by the survey options but raised in the free text answers included Brexit related supply chain problems, lack of consistency around business rates and the listed status of many historical mills and weirs which increases the complexity of the planning process.

Section 6: Discussion

From the dataset created for this report, it is estimated as of 2022, there is 2045 MW of capacity of installed hydropower in the UK. If the hydropower sector was to have a target of providing 1.5% of the electrical generation in 2050, it would need to increase this capacity closer to 3000 MW, an increase of nearly 1000 MW (a 50% increase) over existing installations.

If the UK was to target an increase of hydropower capacity by 2050 it would need to consider:

1. Whether the UK has an underlying hydropower resource to attempt the increase
2. Whether the sector and supply chain are supportive of and capable of delivering the increase over the timeframe
3. The advantages and disadvantages of having an increase of hydropower generation as part of the UK's net-zero electrical generation portfolio?

Does the UK have a hydropower resource to attempt an increase in hydropower generation of 1000 MW?

Analysing the previous studies and accounting for the schemes deployed since 2009/10 gives a mid-level bound of the estimate of remaining hydropower potential capacity in the UK (excluding Northern Ireland) at 1575 MW. This is just above the upper limit of 1550 MW quoted by BEIS in 2013. The lower bound calculated from the same method, of subtracting the installed capacities since 2010 from the lower limit of the resource assessments, would be 556 MW. Moreover, the upper bound from this approach would be 2594 MW. When added to the existing 2045 MW of hydropower capacity, the three scenarios result in a total lower, mid-level and higher hydropower capacity estimates for the UK of 2601 MW, 3620 MW and 4639 MW respectively. These are summarised in Figure 36 (with the 3000 MW target and historical cumulative installation capacity for reference) and in the bullet points below:

- The lower bound estimate for the remaining UK hydropower resource is 556 MW which leads to a total achievable capacity of 2601 MW
- The mid-level estimate for the remaining UK hydropower resource is 1575 MW which leads to a total achievable capacity of 3620 MW
- The higher bound estimate for the remaining UK hydropower resource is 2594 MW which leads to a total achievable capacity of 4639 MW

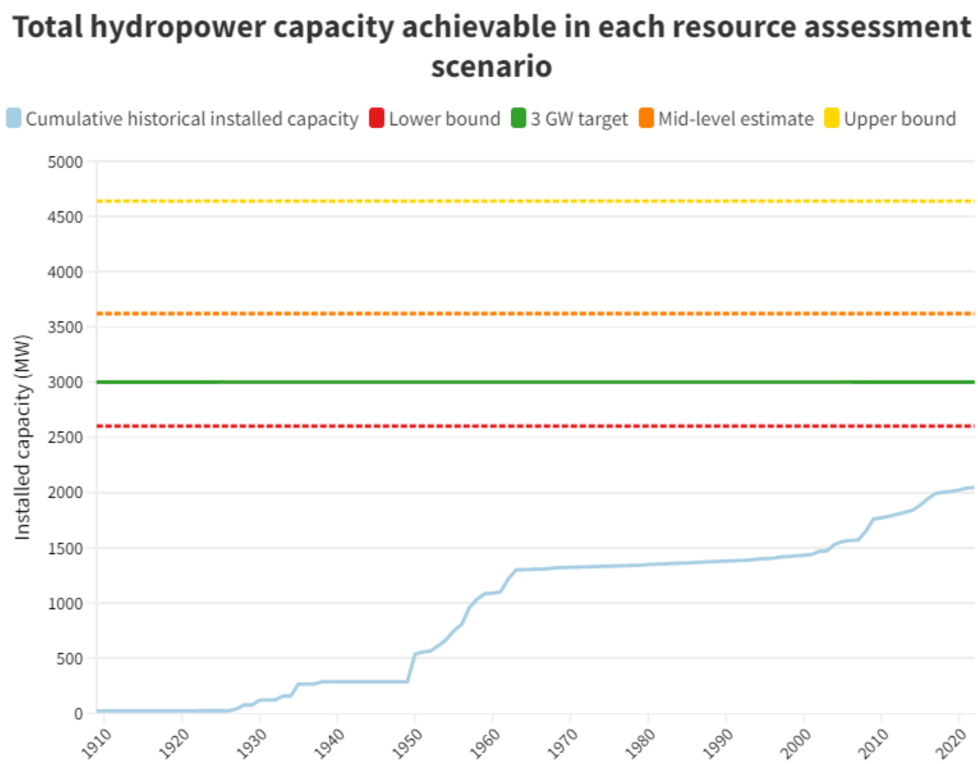


Figure 36 – Chart to show the upper bound (yellow dotted line), mid-level (amber dotted line) and lower bound (red dotted line) estimates for the total achievable hydropower capacity in the UK based on the updated analysis of the resource assessments in section 3. These are shown against the historical cumulative installed capacity (solid blue line) and 3000 MW target (solid green line) prescribed by this report.

On initial observation of this chart, it could be argued that given such a higher technically feasible potential, that a total of 3000 MW is too modest a goal. However, the upper limits (and to some extent the mid-level estimate) do not account for possible economic barriers to a site's development and other issues such as the environmental sensitivity of a location or viability of obtaining a grid connection. The 3000 MW target is therefore felt to be a sensible, pragmatic approach which recognises there are a number of limits to the development of hydropower; for example, of the need to preserve river habitats that will make the cost of various schemes unviable.

Are the sector and supply chains supportive and capable of delivering the increase over the timeframe?

The predominant methodology to assess the sector's appetite for additional development was the survey in Section 5. This analysis was carried out by presenting three scenarios, in which developers of hydropower schemes would be guaranteed £120/MWh, £140/MWh and £160/MWh for 15 years. From the sample of the sector which engaged with the survey (436 schemes, which is approximately 25% of those in the UK), it was found there is a strong appetite to build more hydropower installations given a favourable economic and regulatory climate. It would be logical (although subject to uncertainty) to assume that these motivations are similar across the rest of the sector, hence the extrapolation of the data from Table 7 to Table 8 to reach the following conclusions is provided with some degree of caution:

- At £120/MWh, 117 MW of self-assessed capacity was able to be built by survey respondents, extrapolating to 470 MW for the UK
- At £140/MWh, 218 MW of self-assessed capacity was able to be built by survey respondents, extrapolating to 1430 MW for the UK
- At £160/MWh, 405 MW of self-assessed capacity was able to be built by survey respondents, extrapolating to 2900 MW for the UK

- The survey also identified 48 MW of expandable existing hydropower schemes and 19 MW of 'shovel ready' projects which could be incorporated as a component into these larger estimates.

Interestingly, these figures are broadly consistent with the previous resource assessments and the levels of additional capacity (470 MW vs 556 MW, 1430 MW vs 1575 MW and 2900 MW vs 2594 MW, for the lower, middle and upper most favourable scenarios respectively). These comparisons are shown in Figure 37. This could just be a coincidence or, in the view of this report, a validation of the survey's methodology for producing a sensible upper, middle and lower estimate of the remaining hydropower potential capacity in the UK. Nevertheless, the target of 1 GW additional capacity is felt to be a more realistic for further deployment for UK hydropower, which is also consistent with the mid ranges of the previous resource assessment and survey answers for the mid-level of guaranteed revenue scenario. This is considered a practical goal due to some the barriers to development such viable grid connections which might not have been numerically captured by the survey and allowing for some sample bias (there is the possibility that survey respondents were either over generous of their estimate or more optimistic than the sector as a whole).

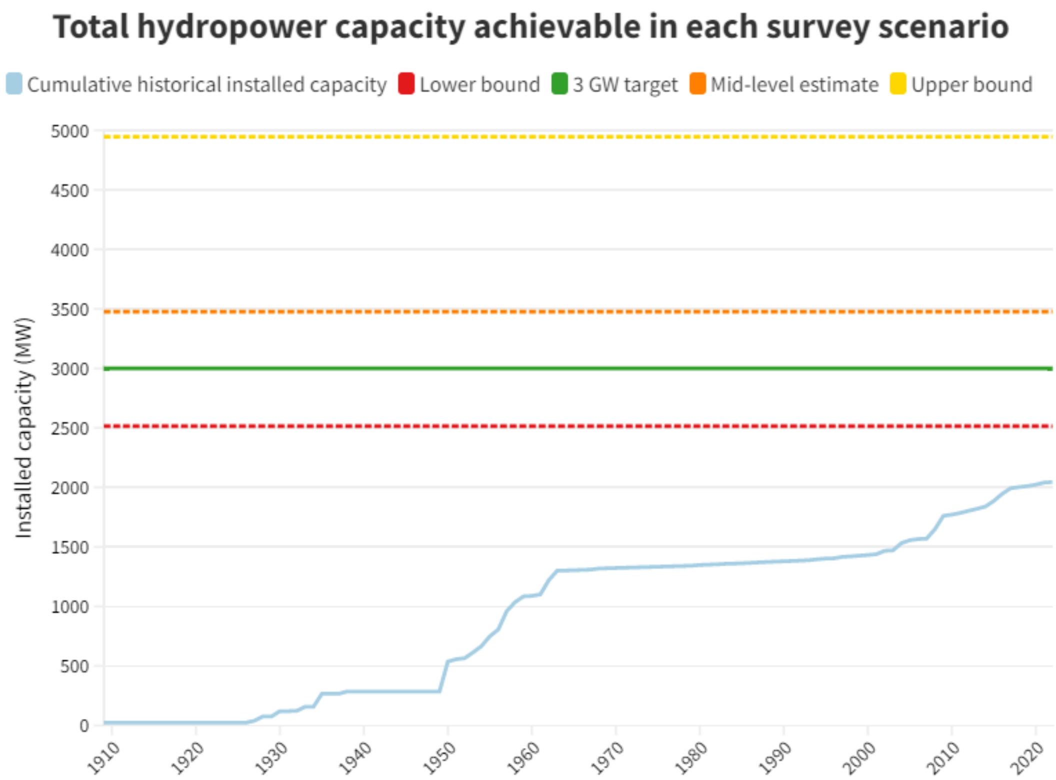


Figure 37 - Chart to show the upper bound (yellow dotted lines), mid-level (amber dotted lines) and lower bound (red dotted lines) estimates for the total achievable hydropower capacity in the UK based on the extrapolated results from the survey in section 5. These are shown against the historical cumulative installed capacity (solid blue line) and 3000 MW target (solid green line) prescribed by this report.

In light of increased volatility of the wholesale electricity price, it is felt unlikely that long term (15 year plus) power purchase agreements with larger electrical customers would be negotiated at an index linked flat rate. Therefore, in order to bring about a guaranteed revenue, two policy levers could be considered: a Contracts for Difference[54] style arrangement or a modification of the Smart Export Guarantee[55].

[54] https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference

[55] https://www.ofgem.gov.uk/environmental-and-social-schemes/smart-export-guarantee-seg

Costs of hydropower installation

During the project timeframe (May to August 2022) a number of hydropower developers were asked to define a range of costs to install and commission hydropower in the UK. These ranged from £4500 per kW for larger schemes to £7000 per kW for smaller schemes.

These values are higher than the range of costs published by the International Renewable Energy Agency in 2021 in the report 'Renewable Power Generation Costs in 2021'[56]. These are shown in Table 10 in the original USD values and converted to GBP using the ONS exchange rate value for 2021.

Given the high levels of uncertainty around average values across a geographical area of 'Europe' and over a longer timeframe from 2016 – 2021, the estimates from the UK developers of between £4500 and £7000 per kW were used for further analysis.

Table 10 - IRENA 2016 - 2021 values for small hydro installation costs per kW in Europe

	From IRENA 2021 USD / kW	USD to GBP exchange rate for 2021[57]	GBP using 2021 exchange rate
5th percentile	$ 1982	1.3757	£ 1440
Weighted average	$ 3492	1.3757	£ 2538
95th percentile	$ 7655	1.3757	£ 5564

Using the UK sector specific estimates from developers of £4500 (larger schemes) to £7000 (smaller schemes) for the cost to install and commission hydropower schemes and a simple payback analysis (the most generous financial condition without net present value calculations). Table 11 shows values from a simple payback timeframe for each level of 'guaranteed' 15-year price support of £120, £140 and £160 per MWh. The load factor has been taken to be an average 40% to derive the annual generated output.

Table 11 – Simplified payback calculations for a 100 kW and 1 MW hydropower scheme based on estimated costs of development and the three funding scenarios suggested in the survey. Only the least generous guaranteed 15-year price for 100 kW scale schemes does not achieve a payback period of less than 15 years.

Guaranteed 15-year price	***1 MW payback period (@£4500 per kW cost)***	***100 kW payback period (@£7000 per kW cost)***
£120 / MWh	10.7 years	16.7 years*
£140 / MWh	9.2 years	14.3 years
£160 / MWh	8.0 years	12.5 years

As an indicative comparison, the round 4 Contracts for Difference results in the UK[58] in December 2021 had a clearing price for Tidal Stream of £178.54/MWh, a price at which the survey shows the conventional UK hydro sector could be not only resuscitated but revitalised. These arrangements can be mutually beneficial to the treasury and energy developers as they mitigate the inherent risk of a project which would otherwise be subject to the volatility of revenues over the long-term based on variable wholesale electricity prices, whilst also resulting in money being transferred back to the treasury when prices are higher than strike price agreed in the contract. Thus, including hydropower

[56] https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

[57] https://www.ons.gov.uk/economy/nationalaccounts/balanceofpayments/timeseries/auss/mret

[58] https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-4-results

generation in future rounds of Contracts for Difference agreements could help the sector with a bankable policy framework to be viable. Competitive bidding into a ringfenced hydro CfD would help to keep the costs down within the sector. An increase in the Smart Export Guarantee from its current typically offered rate of less than £60 / MWh[59] could be another way to stimulate the sector. These suggested policies would have similar impacts in addressing the issue of lack of ongoing financial certainty prohibiting the growth of the sector, although a Contract for Difference system could be superior in terms of policy that allows more favourable rates from lenders.

An area that could also be considered within either of these schemes is to provide a differentiated level of support depending on the time of year. It is clear the UK's electrical demand will increase disproportionately over the winter when major parts of the space heating demand is electrified. It therefore may make sense to incentivise generation to generate more in the winter than in the summer, e.g., for hydropower schemes to be oversized in comparison to historical schemes, so they can generate more in the winter (when the resource is greater) than in the summer. This oversizing also makes the most of the expected change in rainfall patterns from climate change, with a greater amount of rainfall in the winter.

From Figure 8 in Section 3, it can be observed from considering the area under the curve, that during the FiT era, the majority of the overall installed capacity comes from the relatively larger (> 100 kW) installations. Notwithstanding the clustering at the boundaries due to more generous FiT generation payments, this means it is reasonable to assume a future deployment scenario would follow a similar exponential decay type distribution, where the bulk of the overall installed capacity is provided by the bigger schemes. This characteristic is also supported by the 2008 Scotland report, in which 72% of the overall capacity of the most financially viable schemes was from sites with a capacity from 500 kW to 5 MW. Therefore, using the smaller figure of £4.5 million per MW installed, reflecting the tendency towards of the majority installed capacity to come from sites of the order of this size, to build the headline 1 GW additional hydropower target can be estimated to cost £4.5 billion.

This estimate comes with a degree of uncertainty, as the cost of a hydropower scheme will vary based on size and location, whether there will be more of a wide scale uptake of pico/micro hydro in the future and whether gaining consents (which can make up a significant amount of the initial costs of smaller schemes) are subjected to reforms. Despite these factors, the predicted cost per MW installed is broadly aligned for values published in 2015 and 2018 by Renewables First[60] and the Renewable Energy Hub[61] respectively, and the IRENA values published in Table 10. To account for all these unknowns, the total capital expenditure is estimated to be in the range between £4.5 billion and £6 billion.

What are the benefits of having an increase of hydropower generation as part of the UK's net-zero electricity system?

Although the UK government's preferred options for low-carbon generation centre around offshore wind, nuclear, solar and biomass, there would seem to be continued benefits of having hydropower generation within the UK as part of its overall electrical generation portfolio. (Since the North Sea Link 1400 MW high-voltage direct current interconnector opened in 2021, the UK has been able to access to hydropower generation located in Norway).

[59] https://www.renewableenergyhub.co.uk/blog/the-smart-export-guarantee-in-2022/

[60] https://www.renewablesfirst.co.uk/hydropower/hydropower-learning-centre/how-much-do-hydropower-systems-cost-to-build/

[61] https://www.renewableenergyhub.co.uk/main/hydroelectricity-information/costs-associated-with-hydroelectricity/

An area of benefit in comparison to other generation technologies (fossil fuels in particular) is in the number of jobs created in the supply chain. A 2022 report from the UK Energy Research Centre[62] finds that the average number of gross jobs created by small hydro is 9000 for manufacturing and 16,000 for construction and installation for 1 GW of capacity. If the target of an additional 1 GW of hydropower capacity was installed, then with the values from the UKERC report – this would lead to an average of 25,000 gross jobs, with an expectation that the majority of these would be located within the UK.

Other benefits include hydropower generation having:

- a renewable resource that is harvested within the territorial boundaries of the UK, thus benefitting security of supply
- a resource that is higher in winter than in summer, which is therefore seasonally well matched to an increased electrical demand expected from the electrification of part of the UK's heat demand
- a supply chain that is ready to deliver an increased amount of generation (see survey in Section 5) with an appropriate policy landscape
- a typically smaller and more sustainable energy and carbon payback period than other low carbon technologies
- the use of local materials and labour (often more so than other forms of renewable power which can rely on imported steel turbines or silicon modules)
- typically, 70% of the cost of a new hydropower scheme is in civil construction which is procured locally
- the hydropower sector employed 7,400 people in the UK in 2013 according to BEIS[63], so a reinvigoration of the sector would boost the number of high-skilled jobs, especially in rural areas
- opportunities to grow the community energy sector (Community Energy England estimated the UK had 12 MW of community-owned hydropower schemes in 2022[64])
- a higher load factor than solar PV (by a factor of 3) and comparable to that of offshore wind at 35.5%
- improved co-benefits from water flow management and flood defence in certain locations

[62] Hanna, R. Heptonstall, P and Gross, R. Green job creation, quality and skills: A review of the evidence on low carbon energy. 2022. https://doi.org/10.5286/ukerc.edc.000953

[63] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416240/bis-15-206-size-and-performance-of-uk-low-carbon-economy.pdf

[64] https://communityenergyengland.org/files/document/626/1655376945_CommunityEnergyStateoftheSectorUKReport2022.pdf

Conclusions

It is the view from the evidence presented in this report, that hydropower should be viewed as an increasingly useful element of the UKs diversified electrical generation portfolio. It has provided the UK with low-carbon electricity for a century, based on a renewable resource that is harvested within the national boundaries of the UK, and will continue to do so. Although the levels of support such as a Contract for Difference strike price in the range of £160 per MWh are more expensive than other technologies such as onshore and offshore wind, there are benefits from hydropower such as its longevity that provide additional value. In addition, it contributes to a diverse portfolio of low-carbon generation, and its contribution to energy security by being available for supply in times of potential low wind and solar output.

Hydropower has served the UK incredibly well for over a century as a renewable electricity resource, saving 160 million tonnes of CO_2eq through the avoided combustion of fossil fuels. The sector shows it is able to continue to innovate through the co-location of hydropower schemes with battery storage and the development of pico-scale hydropower systems. Analysis of previously published UK resource assessments and the creation of a dataset containing the location, capacity and installation of UK hydropower schemes has allowed updated estimates on the remaining feasible potential capacity to be made with a mid-level estimate of 1.6 GW that is reduced to 1 GW as a conservative target. These predictions were supplemented by a survey which showed that there is a strong appetite for additional hydropower development with supply chains from survey participants alone able to deliver over 400 MW of projects by 2030 in an environment with supportive policies. Furthermore, the survey responses identified the main barriers to further hydropower deployment in the present climate as a lack of ongoing financial certainty as well as difficulty in obtaining environmental licences, grid connections and planning permission. These challenges can be addressed, and the sector reinvigorated by implementing the following recommendations:

1. The UK should target a 50% increase in its hydropower capacity of 1 GW from its existing 2 GW -> 3 GW, so that the sector provides a 1.5% share of the annual electrical demand in a net-zero energy system in 2050.

2. The department for Business Energy and Industrial Strategy should continue to engage with the British Hydropower Association on the relative merits of different funding mechanisms to incentivise 1 GW of additional deployment. For example, to consider Contracts for Difference type agreements vs Smart Energy Guarantees vs other options. The survey of BHA members as part of this report supports the level of certainty provided through a bankable policy such as a Contract for Difference, is a more favourable approach than an upfront grant. Although, upfront grants could be more favourable for small schemes, to help offset some of the initial costs such as consenting and electrical grid connections

3. Consideration should be given to a more coordinated approach to hydropower projects for planning and consenting and a greater sharing of best practice between the devolved environment agencies. Consideration should be given to more proportionate levels of consenting fees which do not disproportionally reduce investment in the sector at the smaller scale of development. Consideration should be given to more proportionate levels of valuation office business rates which do not disproportionally reduce investment at certain capacity levels, and a greater sharing of best practices between the different valuation offices across the UK

4. There should be a single publicly available dataset for all hydropower installations in the UK that defines a unique reference number for each installation. This could be utilised by BEIS, Ofgem, Environment Agencies and Valuation Offices throughout the UK to link this unique reference number to different data. It would be useful if this publicly available dataset had at a minimum: the capacity of the installation, the location of the installation and the date of commissioning. This would help to manage the problem of slightly (or even very different) hydropower sitenames that exist between different public bodies

5. A new detailed resource and techno-economic hydropower assessment should be commissioned and co-ordinated by BEIS with input from relevant bodies from the Scottish Government, Welsh Parliament and Northern Ireland Assembly. This would make use of up-to-date LIDAR data, weather data (with consideration of climate change impacts) and other assumptions to reflect advances in hydropower system designs, the wider electrical generation portfolio, electrical network connections and the challenges of reaching net-zero. The study could also consider low-head and pico-micro sized installations

Appendix A: Methodology to geolocate existing hydro installations

Although there are various datasets that have details of hydropower installations, no single source of publicly available data with a unique hydropower reference number that could be used to tie other data against such as geolocation data was found. A unique hydropower installation reference number would be useful to help reduce the risk of duplicate sites appearing when different datasets are combined. The method described here created a unique hydropower reference number for hydro installations that were deemed to be separate. This could form the basis of a reference system that could be of help to the sector, and to others such as regulators, energy system modellers and electrical system network operators. The method detailed here has was not able to capture when a particular installation was decommissioned or upgraded. Thus, although the data is felt to be robust and an improvement on existing publicly available datasets, it was not possible to manually cross check all data with between data sources.

There were four main areas of data that the project needed to be able to analyse the capacity of the hydropower installations that had been built, when they had been built and where. Datasets had other useful data, but the most important if they were available were:

- the site name, helpful to cross check between different datasets
- the date of commissioning or operation, helpful to determine the rate of deployment and as a cross check for sites with similar names
- the capacity, helpful to determine the rate of deployment and as a cross check for sites with similar names
- the location of the installation, helpful to determine the areas of deployment and compare to previous studies

The main sources of data for site names, capacities, commissioning dates and locational data were from the publicly available datasets from the Office of Gas and Electrical Markets, the Department for Business, Energy and Industrial Strategy. Non-publicly available data was also requested from the Environment Agencies of England, Scotland, Wales and Northern Ireland and from BEIS.

Data

Office for Gas and Electrical Markets (Ofgem) data

There were two main sources of publicly available data from Ofgem

1) the 'Accredited Station' data from the REGO, RO and CCL datasets[65] is a rich source of data with site names, capacity and typically a postcode as part of a site address
2) the Feed in Tariff data, has capacity and commissioning date data, but only partial postcode and Lower Super Output Area as a location. The publicly available data unfortunately has no site names, but a direct request to the information team allowed site names to be shared under conditions.

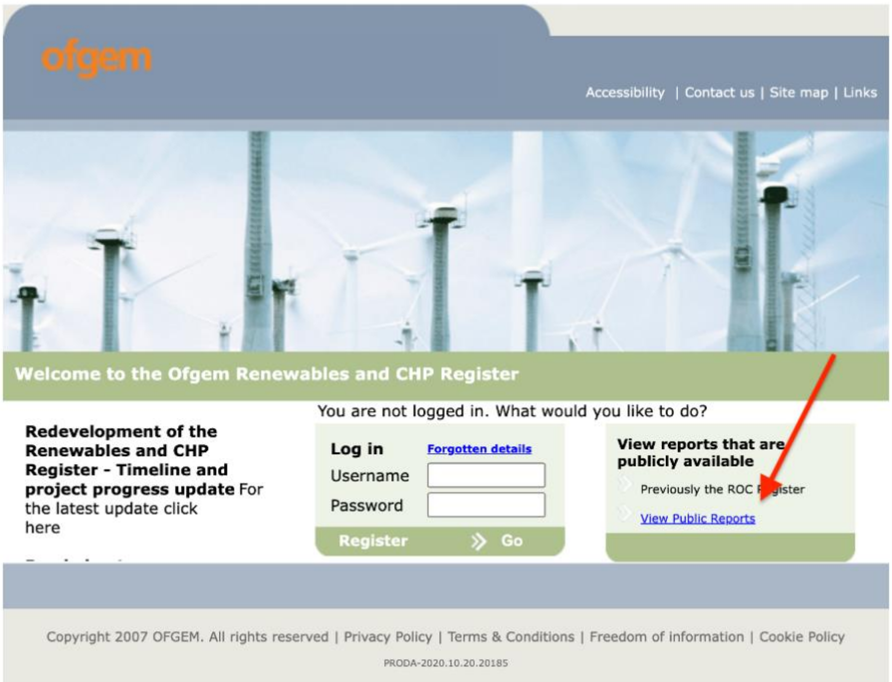
For the methodology, the Ofgem Accredited Station from the REGO, RO and CCL data was useful, but the publicly available Feed in Tariff data was less so, as there was no site name data to provide the basis to text match between datasets. However, a direct request to Ofgem provided the site names that then allowed a comparison and linkage between datasets to take place.

[65] https://renewablesandchp.ofgem.gov.uk/Default.aspx

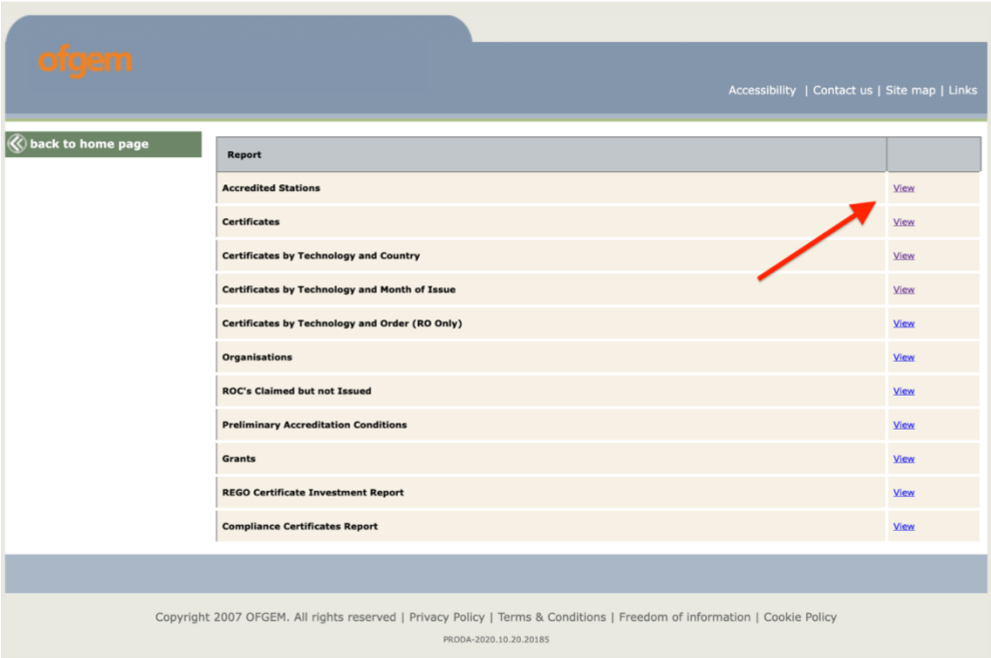
Accredited Stations data for REGO RO and CCL schemes (publicly available data)

In a browser go to the 'Ofgem Renewables and CHP' register at https://renewablesandchp.ofgem.gov.uk/Default.aspx

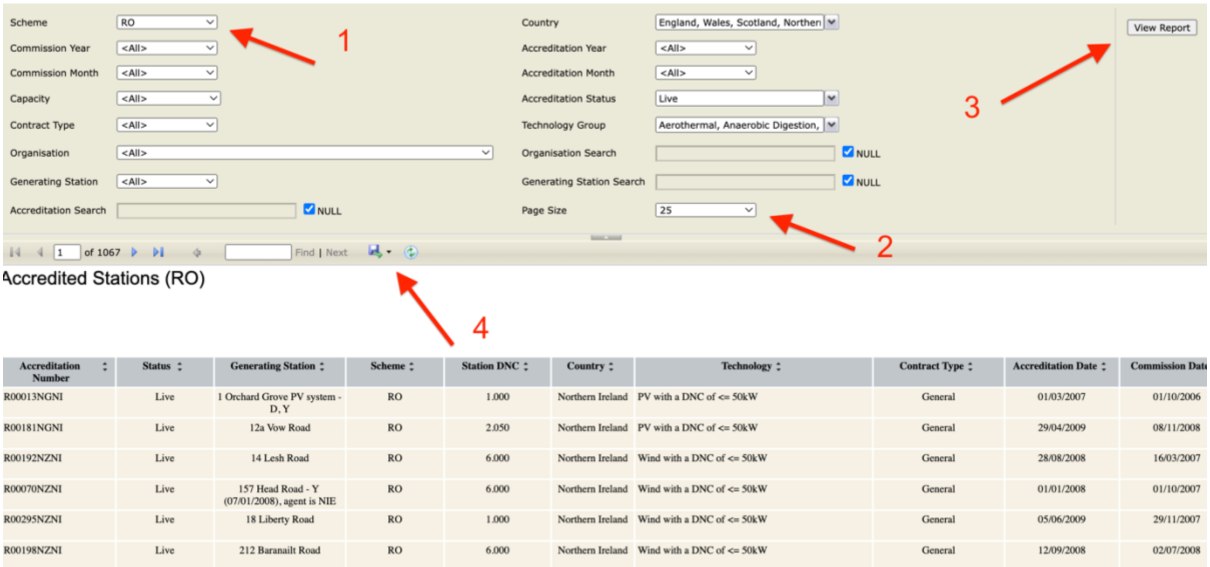
click 'View Public Reports'



Then click View for Accredited Stations



1. Then choose the scheme RO, REGO, CCL or even CHP (although there are no hydro installations under CHP, confirmed after download)
2. Choose a page size (the choice does not matter as all the data will be downloaded)
3. Click View Report and wait
4. Once the table at the bottom appears – the data can be downloaded by clicking the floppy disk icon. The group at the University of Birmingham uses python – so the file type chosen for saving was csv (comma separated values) to make further analysis easier



The previous steps were repeated to provide a csv file download for the REGO scheme, RO scheme, the CCL scheme and the CHP scheme (although the CHP scheme was discounted after confirming there were no hydro installations found in the CHP scheme data).

The Technology Name column in each csv file (REGO, RO, CCL) was filtered to keep values that contained the text 'hydro', then all three were joined into a single file.

GeneratorID	Status Name	Generator Name	Scheme Name	Capacity	Country	Technology Name
G00473HYSC	Live	Sloy Power Station - G00473HYSC	REGO	152500	Scotland	Hydro

Output Type	Accreditation Date	Commission Date	textbox6	textbox61	textbox65
General	29/03/2008	29/03/2008	SSE Generation Ltd	Scottish Hydro Electric plc Inveralmond House 200 Dunkeld Road Perth PH1 3AQ Scotland	Inveruglas By Arrochar Argyll G83 7DP Scotland

The site name address column (textbox61) was parsed to split the address data into separate parts of an address and a postcode. The postcode was checked against all 1.7 million UK postcodes from the Code-Point Open dataset[66] (OS code-point_open_03.02 dataset version number: 2022.2.0) and if it existed it was kept – and if not – it was not considered a valid postcode and was discounted as a typo or another error. This was felt to be a more robust method than checking if the alphanumeric format of a postcode was in the same format as expected of a postcode. If a valid postcode was available, then

[66] https://data.gov.uk/dataset/c1e0176d-59fb-4a8c-92c9-c8b376a80687/code-point-open added 05 November 2021

the x and y coordinates of that postcode were taken from the OS code-point data. This was thought to be the centroid coordinates of the postcode.

Table 12 – Ofgem Accredited Stations details

	REGO[67]	RO	CCL	Total
Number of rows with TechnologyName column containing the text 'hydro'	1269	315	11	1595
Valid postcode in column (textbox61)	774	168	0	942
MW of capacity	1881 MW	724 MW	9 MW	2614 MW
MW of capacity with valid postcode	1513 MW	571 MW	0 MW	2084 MW

The number of hydropower installations detailed in the REGO, RO and CCL datasets was 1597 in total, but a significant amount of these were expected to be duplicates between the RO and REGO datasets. These duplicates were combined in a later step.

An intermediate file was created from the REGO dataset that was filtered to hydropower capacities above 50 kW; this was a file of 863 rows after 3 hydropower installations with a TechnologyName of "Filled storage hydro (REGO code = HP)" had been removed (where 'GeneratorID' was G00003HPSC, G00002HPSC or G00001HPNI). This was to test out a number of manual approaches and the time it would take to add more precise locational data than the postcode data, or to try to fill in the blank values for non-valid postcodes.

It was found that using satellite data was the slowest manually and using Ordnance Survey Roam or QGIS with postcode boundaries loaded could speed up the finding of a location. In most cases, the aim was to locate the turbine building, or close to it. It was found that using the full colour base map of Ordnance Survey often had text that stated 'Power Station' as a label that became visible at high zoom levels. Of the 863, 70 were manually inspected and the location data improved from the postcode centroid, however, the speed at which this could be manually attempted for all 863 installations was not felt to be appropriate for the project.

So, other types of location data for hydropower installations were researched and the web scraped SEPA data in particular proved useful and tractable in terms of comparing to the REGO, RO and CCL Accredited Stations data.

Ofgem Feed in Tariff data (publicly available data)

The Ofgem Feed in Tariff data that was publicly available from https://www.ofgem.gov.uk/publications/feed-tariff-installation-report-30-april-2022 was downloaded and parsed into a single file. This is a rich source of data, has values for installed and declared net capacities, has an application date and commissioning date, and a partial postcode and Lower Super Output Area in many cases. It also has the technology type and the feed-in-tariff code and description.

Unfortunately, the public data does not contain details of site names – so a direct request to the Information Rights Team at Ofgem was submitted with an explanation of the BHA project and the benefit of having site names (where available) to cross check against other data. The information.rights@ofgem.gov.uk were able to consider the request and provide site name data for the project under conditions.

[67] Cruachan Hydro Natural Run-off (440 MW) and Foyers Natural Run Off - G01027HYSC (300 MW) removed

Ofgem direct request (non-publicly available data) to information.rights@ofgem.gov.uk

These data only contained data for the hydro technology type, still only had a partial postcode or Lower Super Output Area geolocation where available, but importantly now did have a site name. There were 1267 entries, and 1250 of these had a site name. Blanks for site names were either because of a lack of data or due to personal information (thought to be names of individuals) that were redacted due to GDPR concerns. Nonetheless, the 1250 site names allowed a comparison against other datasets, as well as the commissioning date and capacity data and allowed much of the FiT data to be linked to other data.

Department for Business, Energy and Industrial Strategy (BEIS) data

Renewable Energy Planning Database (publicly available data)

The dataset can be downloaded from:

https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract

The data for the project downloaded was the quarterly dataset to December 2021 titled 'renewable-energy-planning-database-q4-december-2021.xlsx'

Filtering the 'Technology Type' column to 'Large Hydro' and 'Small Hydro' limits the number of rows in the spreadsheet to 172 entries. Of these 94 were 'Operational' with a combined capacity of 619.5 MW or 'Under construction' 9 entries with a combined capacity of 9 MW. Helpfully, this dataset had x-y coordinates for each entry, a site name, and a capacity amongst other columns.

The x-y coordinates were in the Easting Northing format. A sample of x-y coordinates were checked, and in some cases the coordinates were accurate to the impoundment or hydropower building, in others it was nearby, and in some cases, it was in the centre of a town with no discernible connection to a hydropower installation. It was assumed however that in most cases the x-y coordinates were more accurate than a postcode or Lower Super Output Area centroid, and thus would be used in preference for geolocation data.

Major Power Producers (non-publicly available data)

The Major Power Producers spreadsheet was shared by William Spry of the BEIS Analysis Directorate for use in the project. It has the following columns of data

Site Name	Project Name	Survey	ROC Ref	Capacity (MW)	Region

Country	x	y	NUTS1	NUTS2	NUTS3	LAU1	District

Of interest are the Site Name, ROC Ref, Capacity, x and y coordinates. The ROC Ref allowed a direct link to data in Ofgem's Accredited Stations for the RO download. The x-y coordinates were in the Easting Northing format, and looked to be more accurate than postcode centroids, e.g., a sample of coordinates were placed on or very near the dam our outlet of the hydropower installation. For this reason, the MPP coordinate data was seen as being preferable to the Ofgem Accredited Stations postcode derived x-y coordinates.

There were 328 sites in the BEIS MPP dataset that totalled 1670.3 MW of capacity

Scottish Environmental Protection Agency (SEPA) data

SEPA suffered a data breach in 2020[68] which has impacted their ability to provide the project useful levels of data under a Freedom of Information request. Nonetheless, two sources of publicly available SEPA data with location coordinates were found elsewhere that were found to be helpful.

[68] https://www.audit-scotland.gov.uk/news/sepa-continues-to-count-cost-of-cyber-attack#:~:text=The%20Scottish%20Environment%20Protection%20Agency,s%20cyber%20defences%20were%20good.

SEPABNG (publicly available data)

This was found from through the https://spatialdata.gov.scot/ website under the search for 'Hydropower' which returned a single result shown on the screen grab shown in Figure 38.

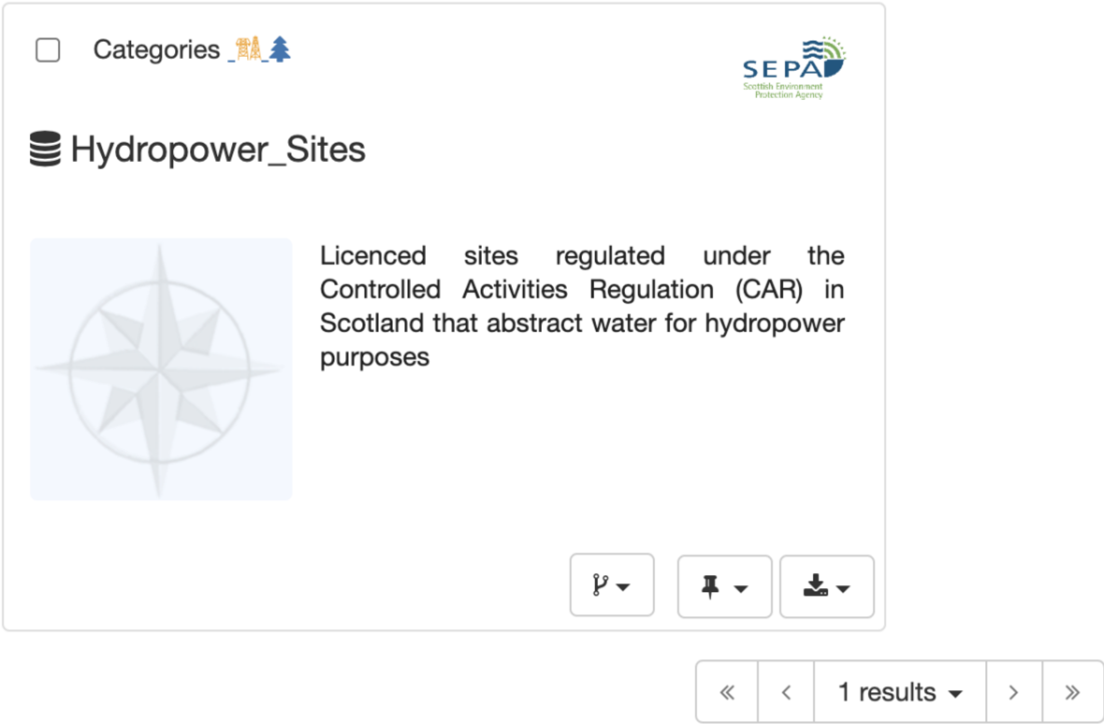
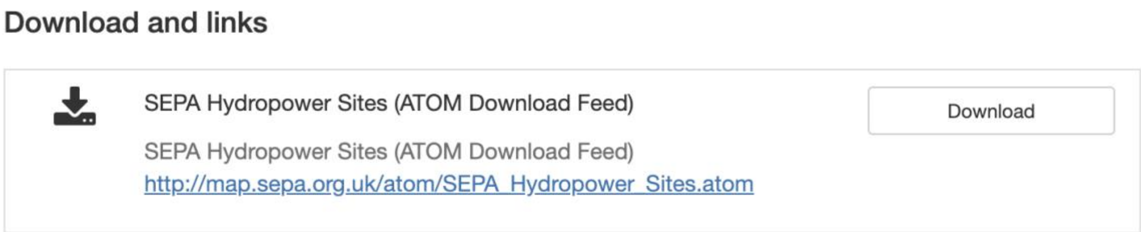


Figure 38 - Screengrab from https://spatialdata.gov.scot/

Clicking this link brings up:



And clicking the http://map.sepa.org.uk/atom/SEPA_Hydropower_Sites.atom link brings up a page of html code (which does not render in a Firefox browser, but show the html code instead)

Contained within the html code is the line:

```
<span><a
href="http://map.sepa.org.uk/atom/Data/SEPA_Hydropower_SITES_BNG_gpkg.zip">Z
ipped <b>GeoPackage</b> of SEPA Hydropower sites in Scotland in British
National Grid</a></span>
```

Which links to a geopackage file that can be downloaded and brought into QGIS (open-source geographic information system software) then exported as a comma separated file for further analysis and comparison with other data. The headers and first row of data are shown:

X	Y	OBJECTID	AUTH_ID	LIC_NO	SITE_NAME	LIC_STA_DA
254555	734995	44	10906	CAR/L/1011412	Breadalbane Section	01/04/2006

The X and Y coordinates were in the Easting Northing format, and looked to be more accurate than postcode centroids, e.g., a sample of coordinates were placed on or very near the dam our outlet of hydropower installations. Helpfully, the data had a site name, which allowed a comparison across to other data, and a link to the Controlled Activities Scotland Regulations (CAR licence). Unfortunately, the data does not contain capacity data.

There were 248 hydro locations detailed in the SEPA BNG data.

SEPA Compliance data for 2019 (publicly available data)

A search for a CAR licence found in the SEPA BNG data brought up a link to the webpage:

https://www2.sepa.org.uk/compliance/?ctl00_ContentPlaceHolder1_rgComplianceChangePage=35_2_0 which itself had a tab that linked to the map:

https://www2.sepa.org.uk/compliance/map.aspx shown in the screengrab in Figure 39

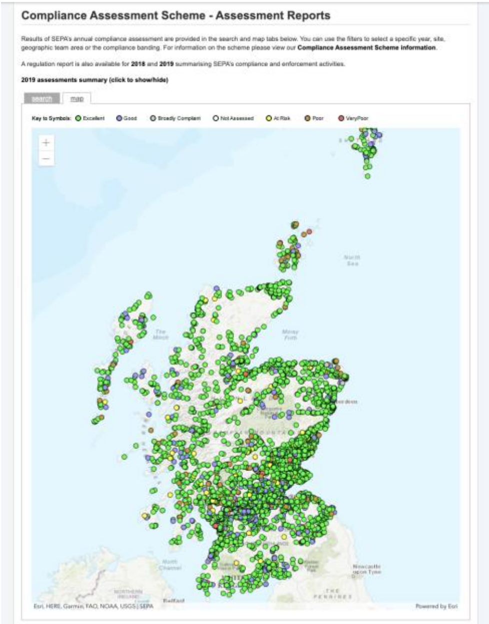


Figure 39 - Screengrab from https://www2.sepa.org.uk/compliance/map.aspx

This was an interactive map that is rendered in the browser and therefore usually has a set of data that is sent the browser in order for it to be rendered that can be analysed. A 1.8 Mb geojson datafile was found to be requested when the page was refreshed, which had a web address of https://forms.sepa.in/compliance.api/api/ComplianceGeoJson

This geojson file was parsed into a csv by copying into a text file, loading this into https://geojson.io/ and then saving as a csv

The csv contained compliance data for regimes other than CAR and for sectors other than 'Renewable Energy'. The csv was therefore filtered by the 'REGIME' column to the value 'CAR' and on the 'SECTOR' column to the value 'Renewable Energy' which gave a dataset with 291 entries. All the entries had a value of 2019 in the column 'YEAR'. The sepa compliance data had entries for LAT and LONG and also for the site name. Similar to the SepaBNG data, there was no capacity data.

This data was then outer-merged with the SepaBNG data on the CAR Licence value (in the SepaBNG this was the 'LIC_NO' column, in the sepa-compliance data it was the 'AUTHNO' column) to combine similar values into a single dataset. The combined dataset had 406 entries.

The x – y coordinate data for the sepa-compliance data was in latitude longitude from, and therefore was changed into Easting and Northing by using the code (after by using the geopandas package in python):

```
gdf = geopandas.GeoDataFrame(
   dfBHA,
```

```
  geometry=geopandas.points_from_xy(
    dfBHA['sepacomp_LONG'],
    dfBHA['sepacomp_LAT'])).set_crs(epsg=4326).to_crs(epsg=27700)
```

Environment Agency (EA) data

A freedom of information request was submitted to the Environment Agency, which returned a dataset under licence conditions that included a ‘Use Description’ column, a ‘Postcode’ column, a ‘Point Name’ column and grid reference column with coordinates in Easting and Northings. The ‘Use Description’ column was filtered to the value ‘Hydroelectric Power Generation’ which reduced the dataset from 40832 to 346 entries. The ‘Point Name’ column contained some site name data. The dataset had no capacity data.

Natural Resources Wales (NRW) data

A freedom of information request was submitted to National Resources Wales, which returned a dataset to April 2022 under licence conditions that included 2251 entries with a ‘Use Code & Description’ column, a ‘Postcode’ column, a ‘Site Name’ column and grid reference column with National Grid coordinates in Easting and Northings as well as the grid letters, e.g., SN, SH or SJ. The ‘Use Code & Description’ column was filtered to the value ‘240: Hydro-electric Power Generation - Very Low’ and this reduced the number to 651 entries. After consideration, the NRW data was not merged with other data as the ‘Site Name’ column only had values for 274 out of 651 entries with any text, and many of the rows had generic data that was not useful to match across to the site name text in other datasets. There were no values for capacity in the dataset.

Northern Ireland Environment Agency data

A direct data request was sent to the Northern Ireland Environment Agency that returned a spreadsheet with 124 rows of data. Of these 44 had a 'Status' of ‘Not Built’ , 5 were ‘Not Operational’ and 75 were ‘Operational’. There was detailed coordinates for the abstraction point and the discharge point (if available), which were in the Irish Grid coordinate system. There was no capacity data and no site name, although in just over half of the operational sites there was a company name. In addition, there was a river name in most cases. After consideration, the NI data was not merged with other data due to the lack of robust site names.

ELEXON time series data

Elexon time-series data is parsed and uploaded to https://doi.org/10.5281/zenodo.3884858. The original raw data is from www.elexonportal.co.uk/fuelhh. Details of the method to clean and prepare the raw data are in https://www.sciencedirect.com/science/article/pii/S2211467X21001280 The Elexon time series data provides a 30-minute aggregate power output for transmission connected fuel types that have a balancing mechanism code. Hydro is a fuel type within the data, and its values are used in section 4 to provide daily or sub-daily values.

Other data sources

Ordnance Survey data

The https://map.sepa.org.uk/ngrtool/ service was used to visually check how close coordinates might be to potential hydro installations, e.g., whether coordinates could be the centroids of postcodes or other geographical areas. When zooming in to the map for closer inspection, the words ‘Hydroelectric power station’ or ‘dam’ etc. could appear on the Ordnance Survey basemap e.g., for the coordinates ‘200562, 754823’. This could provide a basis for more automated location data searching by using the attribute strings of the OS Mastermap topography layer – but the licencing for this for the BHA project was not clarified during timeframe of the project. However, an email to OS directly revealed there were in the order of 350 locations with an attribute with the string ‘hydroelectric’ which is far less than the number of locations found in Great Britain from the other sources such as the feed-in-tariff and the Renewable Energy Planning Database. Thus, although helpful as a visual check step, there was no attempt to automate a cross linkage between the OS location data from Mastermap attributes and site data from other sources.

Kenny Hunter (non-public data)

Personal communication with Kenny Hunter. The data set curated by Kenny includes site names and in many cases a site address with a postcode. A sample was cross checked against FiT and REGO data, and the SEPA location data. The data was found to agree, and the locational data was better than postcode in the SEPA data. After consideration, this data was not merged with other data due to it being covered by other data.

Potential_sites_of_hydropower_opportunity_filtered (public data)

Download links from https://www.data.gov.uk/dataset/cda61957-f48b-4b75-b855-a18060302ed1/potential-sites-of-hydropower-opportunity links to 7 Mb zip file that can be directly downloaded from:

https://environment.data.gov.uk/portalstg/home/item.html?id=f0bec102512e49878f37d3b082f15358

Within the zip download there is a spreadsheet titled 'win-wins-EXTERNAL.xlsx' that has x and y coordinates and a Power column for 4195 rows of data. The power column totals to 448 MW but a data warning states 'There is not a high level of confidence in the power generation calculation. The power category takes account of this uncertainty.' There are no site names in this dataset, and it was not merged with other data.

Valuations office

Valuations office data was downloaded from individual Scottish Assessors web sites and the Valuations Office Agency for England and Wales. The England and Wales VOA data was available as a single download, whereas the Scottish assessors were not. There was a variation in how data was made available at different Scottish assessors.

The England and Wales data was found to be potentially useful for location data at a postcode level as there was detail identifying a category of 'HYDRO POWER STATION AND PREMISES'. After consideration, the data was not merged with other data due to the variation in accessing and parsing data from different Scottish assessors, and the benefit of the data in adding value to locational data. An interesting research question that was not attempted due to time, was the correlation between capacity (and therefore a potentially assumed output) and the business rates that are applicable. Business rates are based on a number of factors, but some degree of correlation would be expected, and it could be informative to evidence the difference in business rates vs capacity in different parts of the Great Britain.

Gazette data

The Gazette is a potentially rich source of data using the 'all notices' search at:

https://www.thegazette.co.uk/all-notices

Hydropower data was found by detailing 'hydro' in the free text search and combining this with a filter of a 'Notice code' of '1803' Environmental protection. A sample of notices showed that there could be detailed abstraction and impoundment location data within the notice itself, or there was likely (depending on the notice) to be a link to a planning application that if found, would itself link to some sort of plan that could be viewed to provide location data. Although the submitted plans would seem to be a highly accurate basis for sourcing location data, the process to do so was challenging to automate. Thus, the data was not parsed and merged with other data, but it could be a useful source for cross checking location data manually.

Merging duplicate data

Python code was used to parse the following datasets into a single file:

7. REGO, RO and CCL data (publicly available data)
8. Renewable Energy Planning Database data (publicly available data)
9. Major Power Producers data from BEIS (non-public from direct communication)
10. SepaBNG and sepa compliance data (publicly available data)
11. Environment Agency data (non-public from direct communication)
12. Ofgem Feed in tariff data (non-public data from direct communication (similar to public data, but with site names))

The combined file had 4107 rows of which many were duplicate sites from different data sources. These required merging into a single site, whilst keeping the useful data from all sources merged into that single site. The combined file had additional columns, such as the source of the site name for that particular row. The initial parsing into the combined file used all the data listed above except the Ofgem FiT data, that was unavailable until much later in the project. This was sorted by the site name column and was used to provide a basis for manually tagging similar sitenames. When the Ofgem FiT data became available, it was merged into this existing combined file by inserting the data after a RO or REGO dataset row that had similar capacity and commissioning date. This meant that inconsistent site names were able to be more easily visually checked against the site names from RO and REGO as they were inserted next to the sites with similar capacities and dates of commissioning. A typical example of this can be seen in Table on the rows tagged as BHA0003 where the REGO site name was 'Aberbodcol' whereas the Ofgem FiT site name was 'Harris Aberbodcol Hydro', something that was easy to pick up visually, but is complex to code robustly using natural language processing techniques for a range of different edge cases. However, methods were investigated to provide an automatic and repeatable method of tagging the same hydropower installation from different sources (such as the use of the rapidfuzz python package to compare strings). However, given the timeframes of the project, the relatively low number of rows to be merged (4000+ rather than 100k+ for solar) and the thought that even if rows could be automatically matched, it was likely that a manual run-through would be need anyway to validate the process, it was decided to manually tag rows that were similar in terms of their site names, capacities and other data characteristics. Rows that were thought to be different from other rows were given their own unique hydro number.

Table 13 -sample set of rows and columns within the combined file.

Unique Hydro Number	Regoro Capacity	Ofgem fit Declared net capacity	Regoro Commission Date	Ofgem fit Commissioning date	Sitenames From All Sources	Site Name Source
BHA0001	14		01/11/2013		58 Lisdown Road	regoro
BHA0001	14		01/11/2013		58 Lisdown Road	regoro
BHA0002	200		22/03/2019		Abbeystead Hydro	regoro
BHA0002		200		22/03/2019	Abbeystead Hydro	ofgemFIT
BHA0002					Abbeystead Reservoir	ea
BHA0003	12		05/05/2015		Aberbodcoll	regoro
BHA0003		12		05/05/2015	Harris Aberbodcol Hydro	ofgemFIT
BHA0004	494		30/10/2015		Aberchalder Hydro Power Station	regoro
BHA0004		494		30/10/2015	Aberchalder Hydro Power Station	ofgemFIT

Table 4 shows a sample of the initial rows and columns of the combined file that had been sorted on the column 'Sitenames From All Sources' and had Ofgem FiT data inserted. Initially, the Unique Hydro Number was blank, but was filled in manually with increasing numerical values (the text 'BHA' was added at a later step using a python script). The sample is typical of the type of manual tagging and consideration, e.g., BHA0001 were very similar, but one was from the RO dataset, whereas the other was from the REGO dataset, so they were both tagged with the same number. BHA002, BHA003 and BHA004 have data from the REGO dataset and the FiT dataset, and although the capacity and commissioning date was the same, BHA0002 had a differing site name from the Environment Agency data, and BHA0002 had a differing site name from the Ofgem FiT data.

This merging of data from different datasets was an iterative process, involved manual steps, and was a method that could lead to errors, e.g., for hydropower installations that were upgraded or decommissioned, the original row of data could be left if not checked against a web search or more detailed information from a planning application. Unfortunately, there was not time to do this for more than a handful of cases. Nonetheless, the method and the dataset was felt to be robust enough for the basis of further analysis for the project.

However, the manual elements of the process were subject to the two areas of weakness where they are neither entirely repeatable (where different people may tag the dataset with slight differences) and it was not scalable to larger datasets.

Appendix B: Potential consideration for further hydrological assessment of the UK

Assumption	Future hydro resource assessment
Lower power output threshold	Could <25kW remote sites be more feasible with advances in storage and off-grid applications (e.g., EV charging)?
Minimum head height	Could advances in ultra-low-head hydro reduce this?
Financial viability	Could investors today consider longer payback periods and higher / more dynamic electricity prices?
Taxation	How has this changed and what does the future hold?
Financial support	What was the deployment during FIT and what could be the deployment in future with and without subsidy?
Plant efficiency	Could advancements in turbine efficiency increase this?
Flow rate used to determine power output	N/A
Grid connections	Could digitalisation of network data increase the accuracy of network modelling?
Environment agency	Could advances in turbine technology reduce the needs for licences?
Planning permissions	Could obligations on local authorities to comply with net zero targets increase the number of schemes accepted?
Other	N/A

Appendix C: The BHA 2022 survey

Page 1: Commissioned schemes

1. How many commissioned schemes do you operate?

2. What is the total installed capacity in kW of your commissioned schemes?

3. What is the total typical annual output in MWh of your commissioned schemes?

4. Are there any of your commissioned schemes where the capacity could be increased if that would not be at odds with receiving existing support (e.g., due to feed intariff capacity limits)?

- Yes
- No

4.a. How many commissioned schemes could be extended?

4.b. In the absence of those barriers, approximately how much additional capacity in kW could be added to your commissioned schemes in total?

Page 2: Licenced but not yet commissioned schemes

5. Do you have any schemes which have all/most of the necessary consents but are yet to be commissioned? (Clicking 'Yes' brings up further questions)

- Yes
- No

5.a. How many of these schemes are there?

5.b. What would be the total installed capacity in kW of these schemes?

5.c. Do you currently expect to commission all of these schemes within the next 2 years? (Clicking 'No' brings up another question)

- Yes
- No

5.c.i. Do you currently expect to commission all of these schemes within the next 5years? (Clicking 'No' brings up further questions)

- Yes
- No

5.c.i.a. What is the total installed capacity in kW of schemes which have the necessary consents but are unlikely to be commissioned?

5.c.i.b. Briefly explain why these schemes are unable to be commissioned.

Page 3: Untapped schemes

6. Are there any local authority areas where you feel you have a strong knowledge of the undeveloped hydropower potential? If so, please list these local authority areas.

7. How many kW of untapped (e.g., no licenses have been granted for) natural flow hydro potential do you estimate to be within the local authority areas you have named above?

- < 1,000 kW
- 1,000 - 5,000 kW
- 5,000 - 20,000 kW
- 20,000 - 100,000 kW
- 100,000 - 500,000 kW
- > 500,000 kW

8. If you were assured of a total income of £120 per MWh for 15 years from commissioning, what total capacity do you expect you could deploy by 2030?

9. If you were assured of a total income of £140 per MWh for 15 years from commissioning, what total capacity do you expect you could deploy by 2030?

10. If you were assured of a total income of £160 per MWh for 15 years fromcommissioning, what total capacity do you expect you could deploy by 2030?

11. Rank the following from 1-5 (5 being a major barrier, 1 being no barrier at all) in terms of barriers to the commissioning of untapped hydro schemes?

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5
Obtaining initial capital finance	☐	☐	☐	☐	☐
Insufficient ongoing financial certainty	☐	☐	☐	☐	☐
Obtaining a grid connection	☐	☐	☐	☐	☐
Obtaining planning permission	☐	☐	☐	☐	☐
Obtaining required EA/SEPA/NRW/NIEA licenses	☐	☐	☐	☐	☐
Opposition from local communities	☐	☐	☐	☐	☐
Land ownershipissues	☐	☐	☐	☐	☐
Lack of information to assess feasibility	☐	☐	☐	☐	☐

12. If you have any further comments on barriers to hydro deployment - please enter them here.