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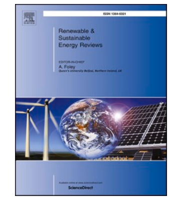

Reviewing the UK's exploited hydropower resource (onshore and offshore)

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A R T I C L E I N F O

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A B S T R A C T

Hydropower and tidal energy are valuable renewable energy resources that can assist in meeting the United Kingdom's net zero greenhouse gas emissions target. Existing studies have attempted to assess what the future energy resource potential is that can be harnessed from the water environment. Although schemes harnessing this energy, particularly hydropower, have been widely developed across the UK, few of the resource assessments account for already operational sites. This study takes the initial step required to holistically assess an accurate available potential by determining where and how much of the combined resource has already been exploited.

During the research it was noted that the extent of development in terms of installed capacity and locations of sites has been poorly recorded. Data collection shows that there is not a single comprehensive database of hydropower and tidal energy schemes. This study has therefore addressed this research gap collating operational hydropower and tidal energy projects.

This research determines the total installed capacity of hydropower is 4.66 GW, with 82 % of the powerhouses' locality identified. The contribution of tidal energy is much smaller at 10.63 MW. This research now makes it possible to fully understand the existing hydropower picture for the UK for the first time, allowing for more accurate resource assessments to be undertaken and for a better understanding of what the current contribution of these renewable energy sources (approximately 14 %) can be towards meeting the UK's energy demand (averaging 33 GW in 2020).

1. Introduction

Hydropower utilising the hydro-environment of both onshore and offshore (i.e. tidal energy as either tidal stream or tidal range) areas is a valuable renewable energy resource that can support the United Kingdom (UK) in meeting its net zero greenhouse gas emissions target. Hydropower can also promote a balanced and diversified energy grid [1] and operate complementary renewable energy generation systems. Critical to this is an objective assessment of the future UK hydro-environment resource potential incorporating both onshore and offshore hydro-energy and the infrastructure capacity supporting it.

A number of studies have been undertaken from the late 1980s to the early 2010s that quantify the future resource potential that can be generated from the hydro-environment. Some of these studies identify site specific locations for development and others determine a general theoretical potential. The majority of these analyse Scotland's onshore hydropower potential, with some investigating the UK as a whole or parts thereof but lacked comprehensive detail. Many of the studies have solely focussed on what the potential is without paying much heed to what has already been developed, the energy contribution of these sites, their locality, or the type of hydropower utilised. This means that the resource estimate may be inaccurate, likely over estimated as existing schemes are not deducted from the future potential estimated. These studies are also dated in the face of climate change forecasts, impacts on water resources, a changing energy grid and demand. A hindrance to including operational hydro-schemes in the studies is that although many onshore hydropower plants and a smaller number of offshore facilities have been constructed across the UK, the extent in terms of installed capacity and locations of sites has been poorly recorded, making it difficult to know their total energy contribution and regional application.

The earliest onshore resource potential study was undertaken by Salford Civil Engineering Ltd. in 1989 [2]. This review examined the whole of the UK to determine sites for run of river developments, as well as potential sources within the water industry. The methodology applied varied across the study areas due to limitations in available information and cost constraints. Overall as site visits and collaboration with other

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Abbreviations

BEIS	Department for Business, Energy, and Industrial Strategy
BHA	British Hydropower Association
DUKES	Digest of UK Energy Statistics
DTI	Department of Trade and Industry
ETSU	Energy Technology Support Unit
GIS	Geographic Information System
GW	gigawatt
IHA	International Hydropower Association
kW	kilowatt
MW	megawatt
REF	Renewable Energy Foundation
REPD	Renewable Energy Planning Database
SEPA	Scottish Environmental Protection Agency
UK	United Kingdom

parties was used as part of the methodology, the Salford Study was both time consuming and costly, but did allow for existing sites to be identified.

The Energy Technology Support Unit (ETSU) for the Department of Trade and Industry (DTI) [3] undertook a study of future UK prospects for renewables across a range of technologies. In their section on small hydropower they discuss the installed capacity status at the time, however there is no mention of how these are incorporated into the future potential resource value that was determined. There is also no discussion of the specific locations of these sites or records of areas in which the resource has already been harnessed.

Advancements in computer resources have subsequently enabled less costly methodologies to be applied, and studies commencing in the early 2000s started to incorporate the use of GIS programmes in their resource assessments allowing for site specific identification without always needing to conduct site visits. The Garrad Hassan study of 2001 [4] utilised the Salford Study as their basis for Scotland's resource potential and removed sites that had been developed since then, which was undertaken through revisiting those specific sites. The study states that some "*site location[s] could not be shown or [were] not known*" but does not go into any detail on where the data was drawn from or what the extent of knowledge was on developed sites.

The first study to conduct an automated review was that done by Nick Forrest Associates [5] in 2008 to determine potential in Scotland. Existing sites with an installed capacity greater than 700 kW were identified from Scottish Renewables and excluded from the analysis. Having only identified schemes greater than 700 kW may mean that a large number of existing sites were excluded in the resource assessment and that the future potential could have been overestimated as sites are already developed. This study was undertaken prior to 2010 when Feed in Tariffs were introduced that incentivised small-scale renewable energy developments (<5 MW) and therefore at the time there may have been a limited number of schemes below 700 kW.

The 2010 British Hydropower Associations (BHA) study [6] examined the resource potential for England and Wales in light of technological advancements, financial incentives and the need to mitigate the impacts of climate change. This study utilised previous national and regional assessments, including primarily the Salford Study. It does not make mention of how it may or may not have excluded sites that had already been developed in the intervening years or refer to any database where it could draw this information from.

The most recent study on Scotland's onshore hydropower resource potential was undertaken by Duncan in 2012 [7]. Duncan took existing schemes into account in his resource assessment, identifying existing weirs and dams with the aid of OS mapping and with the help of asset operators who provided simple maps showing tapped catchments. Duncan acknowledges that despite applying this methodology there may be existing schemes that have not been fully identified and that some of the sites identified through the automated review may conflict with these. This is confirmed in the study where in some instances the future sites identified had to be removed manually as they overlay with known existing sites, which would have required a manual review and double checking of the results of the automated process.

In reviewing the studies discussed, it can be seen that during the onshore hydropower resource assessments, the exclusion of existing sites from the future potential resource assessments is carried out in a haphazard way, with each study having to develop their own means of determining and accounting for existing schemes. This is both a time-consuming process and unreliable as data is not regionally readily available from a single source. This means that some studies do not account for the already exploited resource potential and while others do, they may not account for all of it thus creating uncertainty in the results and possibly leading to double counting. The development of such a combined database would help to overcome the problems discussed and prevent any future resource assessments from having to individually account for existing schemes that have been developed in intervening years. It also offers potential to harmonise exploitation of each resource.

Offshore resource potential assessments of tidal energy for regional areas and the UK have also been undertaken, such as the ETSU 1999 [3], the Garrad Hassan 2001 [4], the Carbon Trust 2011 [8] and the Crown Estates 2012 [9] studies. At this stage there are very few sites of existing tidal stream arrays or single turbines and no tidal range sites. The few tidal stream sites operational are known to researchers, and it is understood that operators are not yet exploiting the full potential of their locality. This means that future potential resource estimate assessments in tidal energy are not experiencing double counting in their results, but that the potential available is not yet clearly understood, especially from a practical resource potential at a UK-wide scale.

Offering a holistic review, this study has undertaken a comprehensive evaluation to determine what the existing status quo of renewable energy generation from the hydro-environment is by updating, refining and compiling data from multiple sources. This is important as in order to truly understand what the UK future potential of energy generated from the combined resources can be, it is necessary to know what has currently been developed holistically, the installed capacity, and where these are located to assess potential for further development or if the optimum exploitation of the resource is already achieved. The existing hydropower (onshore and offshore) picture is not provided for in open source, peer reviewed literature and although provided in grey literature sources this is not comprehensive and widely distributed across many sources. Given the data record deficiencies in both onshore and offshore hydro-energy systems it is essential to have a database of such sites for developing accurate resource assessments that do not capture the existing schemes in their estimates. Knowing what the existing development status is, is also of value in future planning and capturing an accurate reflection to report on the UK's renewable energy targets.

The process in determining what schemes have been developed to harness the energy from the hydro-environment is discussed in Section 2, where the data collection methodology is described. It also further details how the data was sourced and sorted and classified to develop a useable database and how the challenges encountered were overcome. Section 3 provides information on the existing reported datasets from governmental departments and other sources and provides a comparison amongst the installed capacities provided therein. Section 4 provides the results and findings from the data collection process discussed as two parts, one for onshore and the other for offshore. A discussion is provided in Section 5 that provides some background to data holdings of the countries of the UK and then goes into detail on the correlations between the collated database and the governmental records available highlighting the different values of installed capacity across them. Section 6 provides the conclusions summarising the importance of the study and making a case for maintaining a detailed database of hydro-schemes.

2. Material and methods

2.1. Data collection methodology

This study develops a database of the UK's existing hydro-energy extraction environment that can be used in further resource assessments to account for existing development and disregard these from the calculated future potential. It was thus necessary to utilise a wide range of data sources to determine the scale and location of the UK's existing hydropower picture. An initial list was developed from the Renewable Energy Planning Database [REPD] [10] and from the Renewable Energy Foundation (REF) [11]. The REPD is updated quarterly, and the first collation was undertaken from the June 2021 publication providing 96 operational onshore sites and four sites classified as tidal barrage and tidal stream. In September 2021 a new REPD database was released, and this was compared to the June list, to accommodate new additions. The REF has a more extensive compilation of renewable energy facilities under its Renewable Generators list, which was accessed in September 2021, providing information up to December 2020. This provided 1111 onshore schemes with a capacity of 1938 MW and eight tidal and tidal barrage sites with a capacity of 14.15 MW across the United Kingdom.

Additional sites were added to the database utilising data from agencies (Scottish Environmental Protection Agency (SEPA) [12], Forestry and Land Scotland [13], Marine Scotland Assessment [14]), councils (The Highland Council [15,16], Perth and Kinross Council [17]), associations (BHA [18], Renewables UK [19]), research organisations (EMEC [20], Tethys [21]), energy developers (Simec Atlantis Energy [22], Minesto [23]) and general operator and developer's information pages.

Only sites that have been constructed and are operational have been considered. Data sources were compared to remove duplicates and sites that are no longer operational. Those within the planning and construction phase of development are not considered here as part of the existing hydropower resource. The data sources utilised provide information on sites up to the end of 2020. Overall, 1172 operational onshore hydropower schemes and six operational offshore facilities have been identified across the United Kingdom from the various data sources.

2.2. Location and further information

In order for further resource studies to specify locations or assess if the optimal use of the resource is being undertaken it is necessary to know the locations of the existing schemes. Site locations were only provided on the list from the Department for Business, Energy, and Industrial Strategy (BEIS), the Highland Council, and SEPA, and locational information for tidal data from the RenewablesUK interactive map. Further information on location was obtained from reports, drawings, maps, or archaeological studies through developer, contractor or manufacturer's websites, government announcements, licence authority pages, industry news sites, social media and general press. These sources were identified using the Google search engine between September 2021 and February 2022, utilising the name of the energy scheme provided with the following search terms "hydro/hydropower plant", hydro/hydropower station", "tidal energy farm/site". The coordinates (latitude and longitude) of the schemes identified were visually checked using satellite imagery from Google Maps and Apple Maps to ensure that the scheme had been developed in that location. The exact location of the majority of the developed sites for both the powerhouse and the weir for onshore sites and the turbine location and the onshore connection point for offshore sites were found.

Additional information about the schemes, particularly the installed capacity and energy generation type amongst other details was also obtained through the data collection process and recorded in a spreadsheet so that each site has information on some or all the following:

- Site name(s)/Generator name(s)
- Country (Scotland, England, Wales, and Northern Ireland)
- Operator and/or developer
- Installed capacity in MW
- Size classification of the scheme (large, small, and micro)
- Hydropower type (run of river, conventional (storage), pumped storage, compensation flow, water reservoir, water treatment works, and tidal stream)
- Powerhouse latitude and longitude coordinates/onshore connection latitude and longitude coordinates
- Intake latitude and longitude coordinates/offshore turbine latitude and longitude coordinates
- Year of commission (Average age of asset was identified as 19 years old)
- Service life (as of 2021)
- Funding mechanism (Renewable Obligation Certificate (RO), Feed in Tariff (FiT), none, unknown)
- Costing
- Construction period

Establishing this data as a first step in resource assessment and having location information available for such sites will allow for future resource assessments to be undertaken and to identify site specific resource availability more easily. The location and additional details provided through such databases along with site specific data will also enable other studies to conduct further analyses on production capacity, impacts of climate change on energy production and the need for renovations or refurbishment to enhance capacity outputs of the sites identified.

The level of information available for each scheme varies considerably, most notably with the size of the installed capacity. Some projects were presented on company websites, in industry articles and with licencing authorities. Others however may be mentioned briefly on local business sites or through social media channels, and although there was minimal information in identifying these, none of the initial sites were excluded due to lack of information.

2.3. Technology classification

There are a wide range of methods available to extract energy from water, both onshore and offshore. This study attempts to cover all the various methods of harnessing energy from the hydro-environment and classifies them based on common features, to facilitate comparison and analysis. Four features were used to define the hydro-energy devices as onshore or offshore facility, the means by which energy is extracted from the hydro-environment (run-of-river, conventional, storage and tidal stream, etc.), the installed capacity of the scheme and the country of development.

The installed capacity of the scheme was used to further categorise the schemes into size ranges described in Table 1, with the same classification scheme used for onshore and offshore developments as it is based on the schemes output rather than a single turbines capacity for generation. For offshore facilities this would classify a tidal array under one scheme as the overall installed capacity. The hydropower schemes were sized into three scales based on the range provided by the BHA [24]. Currently there is no classification system for offshore hydropower schemes and in the future, it may be preferential to classify them differently as they have the potential to have much larger installed

Table 1
Size classification of hydropower based on the installed capacity for the UK [24].

Micro	<100 kW
Small	100 kW–5 MW
Large	>5 MW

capacities than onshore hydropower.

2.4. Challenges in data collection and approach applied

The REDP and REF were chosen as the base references as they are the most comprehensive listings available. They do not however, account for all sites, and do not provide locality data and have inaccuracies in the installed capacities of sites. Therefore, this data has been used in collaboration with the other sources as well as visual confirmation through satellite imagery to improve accuracy. The limitation in the base data is evidenced by the total numbers provided from these compared to each other and the end database established, as well as being identified using multiple sources of data. The potential errors encountered have been reduced and the reliability of the study improved as information has been cross-checked and confirmed across the various sources. There is currently no numerical confidence available for the data; however, this may be possible in the future though data dissemination. The accuracy of the locations provided in the onshore database are exact for the large sites, high for the small sites and moderate to low for the micro sites, and there is high accuracy for the offshore sites. Further improvement in data accuracy can be established by making the database available to developers and operators to confirm the accuracy therein.

Although it has been attempted to record locality, this was not always possible due to the satellite imagery's quality, dense vegetation, or the imagery date preceded the construction of the scheme. When undertaking this visual check, it was noted that the accuracy of SEPA and BEIS locations was often incorrect, and the new location determined from the visual inspections was used. Through this process the locality of most sites was determined.

The installed capacity reported on the REF database sometimes varied with that provided by the developer/owner. In these cases, the installed capacity recorded was from the developer's or owner's records. This was deemed to be more accurate due to potential changes between the period of authorisation, from which the REF database is primarily created, and the current status or upgrades to the sites in subsequent years after development. The differences in installed capacities were usually not large, but there are sites with extreme differences. For example, Cruachan Pumped Hydro Scheme is reported as 88 MW on the REF data while Drax Group reports the site as having 440 MW. This extreme may in part be due to extensive upgrades that have been undertaken over the years since its construction in 1966. It was not possible to cross check the installed capacity of all sites, due to limitations in access to information and therefore some of values utilised are as presented in the REF database.

Another issue noted is in the reporting of onshore and offshore hydropower scheme names. Site names differ across sources in spelling or having multiple names e.g. the same scheme may have a project name used by the developer, but the authorising agency has stored the site by the name of the river on which it is constructed or its area of development. An example of such a site is the Nevis Range Hydro Scheme (on REF), and the Allt Choille Rais Burn on the Highland's Council Site. Name changes also sometimes occur when there is a change of ownership of the scheme. For some sites establishing that the different names belong to the same scheme is simple due to extensive records, whereas for others this is not an easy correlation to make. Where applicable and possible multiple site names have been recorded in the collated database.

Due to the research and development stage that tidal energy is in, there is a consistent change in the operational status of facilities. The data collection process evaluated all sites that have been listed to determine what their status was. Only those that are currently operational have been recorded on the database. As a result, the database is current as of February 2022 and may require changes and updating on a regular basis. Additionally, although consent has been given for some sites to have installed capacity of a certain amount, only that which has currently been installed has been recorded.

3. Theory/calculation

3.1. Existing reported data

The establishment of the onshore and offshore hydropower database allowed for a comparison in installed capacity to governmental and association records. The contribution of hydropower to the total renewable energy production is recorded and reported on by the BEIS in a number of statistical documents including the Digest of UK Energy Statistics (DUKES) [25], the National Statistics: Regional Renewable Statistics [26], the Renewable Energy Planning Database (REPD) [10], and Energy Trends [27] as well as by the International Hydropower Association (IHA) IHA 2021 Hydropower Status Report [28].

The sourcing of this data was conducted in a similar timeframe to the database development between September 2021 and December 2021 for onshore developments and December 2021 to February 2022 for offshore developments and thus was the latest statistics at the time of the research. The total UK installed capacities in megawatts from these reporting's is presented in Table 2 for onshore hydropower and Table 3 for offshore hydropower. These sources indicate that the total installed capacity of onshore hydropower in the UK as of 2020 is 1875.7–4712 MW and 22–42.5 MW for offshore hydropower.

The approach to what constitutes renewable hydropower differs with some statistics including pumped storage schemes and others excluding this as it is a net user of energy. This is the main reason for the range in the reported data.

Analysing the onshore hydropower reporting further leads to more discrepancies. The REPD data does differentiate between pumped storage schemes and other sources of hydropower. Therefore, taking the pumped storage capacity provided by the REPD data and adding it to the DUKES data provides a total installed capacity of 4704 MW. This gives a value very close to that provided by the IHA, rather than the more than 1 GW difference initially found between the REPD and IHA data. Doing this however raises concerns about the value of the REPD installed capacity for hydropower excluding pumped storage at only 618 MW, and although the REPD does not include hydropower situated in Northern Ireland this does not account for the reported low installed capacity.

The installed capacity of offshore hydropower provided by the official records mostly categorises tidal energy and shoreline wave energy together, with only the REPD data differentiating these technologies. Table 3 shows that there is a disagreement between the different sources on what the contribution is from marine energy, varying from 22 MW to 42.5 MW. There is also little distinction made between tidal and wave energy generation, which is misleading as these are different technologies from different energy sources that should be analysed separately in much the same way that onshore and offshore wind are differentiated. The tidal energy industry within the UK is a relative newcomer to the renewable energy field and as such many of the sites developed are still defined as research and development or testing for commercial development. As a result, the contribution made varies as generators are added for trials in in-situ conditions and removed or decommissioned when this phase comes to an end, therefore resulting in a consistent change in overall energy contribution.

Table 2
Official reporting's of installed capacity of onshore hydropower in the UK provided in MW.

REPD	DUKES[a]	Energy Trends[a]	Regional Renewable Statistics[a]	IHA
3445.8	1876	1876	1875.7	4712

[a] Expressly states or is assumed to exclude pumped storage.

Table 3
Official reporting's of installed capacity of offshore hydropower in the UK provided in MW.

REPD	DUKES	Energy Trends	Regional Renewable Statistics
42.5 (18.5[a])	22	22	22.4

[a] Tidal barrage and tidal stream only.

4. Results

4.1. Onshore hydropower

In total 1172 onshore hydropower sites were collated into a database, for which 82 % of powerhouses and 75 % of weirs could be visually identified. Fig. 1 shows the breakdown of sites that were identifiable on aerial imagery overall and by size (installed capacity). The large (Fig. 1c and d) and small sites (Fig. 1e and f) were easier to identify as there was more information available on them to determine locality as well as being easier to visually identify on aerial imagery than the micro sites. This analysis allows for confidence in the data to be established as it means that there was external information available beyond that of just the site name, while also providing confirmation on some or all of the other parameters.

The location data of the schemes were plotted on ArcGIS. Fig. 2 shows the spatial distribution of the sites. Most of the onshore hydropower schemes have been constructed in Scotland where the climate and the topography are suitable for hydropower development. Clustering of schemes in certain regions can be seen on the map, with sites in Scotland situated more towards the north, in the central regions and along the west coast. In Wales, development is in the north, and those in England have mostly been developed in Cumbria and the surrounding counties. Hydropower schemes in Northern Ireland are distributed throughout the northern and eastern counties.

Fig. 3a shows the statistical distribution of onshore hydropower sites throughout the UK as a percentage of the total sites constructed. From this it can be seen that nearly two-thirds of the schemes are developed in Scotland (57.5 %), 19.8 % in England, 16.04 % in Wales and 6.66 % in Northern Ireland. It is also interesting to note that although Wales only has 16.04 % of the sites developed within its borders the total installed capacity is very similar to that of Scotland, 2.22 GW compared to 2.40 GW as shown in Fig. 3b. This is because most of the pumped storage hydro schemes are constructed in Wales, and these tend to have much larger installed capacity.

In comparing the size classification of the schemes to their total installed capacity (Fig. 3c and d), it can be seen that although there are very few sites classified as large (58 schemes), these account for over 90 % of the total hydropower installed capacity. There is a relatively equal distribution in the number of small and micro sites, but as expected the difference in contribution to the installed capacity of these is large. This analysis shows that overall installed capacity of hydropower in the UK is 4662.4 MW and is a combination of multiple sizes of hydropower schemes.

Onshore hydropower developed across the UK is not solely the three main types, namely, conventional (storage), run of river and pumped storage, but also includes energy extraction from water treatment works (WTW), water reservoirs and from compensation flows. Most of the sites and the majority of installed capacity are contained in the main three schemes as shown in Fig. 3e and f. It is however noteworthy that energy extraction from other water related industries does allow for additional energy generation that may mean that they supply their own energy for their operations, thus reducing the amount of energy needed to be supplied by the grid.

4.2. Offshore hydropower

As tidal energy generation is still within its early development stages it is challenging to quantify the energy contribution to the grid, as projects transition through various phases of establishment. Additionally, not all projects connect to the grid and may be used for alternative purposes such as hydrogen production and electric car charging stations. As a result, this section discusses the energy produced by existing tidal energy sites across the UK, as a whole, that may be available to the grid and the UK's overall energy supply. In total there are currently six operational tidal energy sites that all utilise tidal stream by various means and have a total installed capacity of 10.63 MW. Some of these generators are situated at test sites while others are within the initial phases of their project development or commercial demonstration. The collated value determined is similar to that presented in Coles et al. [29] where their analysis stated that there was 10.4 MW of operational tidal energy. The minor differences are due to slightly different reporting's of the total installed capacity and the exclusion of one of the testing sites by Coles et al. compared to the collated database.

Although there are a number of sites in various stages of obtaining consent, licenced or in planning and development across the UK, the six operational sites are based in Scotland, Northern Ireland and Wales, with 95 % of the energy produced in Scotland as shown in Fig. 4a and (b). Similarly, to onshore hydropower there are currently more smaller schemes as shown in Fig. 4 (c) although most of the installed capacity is accounted for in the large scheme as can be seen in Fig. 4 (d).

5. Discussion

The data collection process has shown that there is not a single body that collates and accurately reflects all information on hydropower in the UK, onshore and offshore. This creates uncertainty around how much hydropower has been constructed, and what its contribution is to the overall renewable energy capacity. There is also limited data on where hydropower and tidal energy sites are constructed, therefore limiting the knowledge of which areas are optimally utilised and those that may have potential for further development and energy extraction. This study provides a comprehensive, locality specific database of hydropower and tidal energy sites therefore providing the initial step required for future resource assessments to be undertaken and greater exploitation.

During the data collection process, it was noted that Scotland has more information available and clearer record keeping than the rest of the UK. However, the level of detail depends on where the site is developed as well as the scheme size. It is interesting to note that the water-environment regulatory body, SEPA, does not hold information on all the sites in Scotland online, so the availability of information is also dependant on the local authority. Northern Ireland had very limited information on the schemes that had been developed, with no official record for this region found. It may be that this information is stored locally within offices and not disseminated online. A public register of licences and permits is available for Wales that allows for some hydropower sites to be found, however, no hydropower database is provided. Information on the larger schemes is also well documented. For England a public register of licences is also available provided the name of the scheme is known, making it difficult to use this as a data collection point.

Having a database of onshore and offshore hydropower that is available to government and policy makers would benefit water resource management. It would be able to readily distinguish a catchment or areas use for renewable energy source exploitation, the type of energy generation utilised and, therefore, water abstraction or storage required. Having this information would increase awareness and knowledge of how other water users and the environment may be impacted.

5.1. Onshore hydropower

An accurate database of onshore hydropower and its locality has been provided as well as categorisation in terms of size and energy

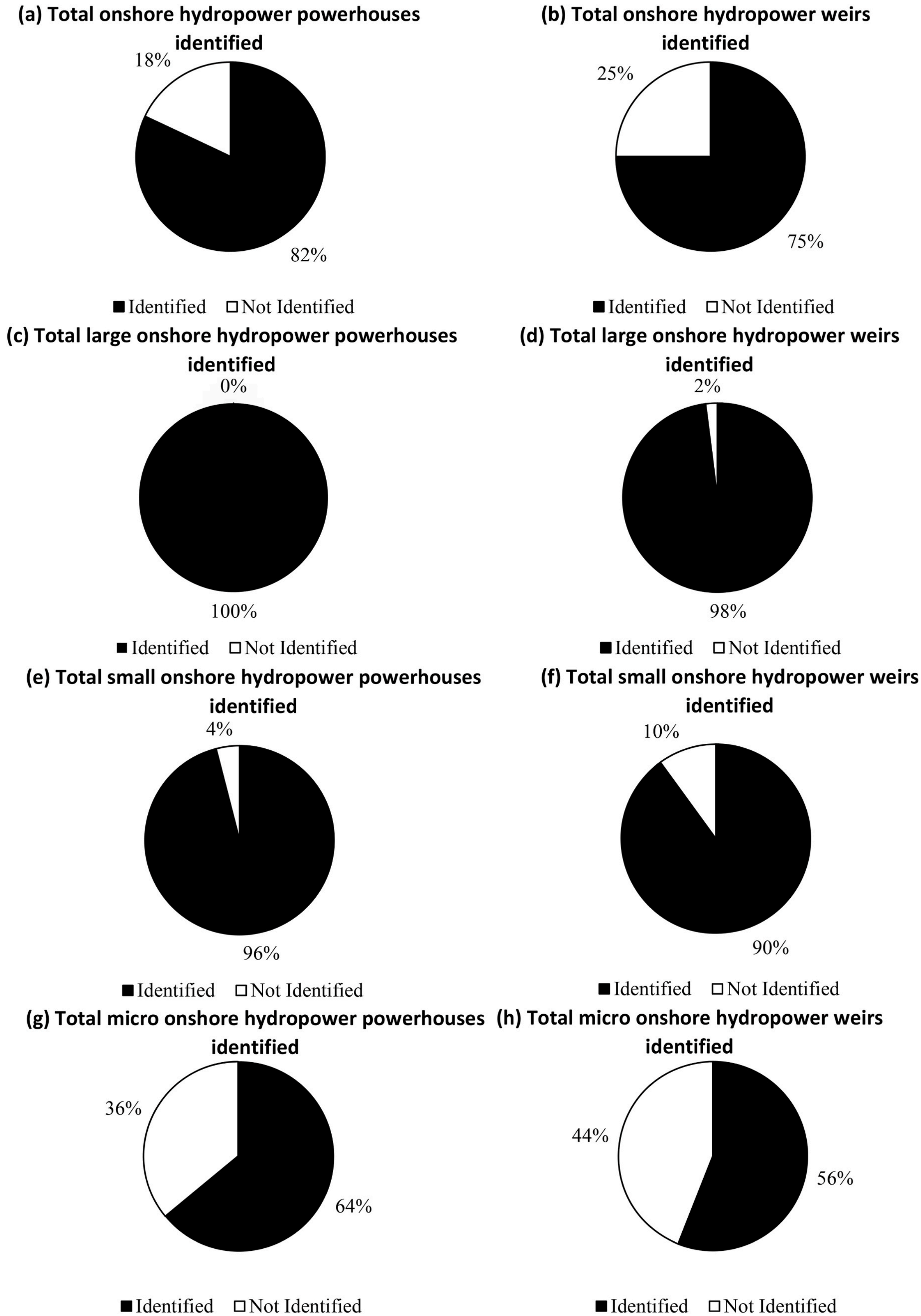

Fig. 1. Percentage of onshore hydropower sites that were identifiable using aerial imagery and where coordinates were recorded, categorised for the powerhouse and intake locations.

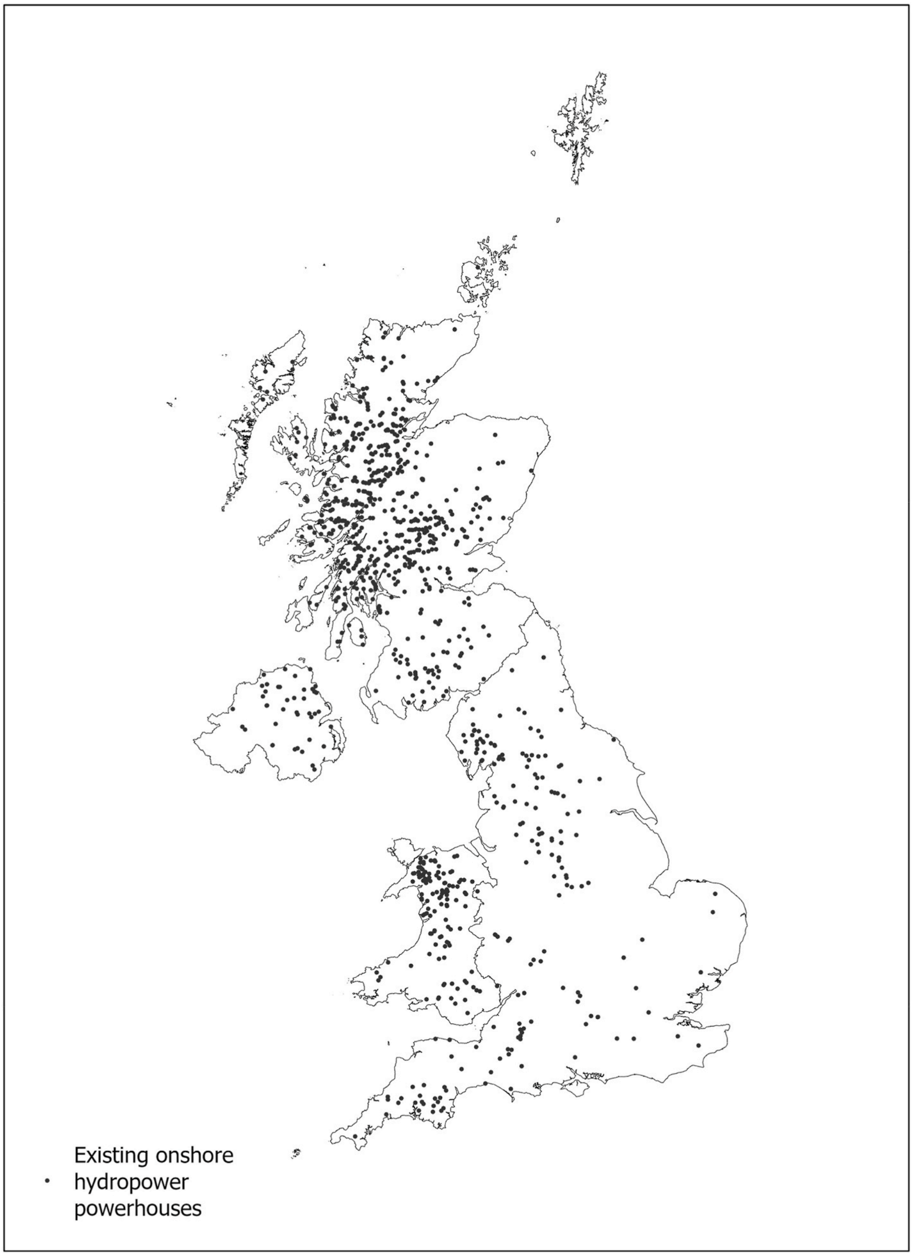

Fig. 2. Geographic distribution of the UK's operational onshore hydropower stations as of December 2020, showing the 963 powerhouses that were able to be geographically identified. Overall 1172 schemes were confirmed with a total installed capacity of 4662.4 MW of which 674 schemes having an installed capacity of 2397.15 MW is located in Scotland, 188 schemes having an installed capacity of 2219.2 MW in Wales, 232 schemes having an installed capacity of 38.15 MW in England and 78 schemes having an installed capacity of 7.89 MW in Northern Ireland.

extraction type. It has been found that the UK has an installed capacity of 4462.4 MW across various types of hydropower installations. The compilation of this data has allowed for interesting observations to be made in the comparison of data sources. It has highlighted that the difference between the installed capacity of the collated data versus that of the source data is high, as shown in Table 4. The percentage difference of the reported values compared to the collated data is also provided, showing the greatest variance is −58.43 %. For instance, although the REF data has similar number of sites to the collated data (1111 vs 1172), it does not include some high-capacity sites such as Dinorwig (1728 MW). The BEIS REPD data source only contained 97 sites, but amounts to 3455.3 MW of installed capacity, more in line with that of the collated data. Again, the difference can be accounted for in the large number of missing sites. The IHA's installed capacity is very similar to that of the collated data 4712 MW vs 4662.4 MW, a +1.06 % difference. The IHA does not specify how they had accumulated their information and it is therefore not possible to conduct a more detailed comparison. In comparing the collated data with the official REPD record where both consider pumped storage it can be seen that there is over 1 GW of installed capacity unaccounted for.

5.2. *Offshore hydropower*

The collation of offshore data, finding an installed capacity of 10.63 MW has also allowed for a comparison to other records of installed capacity. Although not as marked as the onshore hydropower results there are large differences between the installed capacity on the collated data versus that of the other reported results as can be seen in Table 5. This is mostly because the official energy recordings do not separate tidal energy and wave energy. The only valid comparison is between the REPD,

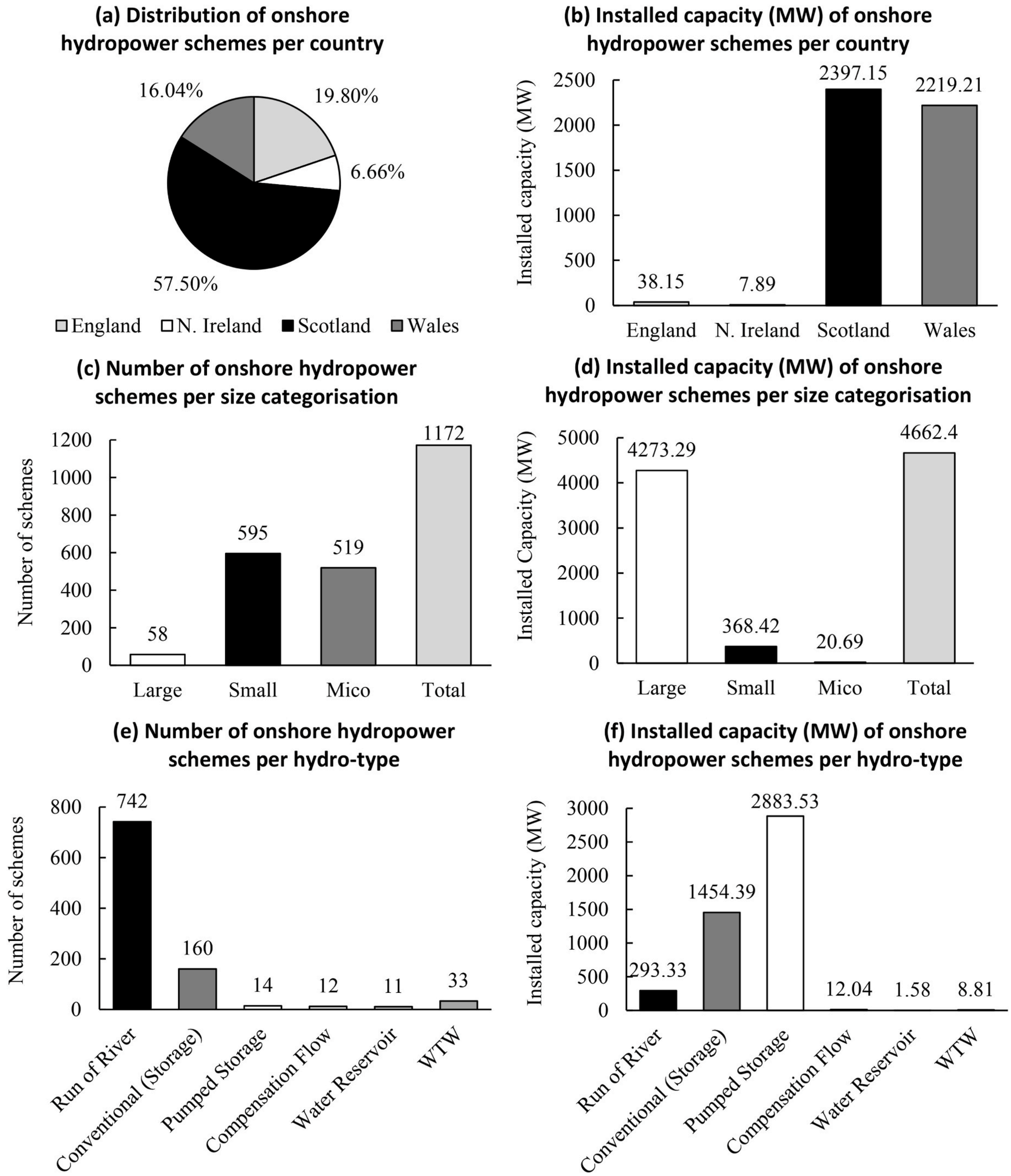

Fig. 3. Statistical results of the United Kingdom's operational onshore hydropower schemes as of December 2020, (a) the percentage distribution of onshore hydropower schemes across the countries of the UK (b) the total installed capacity in MW of onshore hydropower schemes per country of the UK (c) the number of onshore hydropower schemes developed in terms of the size of the installed capacity as described in Table 1 (d) The total installed capacity in MW of onshore hydropower schemes in terms of the size of the installed capacity as described in Table 1 (e) the number of onshore hydropower schemes in the UK categorised per the type of energy production (f) the total installed capacity in MW of onshore UK hydropower schemes categorised per the type of energy production.

the REF and the collated data which too differs as shown by the percentage differences to the collated data of +42.54 % and +24.88 % respectively. This is due to the constantly changing operation of testing stations, different recordings of what the installed capacities are as well as the number of identified sites. The REPD data source lists four generators, one of which was recorded as 10 MW although only installed as 2 MW, and has since completed its testing phase and been removed. These differences in results are likely to remain for the foreseeable future due to different dates in data collection and reporting and the consistently changing landscape of tidal energy development.

6. Conclusions

Previous resource assessments undertaken have generally not explained how energy from the existing hydro-environment has been harnessed nor have they utilised a common method and thus have had to develop their own method each time to determine what extent of the resource has already been exploited. In some cases, this has led to uncertainties in results or potential overestimates in the future resource assessments. This is particularly important in determining site specific resource potential where it is necessary to know the exact locality of

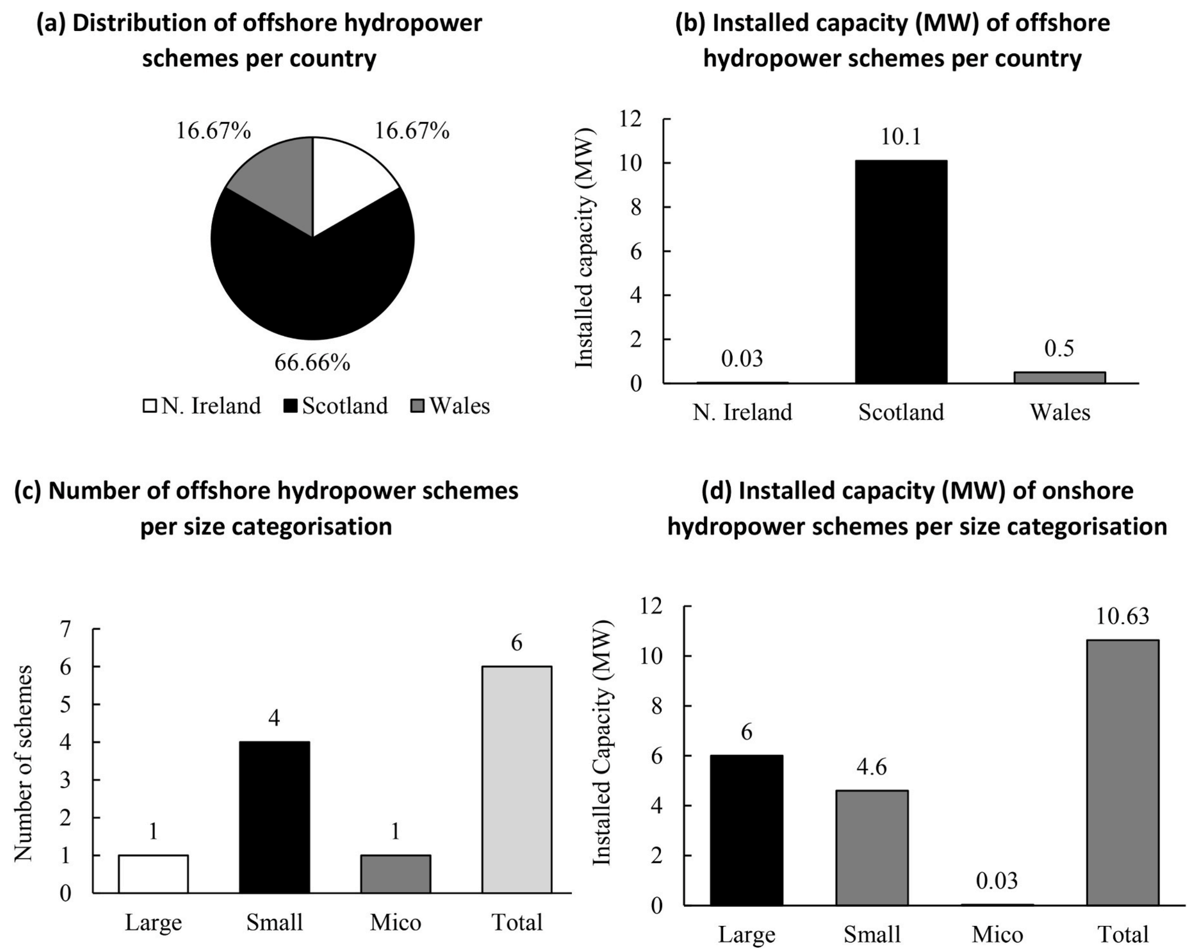

Fig. 4. Statistical results of the United Kingdom's operational offshore hydropower schemes as of December 2020, (a) the percentage distribution of offshore hydropower schemes across the countries of the UK (note England is not included as no offshore hydropower schemes had been developed); (b) the total installed capacity in MW of offshore hydropower schemes per country of the UK (note England is not included as no offshore hydropower schemes had been developed); (c) the number of offshore hydropower schemes developed in terms of the size of the installed capacity as described in Table 1; (d) The total installed capacity in MW of offshore hydropower schemes in terms of the size of the installed capacity as described in Table 1.

Table 4
Comparison of the collated installed capacity to the reported installed capacities of onshore hydropower provided in MW as well as the percentage difference between these.

Collated Data	REPD	DUKES[a]	Energy Trends[a]	Regional Renewable Statistics[a]	IHA	REF
4662.4	3445.8 (−26.09 %)	1876 (−59.76 %)	1876 (−59.76 %)	1875.7 (−59.77 %)	4712 (+1.06 %)	1938 (−58.43 %)

() % difference between collated installed data and reported value.
[a] Expressly states or is assumed to exclude pumped storage.

Table 5
Comparison of the collated installed capacity to the reported installed capacities of offshore hydropower provided in MW as well as the percentage difference between these.

Collated Data	REPD	DUKES	Energy Trends	Regional Renewable Statistics	REF
10.63[a]	42.5 18.5[a] (+74.99 %) (+42.54 %[a])	22 (+51.68 %)	22 (+51.68 %)	22.4 (+52.54 %)	14.15 (+24.88 %)

() % difference between collated data and reported value.
[a] Tidal barrage and tidal stream only.

schemes to determine if there is potential for further development or better optimisation of the existing water resource in a particular area. This research is therefore providing the initial step required for future combined potential energy resource assessments to be undertaken in a more accurate and timely manner by determining the current onshore and offshore hydropower development in the UK.

As there is no single energy database that collates all hydropower and tidal energy sites constructed and operational in the UK, there is no consistency in the way that water-energy resources are managed, existing hydropower generators are recorded, and the records maintained across the United Kingdom. Having this data available is necessary for a number of reasons. It would ensure accurate representation of the renewable energy harnessed from the hydro-environment that can then be accounted for in determining the progress towards net-zero. Additionally, it would be beneficial for regulators so that they are able to accurately and fairly allocate water resources amongst various water users and to keep a record of water use within catchments and regions so that water management measures can be implemented for climatic events. Having a database of hydropower and tidal energy sites is also beneficial to developers, operators and researchers as it would allow for further analyses on production capacity, impacts of climate change on energy production and the need for renovations or refurbishment to enhance capacity outputs of the sites identified.

The categorisation into scheme size and type of hydropower demonstrates that all are of value, but may serve different purposes. They can be used to generate electricity on a very small scale, for a singular business or on a larger scale such as a community. Being able to visualise the locality of such schemes and their outputs is important in future understanding of energy demand, climate change impacts and the potential for energy distribution decisions to be made such as harnessing the schemes to meet peak and base demands as well as distribution of the electricity over larger areas or to identify when there may be energy shortfalls if hydropower schemes fall within areas impacted by a climatic event or changes (e.g. catchment drying and flow reduction, or changes in coastal waves and flows).

This study addresses an important gap in resource assessments to provide an accurate holistic reflection of current UK hydropower. The collated data provides a new total value for UK installed capacity of onshore hydropower, including pumped storage, of 4662.4 MW. This aligns well with that reported by the IHA. Offshore hydro generation accounts for 10.63 MW. The collated data provides geographic locality for 82 % of the onshore hydropower powerhouses and all the offshore hydropower sites, which will assist in future site-specific resource potential assessments. It will also allow for better understanding of resource utilisation and potential regional optimisations in energy extraction. This is important in the face of climate change and the need for further renewable energy development, as well as competition for water resources across different industries.

The collated data was compared to existing records and showed that reported values of installed capacity of onshore and offshore hydropower vary, with the differences of some estimates of onshore hydropower exceeding 1 GW. This in turn may mean that the reported official record of what the UK states as their renewable energy supply to meet the renewable energy goals and emission targets is incorrect, but provides a means of comparison and potential correction.

In 2020 the energy demand for the UK was approximately 33 GW [30]. By determining the installed capacity of the hydro-environment at 4.67 MW (combining onshore and offshore resource) it is now possible to better understand that its current contribution as a renewable energy source is approximately 14 % of the UK's energy demand.

Due to the manner in which the data was collected using multiple sources, there may be errors incorporated due to the issues encountered. These include different naming conventions making it difficult to confirm all sites are captured and only recorded once. Although the use of multiple sources has the advantages in allowing for confirmation of results, this highlights the importance of maintaining a single source living record of hydropower schemes to mitigate against inaccuracies in the reported capacities. Sites that change capacity during construction or undergo upgrades over their life should be updated to accurately record those changes to maintain reliable information that can keep track of the renewable energy supply of the UK. Overall national records should keep track of what renewable energy projects have been developed and where and these should be updated when changes to schemes are undertaken. This study's approach can be used as a starting point for such record keeping with confirmation and additions added by others involved in the hydropower industry. Ensuring that this process is undertaken for the offshore hydro-energy field in the early stages of development will be advantages in mitigating against the problems and large differences that are experienced in the onshore records. It is therefore recommended that a regional or national database be maintained so that future researchers or developers are aware of areas that are utilised to their full extent or may be underutilised.

Credit author statement

Claire Kennedy: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Douglas Bertram: Conceptualization, Validation, Writing – original draft, Writing – review & editing, Supervision. Christopher J. White: Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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