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Review

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A review of global tidal stream energy resources

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This review identifies 426 candidate sites with potentially suitable characteristics for tidal stream energy development, across 19 countries in Europe, the Americas, Asia and Australasia. The most common site assessment quantifies the theoretical resource, which is the maximum amount of total energy that can be extracted. The aggregated theoretical resource estimate, of 1000 TWh/year, from 262 sites (62% of those identified), across 6 countries, is equivalent to 115 GW of continuous annual power.

A more informative, albeit less common assessment, considers technical, environmental and economic constraints on energy extraction. New data from UK assessments is presented that indicates relationships between the theoretical and this more practical level of energy extraction, which are used to derive practical levels of electricity generation at other sites across the world. Results indicate a quasi-practical resource of 110 TWh/year from 90 sites (20% of the candidate sites) across the UK, France, Canada, USA, China and New Zealand. When assessed against national/regional electricity production, the UK, Indonesia and New Zealand show the greatest potential to make national-scale electricity supply contributions, whilst France, Canada, USA and China exhibit lower, regional-scale impact potential. Resource estimation is highly sensitive to turbine/array design and practical constraints, and studies adopt a wide range. Consequently, reported P10 and P90 resource estimates can lie 40% above/below their P50 estimate, respectively. Recommendations are made to characterize this sensitivity of the resource to these drivers.

1. Introduction

The tidal stream energy sector has reached over 35 MW of total global cumulative installed capacity from operational and decommissioned turbines, predominantly in the UK (19 MW) and France (6.5 MW). The Faroe Islands, Netherlands, Canada, USA, China and Japan have also begun offshore testing of tidal stream turbines in order to explore their utility. Future projects are contracted in the UK and France that, if delivered, will increase global cumulative installed capacity by 440%, to 188 MW, by 2030. Figure 1 shows the progression in cumulative installed capacity in countries around the world, as well as the planned future build out. A detailed breakdown of tidal stream turbine installations is provided in the supplementary materials. Based on the 2030 projections, tidal stream will of reached a similar stage of development to that the offshore wind sector achieved around 25 years ago, in terms of cumulative installed capacity, and the installed capacity growth rate. This raises the central question of this review: what is the potential of tidal stream to contribute to electricity supply over the next 25–35 years, over time frames set by nations for reaching net-zero carbon emissions?

The European Commission estimates that up to 8 GW of tidal stream capacity may be installed in Europe by 2050, based on project pipelines currently being developed, and current/expected build-out rates [15]. Ocean Energy Systems have developed an ocean energy roadmap that sets out 120 GW of tidal stream energy capacity installed globally by 2050 [16]. The roadmap is derived by assessing market pull (i.e. the need for tidal stream), technology push (i.e. innovation required to deliver large scale build out), the cost of upgrades to/new infrastructure such as ports and manufacturing facilities, and regulation and legislative requirements. The European Commission and Ocean Energy System studies do not provide evidence that the projected installed capacities are underpinned by resource assessment of specific sites, and it is unclear where their projected capacities would be installed. This ambiguity in tidal stream energy resource estimates/roadmaps prevents an ability to robustly establish (i) the level with which tidal stream may integrate with future energy systems, (ii) suitable Government support requirements, (iii) investor confidence and (iv) location-specific supply chain requirements. For this reason it is important that estimates of tidal stream energy potential are underpinned by both market studies and robust resource assessment.

For the first time, this review provides an evidence-led catalogue of site and country specific tidal stream resource assessment. The review focusses on studies of UK, French, Canadian, North American, Chinese, Japanese and Indonesian resources, given the stage and rigour of resource assessments conducted, and the magnitude of resource estimates. The review describes resource estimates in terms of annual energy. This helps prevent ambiguity arising from the many different ways of describing resource in relation to power that are used in the literature, such as installed

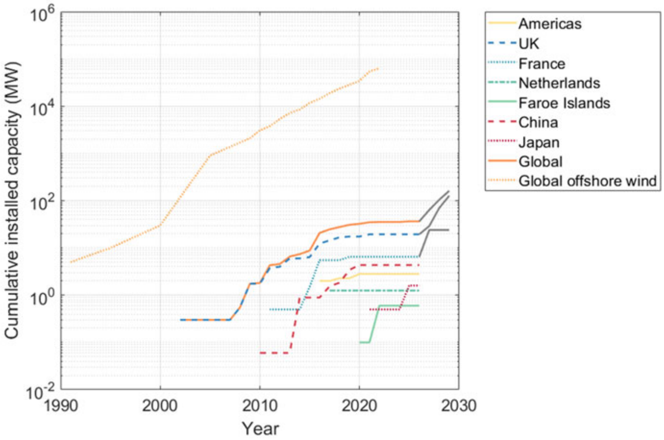

Figure 1. Increase in cumulative installed capacity of tidal stream between 2002 and 2029 [1–14], including future projects to be delivered between 2023 and 2029 that have successfully secured subsidy support (plotted grey).

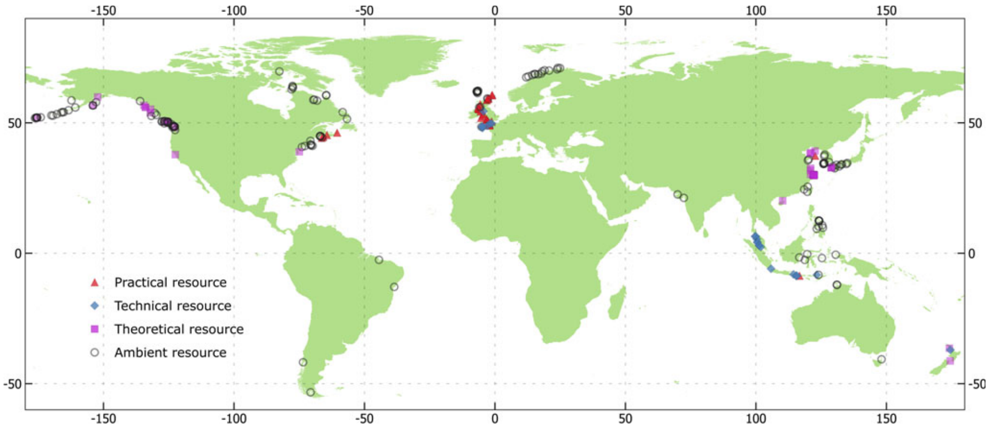

Figure 2. Overview of sites identified in this review, and their stage of resource assessment.

power capacity and time-averaged power. Quoting resource in terms of annual energy also allows results to be contextualized through comparisons against national/regional electricity demand.

The paper is split into five main sections (§§2–6). First, §2 reviews ambient tidal stream energy assessment, which has the primary aim of identifying sites that may be suitable for tidal stream energy development. Section 3 reviews theoretical resource assessments, which estimate upper-bound total energy extraction. Section 4 reviews technical resource estimates, which generally focus on the energy that can be extracted using specific tidal turbine and array design. Section 5 reviews practical resource estimates, which builds upon technical resource assessments by also considering economic, environmental, regulatory and/or social constraints to electricity production. Figure 2 provides a summary of the sites reviewed, and their stage of resource assessment. Site-specific resource estimates are tabulated in supplementary materials. Section 6 provides discussion on the relationship between theoretical and more practical levels of energy extraction, assesses the scale with which tidal stream may contribute to national/regional electricity supply and recommends priorities for future resource assessment based on the gaps in knowledge identified in this review.

2. Ambient resource

This section reviews the methods for carrying out ambient resource characterization and site identification. Sites identified for development are mapped in figures 3–9. Data from the ambient resource assessments discussed here are tabulated in the supplementary material.

(a) Definition

The primary aim of ambient tidal stream energy assessment is to identify energetic sites for further study (often termed ‘reconnaissance’). Site identification is generally based on depths, current speeds, power density, turbulence and wave climate from field measurements and/or hydrodynamic modelling. Power density is defined as the power per plan area, as opposed to the power integrated over the swept area of a turbine rotor. Practicalities such as proximity to grid are also considered in some cases.

(b) Methods

(i) Ambient resource characterization

The latest UK wide resource assessment, commissioned by the Carbon Trust [17], characterized the ambient flow based on current speeds derived from the 2008 version of the Marine Energy Atlas (MEA) [18]. The MEA is typical of national-scale modelling, where compromises on spatial resolution are necessary to achieve acceptable computational efficiency, given the extent of the domains. The MEA data is derived from km scale resolution hydrodynamic modelling. Leading standards for phase 1 reconnaissance assessment requires resolution of around 500 m [19]. The study reports that one of the most significant sources of uncertainty in the results is the underlying resource data, and significant differences in current speeds of up to $2\,\mathrm{m\,s^{-1}}$ between such models have been reported [20]. A key source of such error arises from low resolution spatial modelling is poorly resolved bathymetric features [21].

The study developed site specific two-dimensional parametric hydrodynamic models to simulate the tidal flows at 30 sites in greater spatial resolution. The models were forced by M2 and S2 constituents. Validation of this parametric modelling approach is limited to the Strangford Lough site in Northern Ireland [22]. It is noted that parametric modelling is not intended to provide reliable results for any specific site. Clearly validation at one site does not imply validation at all. Comparison of results against subsequent, higher resolution modelling, highlights significant differences in ambient resource characterization. For example, site specific hydrodynamic modelling of the Big Russel in the Channel Islands estimates that the plan area over which time-averaged power density exceeds $2.5\,\mathrm{kW\,m^{-2}}$ is $14\,\mathrm{km^2}$ [23]. This is $13\,\mathrm{km^2}$ greater than the Carbon Trust study estimate of plan area that exceeds $1.5\,\mathrm{kW\,m^{-2}}$.

Subsequent assessments of the Isle of Wight and Portland Bill sites on the south coast of England derived deployable areas based on site-specific hydrodynamic modelling and geo-spatial analysis that brought together over 50 different datasets of practical constraints [24,25]. Deployable area was limited to regions where spring tides exceed $3.5\,\mathrm{m\,s^{-1}}$, and disregarded areas close to shipwrecks, ports, oil and gas operations, offshore wind farms, dredge spoil dumping sites, mineral/aggregate extraction and dumped munitions. Areas impacted by vessel traffic, fishing activity, marine-protected areas, seabed sediment type, distance to shore, distance to grid and seabed gradient were also excluded. Based on these constraints it was concluded that the deployable areas at the Isle of Wight and Portland Bill are 10 and $2.2\,\mathrm{km^2}$. Relative to the Carbon Trust study, this represents a 50% reduction in deployable area at the Isle of Wight, and a 120% increase at Portland Bill.

Subsequent UK pre- and full-feasibility studies have identified a further 13 UK sites, underpinned by enhanced hydrodynamic modelling at resolution down to 200 m, three-dimensional modelling, and enhanced calibration/validation [26–33]. These include Burra Sound, Hoy Sound and Lashy Sound, which all exhibit maximum current speeds of $3\,\mathrm{m\,s^{-1}}$ or greater.

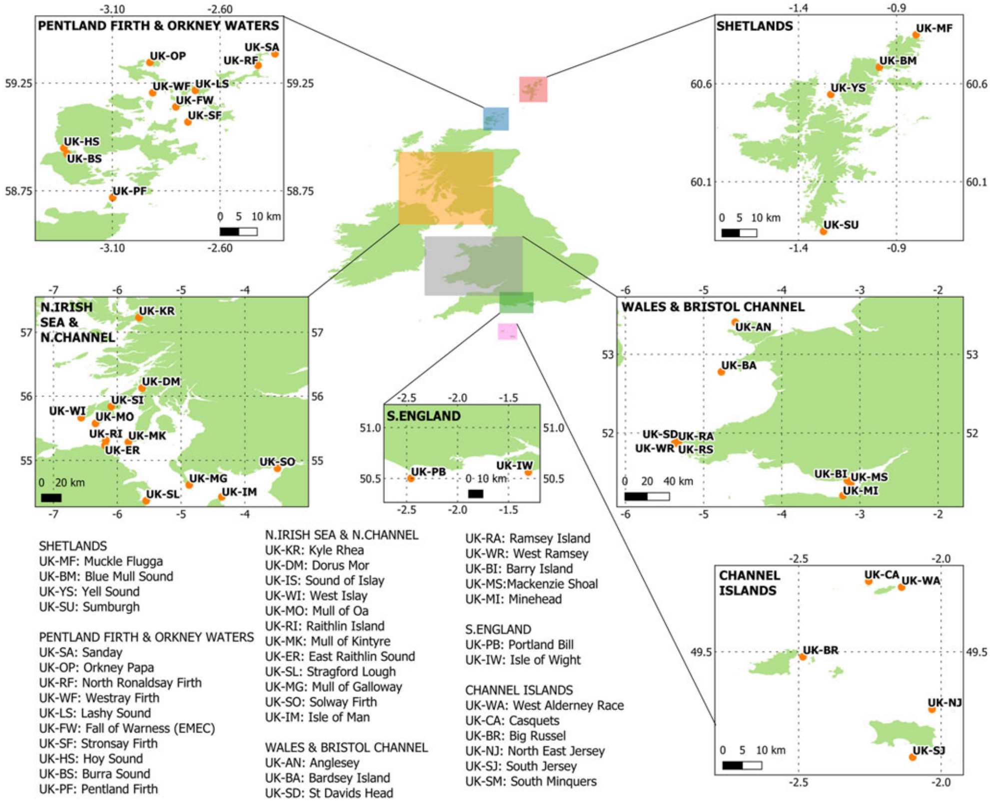

Figure 3. Overview of UK and British Channel Island tidal stream energy sites.

These additional sites have the potential to increase the national total, subject to further investigation. Based on these studies it is evident that the majority of the UK's resource lies in the Pentland Firth, between mainland Scotland and the Orkney Islands. The location of the sites is shown in figure 3.

Site selection of French sites [34,35] has relied mainly on the Model for Applications at Regional Scale (MARS) two-dimensional hydrodynamic model [36,37], with M2 and S2 forcing, and 250 m resolution in the regions known to exhibit energetic flow. A potential issue with this approach of limiting mesh refinement in other regions is that it may prevent other energetic sites from being identified. The models identified the greatest kinetic resources in the Alderney Race and the Raz de Barfleur off the Normandy coast, and the Fromveur Strait in Western Brittany, with a further five sites identified in Brittany (figure 4).

Canada's National Research Council characterized the ambient resource at hundreds of sites based on tide tables, nautical charts, and advice to mariners published by the Canadian Hydrographic Service, as well as regional scale hydrodynamic modelling [38]. Minas Passage, a 5-km wide by 10 km long by up to 160 m deep channel in the upper part of the Bay of Fundy, is identified as the area with the greatest potential for large scale development. Consequently improved resolution modelling effort has been made in the region [39–41], as well as the Pacific coast [42], the Salish Sea (near Vancouver) [43], Johnstone Strait (the channel between Vancouver Island and the mainland) [44] and the Eastern Arctic including Ungava Bay [45], where it is concluded that significant resource exists also.

Similar challenges arising from the aforementioned low spatial resolution modelling are identified in North American ambient resource assessment studies. The first national scale resource assessment defined over fifty regional domains for ambient hydrodynamic modelling

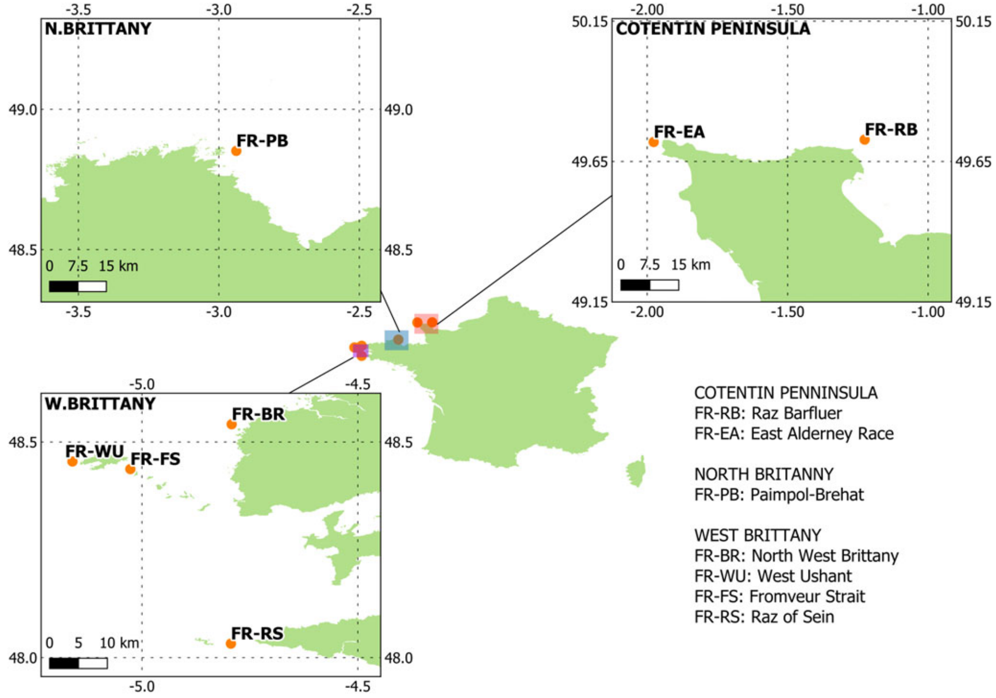

Figure 4. Overview of French tidal stream energy sites.

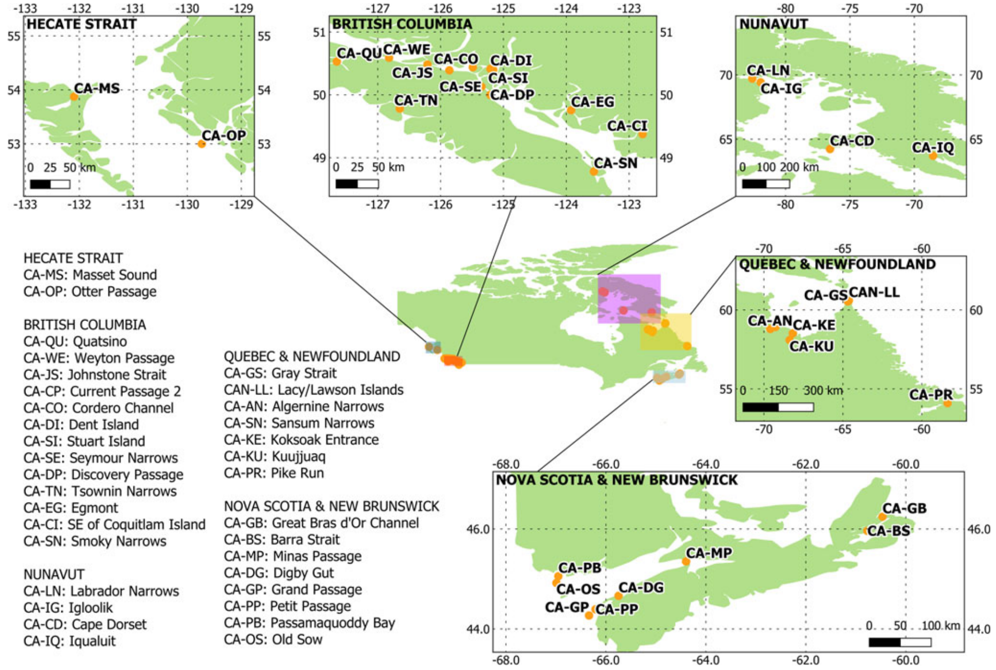

Figure 5. Overview of Canadian tidal stream energy sites.

[46,47]. The models were forced with the nine dominant tidal constituents: M2, S2, Q1, O1, K1, N2, K2, M4 and M6. The West coast and Alaska models dropped the K2 and M6 constituent forcings. The hydrodynamic models were validated against available data, which included comparisons against 25 primary National Oceanic and Atmospheric Administration (NOAA) tidal station data located close to high energy sites. Whilst the models used a mesh resolution of up to 350 m in the regions of interest, which is within International Electrotechnical Commission (IEC) guidelines for reconnaissance, some significant differences between the models and ADCP measurements, of up to 30% were observed. This error translates to an error in power estimation of around 100%. The differences between modelled and field data were also reported to likely be as a result of the 350 m limit on the spatial resolution of the meshes, causing unresolved bathymetric features [48].

New assessments of U.S. sites provide enhancements through the implementation of new regional-scale hydrodynamic models [49,50] that use domain coupling, unstructured meshing and mesh resolution refinement. These advancements resulted in significant changes to the modelled current speeds in some cases. For example, the M2 tidal constituent amplitude estimated from the output of a new Long Island Sound (New York) model falls within 3% of measured data, and is 120% greater than the M2 tidal constituent amplitude derived from the 2011 model. Further examples of this subsequent work include assessments of Cook Inlet (Alaska) [51], the Western Passage (Maine) [52], the Salish Sea (Washington) [43], Cape Cod, (Massachusetts) [53], Portsmouth Harbor (New Hampshire), Florida Keys (Florida) [54], Cape May (New Jersey) [55] and the East River [56] and Long Island Sound (New York) [50], with site locations illustrated in figure 6. It is noticeable that a high number of sites are located in Alaska. This is discussed further in §§5 and 6 with respect to the practicalities of connecting the resource to demand.

Resource assessment of sites in Japan has also made strides in enhanced spatial resolution hydrodynamic modelling. Aljber *et al.* [57] conducted three-dimensional modelling that implemented 100-m horizontal resolution and 30 layers to identify sites in the Seto Inland Sea, a semi-enclosed body of water located between the islands of Honshu and Shikoku. This work represents significant improvements on previous ambient resource assessment, which relied on flow characteristics derived from hourly current speeds from hydrodynamic modelling undertaken by the Japan Coast Guard [58,59]. At sites where current speed time series data was available, astronomical tidal constituents were obtained to reconstruct current speeds over a year period, following the method presented by Pawlowicz *et al.* [60]. At sites where only maximum current speed data was available, a simple lunar day algorithm was used that assumes mixed semidiurnal tides based on a 12.5 hour sinusoidal tide [61]. Figure 8 shows that majority of the Japanese resource identified to date is located in the South and West of the country. Many sites have been identified in the Inland Sea between Honshu and Shikoku, in the Kanmon Strait between Honshu and Kyushu, in Hayasui Strait between Shikoku and Kyushu and various locations in Nagasaki Prefecture.

Three national scale assessments of the Chinese tidal stream energy resource have been conducted over the last 40 years. The first, based on field measurements, with no numerical modelling, provides an estimate of the time-averaged kinetic power flux, at approximately 130 sites, of 14 GW [62]. 79% of this kinetic power flux is located at sites in the East China Sea, with particularly energetic sites identified in the Zhoushan archipelago, in Zhejiang province. The second implemented hydrodynamic modelling using the Princeton Ocean Model (POM), along with over 17 000 days of field measurement data, to assess resources in the Yellow Sea, East China Sea and South China Sea [63]. The study re-estimated the time-averaged kinetic power flux at the 99 selected sites, to 8.33 GW. The third study, from 2010, implemented higher resolution hydrodynamic modelling using the Finite Volume Community Ocean Model (FVCOM), alongside field measurements. The estimated time averaged kinetic power flux from 75 sites is 5.6 GW. The main contributing factor to this reduction in resource estimate with time is enhanced accuracy from more extensive field measurements and hydrodynamic modelling. Zhejiang is the Province with the greatest ambient resource, and many subsequent studies focus on the area. Specifically Zhoushan archipelago, with Guishan, Guanmen and Xihoumen Channels identified as three of the most promising sites [63–68]. Their locations are shown in figure 7.

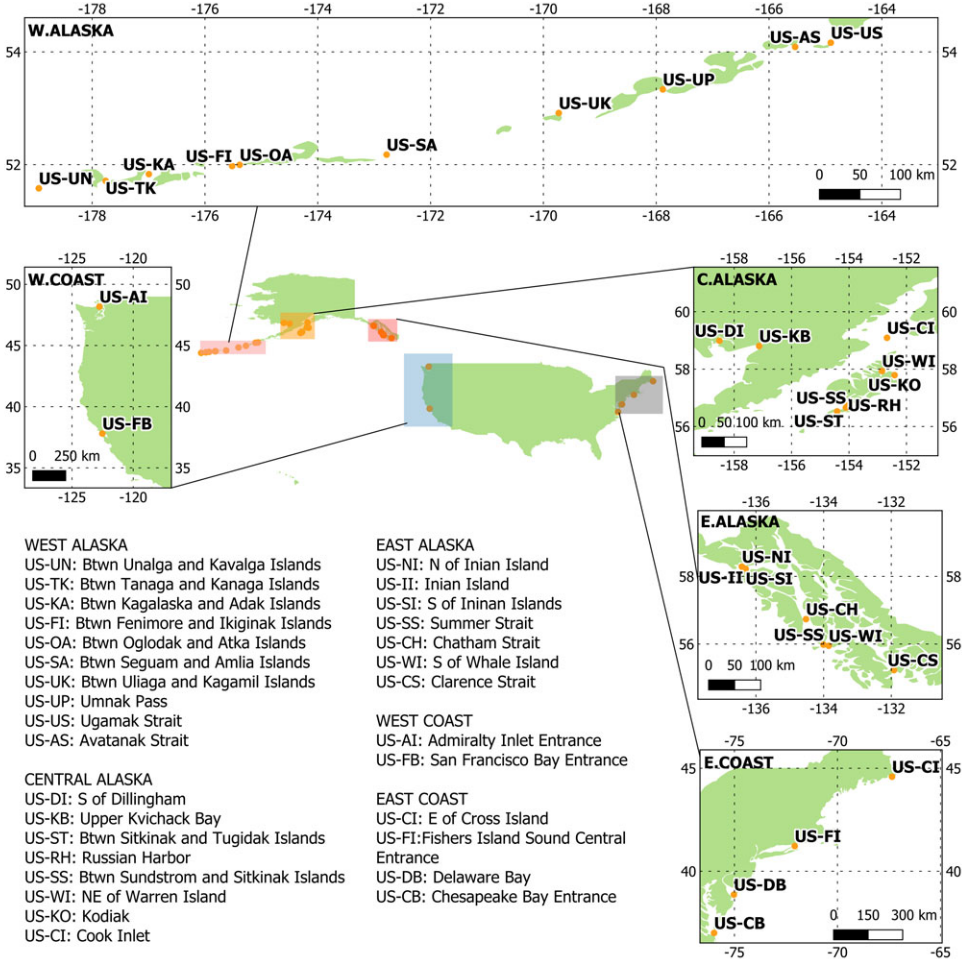

Figure 6. Overview of American tidal stream energy sites.

Some of the highest resolution hydrodynamic modelling has been conducted by Orhan *et al.* of the seven Sunda Island chain sites in Indonesia, namely Alas, Badung, Bali, Boleng, Larantuka, Lombok and Sunda Straits [69] (figure 9). The Delft3D hydrodynamic modelling used meshes with a horizontal and vertical resolution of 20 and 3 m, respectively. The model was forced with 11 harmonic constituents, as well as meteorological forcings (temperature, atmospheric pressure and wind). The greatest ambient resources are identified in Bali and Larantuka Strait, where maximum kinetic power density exceeds 14 and 10 kW m^{-2}, respectively.

(ii) Site selection criteria

The Carbon Trust's study of UK sites adopted a criteria designed to achieve 'reasonable project economics', which limits the study to sites with depth greater than 15 m, and time-averaged power density exceeding 1.5 kW m^{-2}. Since the time of the study other sites have been identified that fit The Carbon Trust's selection criteria, as a result of field measurement and hydrodynamic modelling effort, namely Dorus Mor, Orkney Papa, Lashy Sound (Eday) and Yell Sound (Shetland).

Canada's National Research Council study implemented a constraint on the time-averaged kinetic power, selecting sites that exceed 1 MW [38]. 191 sites were identified, with 89 along Canada's Pacific coast, 54 along the Atlantic and Gulf of St-Lawrence coasts, and 48 across Canada's Arctic. Data from sites with maximum current speeds greater than 1.5 m s^{-1} are

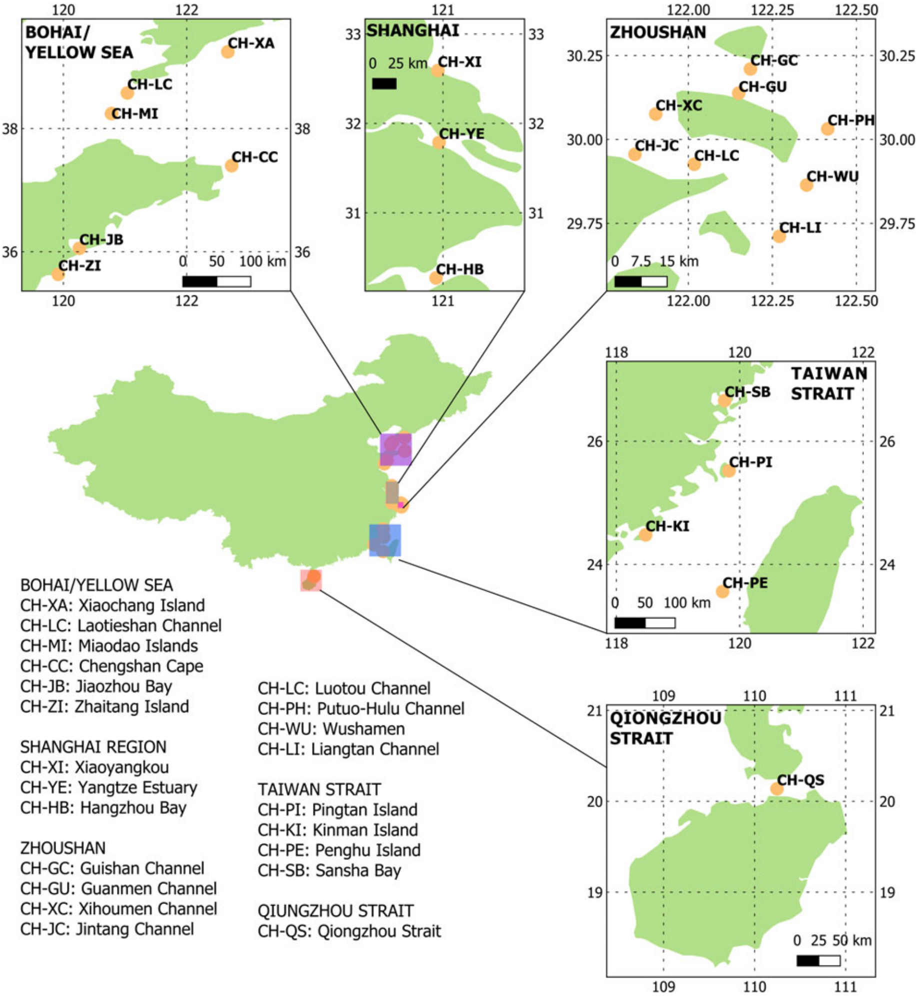

Figure 7. Overview of Chinese and Taiwanese tidal stream energy sites.

summarized in table 5 (supplementary material). Subsequently Cousineau *et al.* [42] used high resolution two-dimensional hydrodynamic modelling (down to 70 m) to identify sites along the West coast of Canada with potentially suitable conditions for tidal energy development, based on average depth between 10 and 60 m, median current speed greater than 1.5 $\mathrm{m\,s^{-1}}$, and sites within 5, 10 and 30 km of shore, transmission grid and a port, respectively. While many sites with strong currents exist on the Pacific coast, only four were identified that satisfy these five criteria; Egmont, Stuart Island, Quatsino and Southeast of Coquitlam Island. In addition, sites were identified as providing electricity generation opportunities for remote communities, mainly in the network of narrow inlets between Vancouver Island and the mainland.

The first national scale resource study in the United States (U.S.) considered sites that exhibit time-averaged power density that exceeds 0.5 $\mathrm{kW\,m^{-2}}$ (equivalent to a time averaged current speed of approximately 1 $\mathrm{m\,s^{-1}}$), within depths greater than 5 m [46,47]. This identified over 9400 $\mathrm{km^2}$ which fitted these criteria, with 8302 $\mathrm{km^2}$ located in Alaska, equivalent to 88% of the total area. Alaska is followed by Maine, Washington, Oregon, California, New Hampshire, Massachusetts, New York, New Jersey, North and South Carolina, Georgia and finally Florida.

This work was extended by Kilcher *et al.*, who considered U.S. site identification based on practical considerations that included shipping cost, market size and energy price, as well as depth and power density [49]. A multi-criteria decision analysis framework was developed to generate an overall composite score that ranks potential tidal energy sites. The top 10

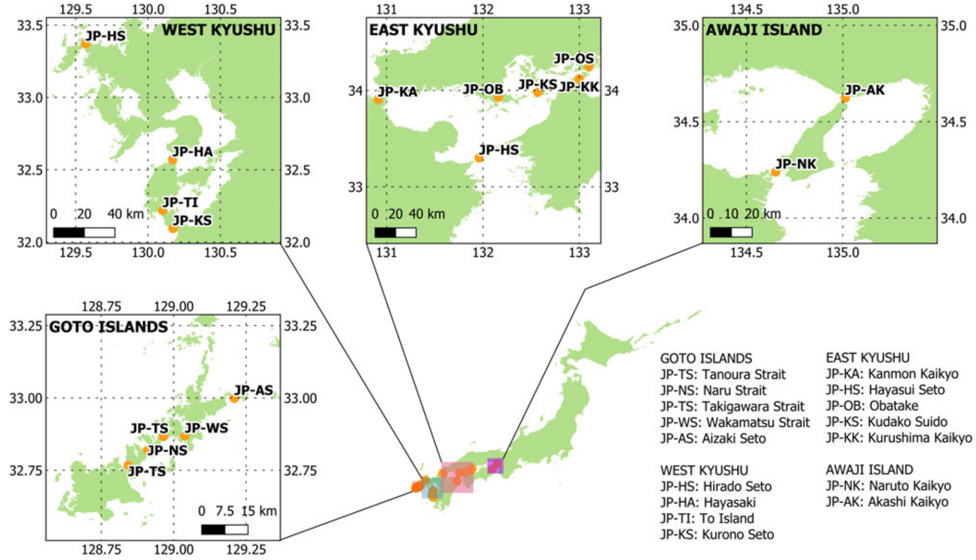

Figure 8. Overview of Japan's tidal stream energy sites.

sites identified for near-term development are Cook Inlet (Alaska), Western Passage (Maine), East River (New York), Long Island Sound (New York), Vineyard Sound (Maine), Muskeget Channel (Maine), Tacoma Narrows (Washington), Roasario Strait (Washington), Portsmouth Harbor (Maine/New Hampshire) and Bellingham Channel (Washington).

Aljber *et al.* [57] identified Japanese sites with depth less than 150 m, and peak spring tide currents greater then 2 m s^{-1}. Site selection was extended to additional, practical criteria such as distance from ports, power stations, shipping lanes, highly populated areas and coastlines. This work builds on the less stringent site selection approach by Bricker *et al.* [59], who selected 16 sites across Japan that exhibit maximum current speeds exceeding 0.7 m s^{-1}. Site selection required sites to be within 35 km of a city with a population greater than 100 000 people to help address transmission challenges when developing remotely located tidal resources. The economic viability of tidal stream development across Japan was assessed, based on an assumed capital and installation cost of around 1.5 £m MW^{-1} [61]. This is 80% lower than recently reported costs of 8.6 £m MW^{-1} CapEx for the MeyGen Phase 1A project [70].

The site selection criteria implemented in Chinese assessments has developed over time, with the first nation-wide study selecting sites that exceeded a maximum current velocity of 1.3 m s^{-1}, which corresponds to a power density of approximately 1 kW m^{-2} [62]. The latest Chinese site selection study sets a lower limit on power density for site selection, of 0.8 kW^2 [67]. This latest assessment actually reports a reduction in the number of sites, and the estimated annual resource, of 42 and 64%, respectively. This is expected to be as a result of an overestimation of the resource in early studies due to poorly resolved flow modelling. More recently, Liu *et al.* [71] identified large-scale sites (> 50 MW, in line with European Marine Energy Centre standards [72]), based on practical considerations including shipping routes, policy support and regulatory constraints. The Bohai/Yellow Sea region was identified as having favourable conditions for large scale development, in particular due to regulation that authorized the National Shallow Sea Comprehensive Testing Site (NSSCTS) to be built in nearby waters [73]. This is also true of the Zhoushan region, where the Zhejiang Zhoushan test site is operational. Laotieshan Channel (Bohai/Yellow Sea) is used for National defence activities, and both Laotieshan Channel and the Yangtze Estuary (Shanghai) have heavy shipping, so under current circumstances, these practical constraints are likely to prohibit tidal stream energy development in these areas [71,74], regardless of the significant resources at the sites (Yangtze exhibits a maximum power density of 10 kW m^{-2} [67]). Similarly, Jiaozhou Bay is an important shipping channel that will likely

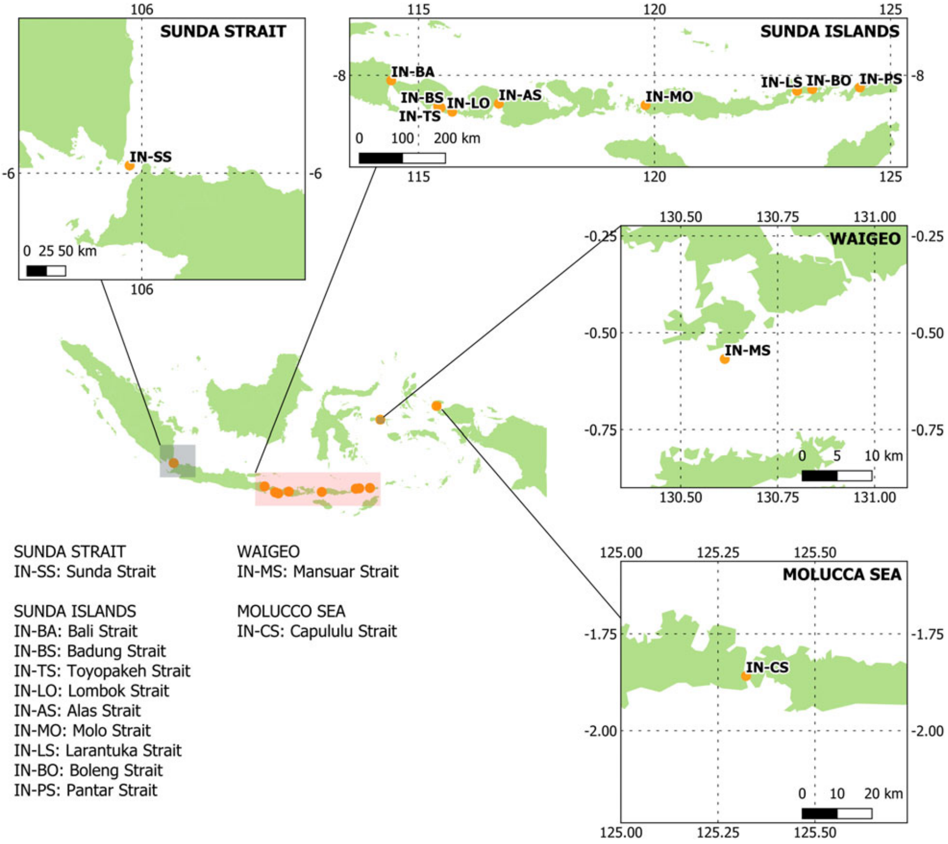

Figure 9. Overview of Indonesian tidal stream energy sites.

prevent, or at least limit, tidal stream energy development [71]. In Sansha Bay (Fujian Province) there are considerable marine aquaculture activities that are likely to limit tidal stream energy development [74], but estimating the extent to which this is the case requires further study. Studies at Chengshan Cape, located in Shanndong Province to the East of the entrance to the Bohai Sea, estimate maximum current speeds of $2.5\,\mathrm{m\,s^{-1}}$, and maximum and average power density of 7 and $2\,\mathrm{kW\,m^{-2}}$, respectively, [75–79].

Orhan *et al.* [69] considered conflicting uses of the marine environment in future Indonesian site identification activities. Uses include fishing, shipping, offshore wind and habitat protection. It was concluded that shipping lanes in Lombok Strait will likely impact its practical resource significantly. Pantar and Mansuar Straits are important national parks for marine life conservation and popular diving spots in Indonesia [80]. The inter-sectoral Zoning Plan for Marine, Coast and Small islands proposed by the Directorate General of Coastal Zones and Small Islands is working to address these practical constraint challenges by developing guidelines on permitted activities and licensing.

(c) Additional resource identification

This review focuses on resource assessment of sites in countries that show evidence of gigawatt scale electricity production potential, and/or a political/regulatory will to develop tidal stream energy. It is important to acknowledge that this is not an exhaustive list of tidal stream energy resources. Many more sites exist in the countries selected for review, and many more countries have tidal stream energy resources. They have not been reviewed in-depth in this paper because the literature has not developed to a point that site characteristics can confidently be reported.

This section gives a brief overview of the progress and leading research relevant to these less-understood sites.

In Europe, Sustainable Energy Ireland estimates the kinetic flux through Irish sites based on two-dimensional hydrodynamic modelling [81]. The study goes on to consider the practical constraints to development. A review of the study concludes that further work is needed to address potential sources of error that include model resolution that likely led to an underestimation of the resource at Strangford Lough, and potentially outdated practical constraints based on turbine technology at the time of the study [82]. Significant progress has been made to characterize the kinetic resource at a total of 104 Norwegian sites through hydrodynamic modelling by the University of Bergen [83], the University of Oslo [84,85] and later a review/analysis by Grabbe *et al.* [86]. The studies identified 28 sites with mean maximum spring speeds greater than 3 m s^{-1} [83,86–90]. Velocity data taken from pilot books is a source of significant uncertainty in some of the kinetic resource estimates, leading to some large variations in kinetic resource estimates between studies. Detailed hydrodynamic modelling of the Faroe Islands archipelago has identified areas totalling 35 km^2 where peak current speeds exceed 2.5 m s^{-1}, and a kinetic energy flux of 17.5 TWh/year from 13 sites [91]. The first national scale tidal stream energy resource assessment of the Netherlands was carried out by Alday *et al.* [92]. Based on results from hydrodynamic modelling with 500 m resolution along coastlines, the study concludes that the resource is relatively low energy, and shallow, making it unlikely that tidal stream energy will play a significant role.

In South America, maximum current speeds of 4 and 4.5 m s^{-1} have been reported in Chile's Chacao Channel [93] and the Strait of Megellan [94], respectively. Both sites are located in the South of the country. The Chacao Channel is a marine ecological area, and is a nursery and feeding ground for blue whales [95]. As with the majority of sites, grid infrastructure would need upgrading to prevent transmission/distribution constraints, which currently limit installed capacity at the Chacao Channel to 45 MW [93]. In Brazil, annual energy density estimates from hydrodynamic modelling of 9–11 MWh m^{-2} in São Marcos Bay (Maranhão State) have been reported by González-Gorbeña *et al.* [96]. Marta-Almeida *et al.* implemented hydrodynamic modelling to estimate peak power density in Baía de Todos os Santos (near Salvador), of 2.5 kW m^{-2} [97]. The Rio Grande do Sul exhibits peak current speeds of over 1.5 m s^{-1}, with flow speeds further enhanced in some coastal areas [98]. In Argentina, maximum current speeds of 3 and 2.5 m s^{-1} have been reported at San Josè Gulf inlet and Leones Island, respectively, based on data collected from nautical charts and in situ measurements [99].

In East Asia, observational data provided by the Korean Hydrographic and Oceanographic Agency shows that the Incheon-Gyeonggi and Jeollanam-do regions in the North-West and South-West of the country have the most promising tidal stream energy resources, with high current speeds and a limited wave climate [100,101]. Byun *et al.* [102] used in-situ measurements obtained from 264 locations spanning from the North-West to the South-East coastlines to characterize the kinetic resource. Particularly high current speeds ranging between 2–6.5 m s^{-1} were recorded at Uldolmok, Maenggol Strait, Geocha Strait and Jaingjuk Strait. In the North-West of the country (Incheon-Gyeonggi region), the site identified as having the greatest potential is Gyudong Strait in Gyeonggi Province's Gyeonggi Bay, with a maximum recorded current speed of 2.9 m s^{-1}. Three-dimensional hydrodynamic modelling by Hwang *et al.* [100] used the Environmental Fluid Dynamics Code (EFDC) to simulate tidal currents in Incheon-Gyeonggi and Jeollanam-do regions. The model estimates that in Incheon-Gyeonggi, Gyodong Strait exhibits time-averaged and maximum current speeds of 1.2 and 2.4 m s^{-1}, respectively.

In South East Asia, a collection of studies have investigated the kinetic resource at sites across the Philippines. These include studies of the whole archipelago including the well known San Bernadino Strait [103], Liloan Port, Hilutungan Channel, Surigao Strait and Banug Strait [104], and Verde Island Passage [105]. Malaysia has a substantial coastline, with most focus on sites in the Malacca Strait between Malaysia and the Indonesian island of Sumatra [106,107]. Bonar *et al.* [108] conducted numerical modelling of eight sites in the Malacca Strait. The study concludes that the resource is too small to ever play a substantial role in meeting the country's

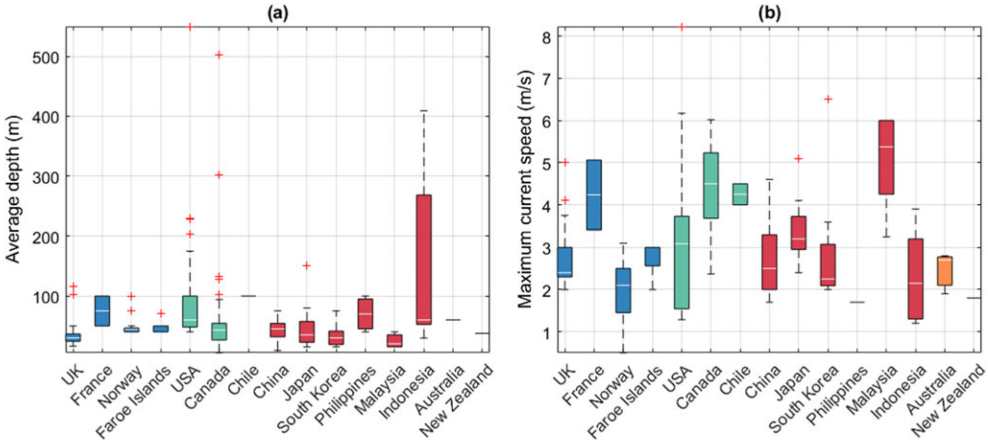

Figure 10. (a) Summary of average depth and (b) maximum current speed data. Box plots show median (white horizontal lines), 25th–75th percentile range (boxes)and extreme values (red crosses).

energy needs, given that Malaysia's current electricity demand is around 145 TWh/year, however tidal energy may play a role in supporting isolated communities where a conventional grid connection is difficult. Lim *et al.* [109] used outputs from the Princeton Ocean Model (POM) to also identify a further eight sites in the South Chinese Sea, around the North and East of Borneo, where maximum current speeds exceed $2\,\mathrm{m\,s^{-1}}$, namely Kapar, Pulau Jambongan, Semporno, Barangbongan, Kuching, Kota Belud and Sibu. Rahim *et al.* [107] considers some of the technical, polictial, environmental drivers to tidal stream energy development in Malaysia.

In India, early stage research has identified peak current speeds equal to or greater than $2.5\,\mathrm{m\,s^{-1}}$ in Khambhat, Kutch, South Gujurat and Sunderbans regions [110].

Finally in Australia, a multi-criteria evaluation of tidal stream energy sites identified three regions that show potential for tidal stream energy development; North of Broome in Western Australia ($534\,\mathrm{km^2}$), Banks Strait between Australia and Tasmania ($67\,\mathrm{km^2}$), and Clarence Strait located in the Northern Territory ($< 1\,\mathrm{km^2}$) [12]. The evaluation considered resource, distance to infrastructure and population, and constraints set by bathymetry, marine users and conservation areas.

(d) Synthesis and recommendations

Figure 10 summarizes the range of ambient site conditions at sites included in this review, by country. The site characteristics are expressed as median, 25th/75th percentile, extreme values and outlier values. The data in figure 10 provides only a limited representation of depth and maximum current speed across sites, as the spatial variability in these site characteristics can be significant. Figure 10a shows that in general, the average depth of sites varies between 15–100 m, with exceptions in the USA, Canada and Indonesia, where studies include sites with depths up to 400–550 m. It is currently unclear whether such depths are technically viable for tidal stream turbine deployment.

Figure 10b shows that most sites exhibit maximum current speeds of $2–5\,\mathrm{m\,s^{-1}}$. Sites in Norway and the USA with $1.5–2\,\mathrm{m\,s^{-1}}$reflect less stringent site selection criteria. These inconsistencies skew the data in figure 10, and prevent like-for-like comparisons of ambient resource across studies, sites and countries.

Several studies have investigated the sensitivity of site selection to site selection criteria. Lewis *et al.* [20] concluded that the UK resource may increase seven-fold if the requirements on depth and spring tide velocities are loosened from 25–50 to 5 m, and 2.5 to $2\,\mathrm{m\,s^{-1}}$, respectively. Campbell *et al.* [34] showed that increasing the time averaged current speed criteria from 0.5 to 1.0 and $1.5\,\mathrm{m\,s^{-1}}$ increases the size of the resource across French sites by approximately 700 and

2550%, respectively, when the maximum depth is constrained to 60 m. Guillou *et al.* [35] identified French sites exceeding 1 kW m^{-2} time averaged power density, resulting in significant differences, where at Raz of Sein, the array extent is seven times smaller than that proposed by Campbell *et al.* [34], for example. Orhan *et al.* [69] showed that the utilization area of the Indonesian Sunda island chain reduces by 77% when the time average kinetic power density requirement doubles, from 0.5 to 1 kW m^{-2}.

Whilst harnessing tidal energy at lower flow sites sounds promising from the perspective of unlocking significant additional resource, the current cost of tidal energy is relatively high, based on development at particularly energetic sites, such as the Pentland Firth. It is therefore unclear if economically viable development at lower energy sites can be achieved in the future.

It is recommended that a consistent site selection methodology is developed to address ambient flow characterization and site selection criteria inconsistencies identified in this review. Site selection must acknowledge the rapidly evolving landscape of the energy sector. For example, site selection should acknowledge the fact that the levelized cost of tidal stream energy is projected to reduce over time, with estimates of around 25% by 2030 [111]. In contrast, the LCoE of some competing technologies are either expected to fall by a slower rate (e.g. offshore wind: 11% drop), or increase (e.g. combined cycle gas turbines: 22%) over the same time period [112]. Fixed site selection criteria fails to reflect that a site that is not viable now, may become viable by 2050-60, as costs, policy and markets evolve. To address this, ambient resource assessment should adopt site selection criteria ranges that represent current *and* expected future criteria for viable site development, to enable analysis of how criteria magnitude (e.g. time-averaged speed) influences site number and scale.

3. Theoretical resource

(a) Definition

As turbines are added to a site, they block the flow. This choking of the flow reduces the volume flux through the turbine array [113], limiting the energy that is available to the turbines. At some upper bound number of turbines, when evenly distributed across the entire width of a site, the energy that is available to the turbines reaches an upper limit, known as the theoretical resource [114]. When extracted, not all of this available energy can be utilized usefully for electricity production. Energy losses associated with turbine operation, such as drive train losses, support structure drag losses and wake mixing losses [115], as well as added seabed drag losses that may arise from flow acceleration underneath the turbine rotors [116], are expected to be significant. The theoretical resource is the upper bound energy that can be extracted from the flow, and is the sum of useful energy for electricity production, and these aggregated energy losses.

Extracting the theoretical resource results in a reduction in the volume flux through a site of around 60% [23,44]. For this reason it is not practical to extract this upper-bound level of energy, due to severe environmental impacts. For example, disruption to the flushing rate of a bay can detrimentally effect pollution and drive seasonal temperature extremes that impact upon aquaculture [117]. Nevertheless, research shows that more environmentally sensitive levels of turbine deployment can be achieved without compromising significantly on energy extraction [113]. So whilst theoretical resource does not reflect the level of electricity that could be generated from a site, it is a useful indicator of a sites potential for tidal stream energy development. Theoretical resource estimation is also relatively straightforward, as described in §3b, and consequently estimates are more prevalent than technical and practical resource estimates.

The theoretical resource is, in general, considerably less than the average kinetic power flux through the most constricted cross-section of a channel [113]. This is an important point since many resource assessments incorrectly quantify the theoretical resource as the kinetic flux. In some cases this has understandably arisen because the resource assessment was conducted prior to the publication of the now widely adopted theoretical resource definition [113]. Incorrect interpretation of theoretical resource may also have arisen as a result of ambiguous published definitions, where for example, the National Academy describe the theoretical resource simply as 'the average annual power available at a site [114].

(b) Methods

Theoretical resource can be derived using a simple force balance between the acceleration, pressure gradient, inertia, friction and turbine drag [117]. In general, the theoretical resource, expressed as the maximum average power, lies between 20 and 24% of the product of peak pressure head, and the peak undisturbed mass flux through the channel [113]. The model can be extended from a simple sinusoidal tide to adopt multiple constituents. The approach for doing so depends on the extent to which force terms contribute to the overall balance, with friction dominated flows behaving differently to flows where the dynamical balance is between pressure head and acceleration, for example.

This derivation of theoretical resource makes several simplifying assumptions, such as no change to the surrounding flow field from the back effect that arises from adding drag to a site. In reality there is an increase in head upstream of the turbines which increases available power. Whilst this is likely to be small at large, deep sites, it is more significant at small, shallow sites [113]. It also neglects vertical and lateral shear, and instead assumes a uniform flow throughout the water column and across the site. Acceleration terms are also ignored. Finally, the derivation is based on constricted flow through a channel connecting the open ocean to a bay, or connecting two basins, for example. An extension was made to consider partially blocked channels [118], but does not account for less constrained sites, such as those at a headland or open sea.

Hydrodynamic modelling has also been adopted to quantify theoretical resource, and this approach helps address some of the assumptions adopted in the analytical force balance method. In general the method applies a uniformly distributed drag over the width of a site. The drag is incrementally increased until the upper-bound energy extraction is reached (e.g. [23,119]). An equivalent way to model energy extraction in hydrodynamic models is as a line discontinuity in elevation that relates the water levels upstream and downstream to the drag force (e.g. [120,121]).

(c) Theoretical resource estimates

The Carbon Trust study estimates that the theoretical resource from 28 UK sites is 340 TWh/year. Estimates were derived based on the two-dimensional parametric models discussed in §2, forced by M2 and S2 constituents. Comparisons against subsequent theoretical resource estimates are useful in helping establish the accuracy of theoretical resource estimates derived from this parametric modelling approach. By far one of the largest UK resources is the Pentland Firth in Scotland. Draper *et al.* [119] estimated the Pentland Firth's theoretical resource using the DG-ADCIRC two-dimensional hydrodynamic model [122], with M2 and S2 boundary forcings. The estimate, of 37 TWh/year, agrees within 5% of the Carbon Trust estimate, and is equivalent to 11% of the Carbon Trust's UK-wide theoretical resource estimate.

The same method was adopted to estimate the theoretical resource of sites in the Channel Islands [23]. The reported theoretical resource estimate for Alderney Race, the largest site in the region, is 49 TWh/year, based on M2 and S2 forcing. The West side of Alderney Race is located in the Bailwick of Guernsey, which is a British Crown dependency. The East Race lies in French Territorial Waters. For this reason a significant proportion of the Alderney Race's 49 TWh/year theoretical resource estimate is located outside of UK waters and is attributed to the French resource. The Carbon Trust's theoretical resource estimate of West Alderney Race is 23 TWh, approximately half of the 49 TWh/year estimate that considers the whole of the Alderney Race. There is significant disagreement in the theoretical resource estimate of Big Russel, with the Carbon Trust estimate 145% greater than the subsequent study. The improved flow resolution modelling is an important contributing factor to this difference.

Karsten *et al.* used a two-dimensional numerical model to derive a theoretical resource estimate for Minas Passage in the Bay of Fundy, East Canada, based on M2 harmonic constituent forcing only, of 61 TWh/year [39]. Subsequent hydrodynamic modelling by Walters *et al.* re-estimated the theoretical resource of Minas Passage, using nine harmonic constituent phase and amplitude forcings, giving 53 TWh/year [123]. Similar to the evolution of theorectical resource estimates at UK sites, the enhancement in coastline and bathymetry definition is the main change that has led to refinement in the theoretical resource estimate.

Sutherland *et al.* [44] used a two-dimensional finite-element hydrodynamic model to investigate the theoretical resource at sites in and around Johnstone Strait on the West coast of Canada between mainland and Vancouver Island. The estimated theoretical resource in North-West Johnstone Strait, Discovery Passage and Cordero Channel is 13.1, 4.4 and 2.6 TWh/year, respectively.

The aggregated Canadian theoretical resource estimate is 67 TWh/year, from just three sites out of the 46 identified as potentially suitable for development. The Discovery Passage and Cordero Channel theoretical estimates are neglected from the cumulative total since they are linked to Johnstone Strait, which if included would lead to double counting.

The latest national scale assessment of sites in the USA used hydrodynamic modelling of the ambient flow to determine the tidal constituents for calculating the theoretical resource of estuaries and bays [46]. The total theoretical resource estimated from approximately 208 sites is 445 TWh/year. Given the high number of sites, the map in figures 6, and tabulated data in the supplementary material is limited to sites with estimates greater than 1 TWh/year. Results highlight that the USA has some of the most energetic sites in the world, specifically in Alaska. Namely Chatham Strait and Cook Inlet, where theoretical resource estimates are 105 and 160 TWh/year, respectively, which when combined, make up 60% of the national total.

Firdaus *et al.* [124] used the ADvanced CIRCulation Model (ADCIRC) to estimate the theoretical resource of Indonesian sites, namely Badung, Toyopakeh and Lombok Straits, located South/East of the island of Bali in the Sunda Island chain. Energy extraction was estimated based on the ambient flow field, using linear momentum actuator disk theory, with consideration of the changes in the flow field as a result of turbine fences spanning the entire width of the three Straits [125]. The study estimated the theoretical resource of Badung, Toyopakeh and Lombok Straits to be 2.2, 0.2 and 15.6 TWh, respectively.

Resource assessment in New Zealand has focused on the energetic sites of Kaipara Harbour in the North West, Cook Strait that separates the North and South Islands [126], and Foveraux Strait/Stewart Island at the Southern end of the country [127]. Cook Strait has a very large estimated theoretical resource of 131 TWh/year. Kaipara Harbour exhibits a much smaller theoretical resource, of 2 TWh/year [128].

(d) Synthesis and recommendations

Figure 11a summarizes the proportion of sites with a theoretical resource estimate, and their cumulative theoretical resource, when the data is aggregated by country. Of the 426 candidate sites identified as exhibiting potentially viable conditions for tidal stream development in this review, theoretical resource estimates have been conducted at 264 sites (62% of sites). The countries with the greatest estimated theoretical resource contributions are the USA (445 TWh/year from 208 sites), the UK (332 TWh/year from 31 sites) and New Zealand (132 TWh/year from 2 sites). The remaining three countries with theoretical resource estimates are Canada (73 TWh/year from 5 sites), China (31 TWh/year from 17 sites) and France (30 TWh/year from 1 site). 55% of the aggregated 1000 TWh/year theoretical resource is located at just six sites; the Pentland Firth in the UK (4% of 1000 TWh/year), the Alderney Race in the UK/France (5%), Minas Passage in Canada (5%), Chatham Strait (11%) and Cook Inlet (16%) in the USA and Cook Strait in New Zealand (13%).

Given that 162 candidate sites are without a theoretical resource estimate, the global aggregated theoretical total has the potential to increase significantly. While the majority of these additional sites are expected to each exhibit relatively low theoretical resource individually,

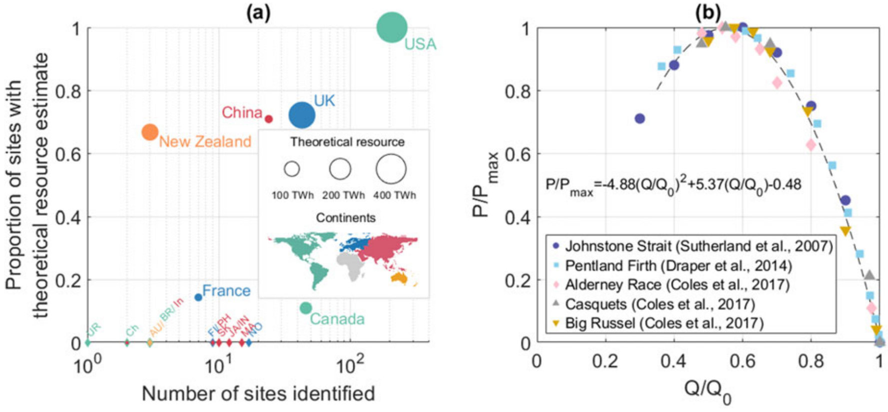

Figure 11. (a) Summary of national theoretical resource estimates by country. Country naming convention is as follows; AU: Australia, BR: Brazil, Ch: Chile, FI: Faroe Islands, IN: Indonesia, In: India, JA: Japan, MA: Malaysia, NO: Norway, PH: Philippines, RI: Republic of Ireland, SK: South Korea, UR: Uruguay. (b) Relationship between the the change in volume flux as a result of adding turbines across the width of a site, and the total extracted power as a proportion of the theoretical resource, based on results from studies of sites across the UK [23,119], France [23] and Canada [44].

theoretical resource at sites such as San Bernardino Strait in the Philippines are expected to be significant, based on early stage site characterization [104].

Quantification of theoretical resource is not just useful for estimating maximum energy extraction potential of a site. Figure 11b shows the relationship between the change in volume flux as a result of adding turbines across the width of a site, and the total extracted power as a proportion of the theoretical resource, based on results from site-specific studies across the UK, France and Canada. Results show that the theoretical resource is reached when the volume flux through the site reduces to approximately 55% of the volume flux without turbines. Whilst this very significant change in volume flux is unlikely to be environmentally acceptable, significant total energy extraction, of between 20–40% of the theoretical resource, is still achieved with much lower changes in volume flux, of between 5–10%. This insight is helpful in providing an initial indication of the proportion of theoretical resource that may be practically extracted once environmental constraints on the change in volume flux are imposed. Further research is needed to establish how this relationship between volume flux and extracted power may change for more practical array layouts (i.e. arrays that do not span the width of a site). This link between theoretical resource and more practical levels of energy extraction, is explored further in §§4, 5 and 6.

4. Technical resource

(a) Definition

The National Academy defines the technical resource as the ‘portion of the theoretical resource that can be captured using a specific technology’ [114]. Definition of turbine specification requires the rotor diameter, rated power, and cut-in/cut-out speed of each turbine to be determined. Technical resource also requires the array specification to be determined, which describes the number of turbines and their layout, which in turn, determines the array footprint.

(b) Methods

The majority of technical resource estimates are derived using regional scale hydrodynamic modelling. The representation of turbines varies widely. In the simplest cases, turbine drag is neglected completely, and instead it is assumed that the added turbine drag has a negligible impact on the resource that is available to the turbines. In other cases simple analytical wake models are used to estimate the velocity deficit downstream of turbines.

In the majority of cases, turbines are represented within hydrodynamic models as a continuous drag that is applied over the entire array footprint. The array drag is parametrized based upon the turbine and array specification. The advantage of this approach is that the computational mesh does not need to be refined down to sub-turbine scale. The disadvantage is that because the flow is not resolved down to the sub-turbine scale, individual turbine wakes, their interaction with downstream turbines, and wake mixing are not modelled. This is important because energy is dissipated as a result of wake mixing and blade induced vortex shedding. Turbulent structures arising from blade tip vortices, and in the shear layer between the wake and the faster bypass flow, causes a cascade of turbulent kinetic energy that is dissipated as heat. At the Betz limit, the maximum conversion efficiency is 2/3, with the remaining 1/3 of the energy lost by thermal dissipation [118,129,130]. Mixing losses, as a proportion of total energy extraction, can differ significantly from site to site, depending on their force balance, ranging between 24 and 70% of the maximum power available for electricity generation in some examples [115,130].

Representing turbines as discrete drag terms in the momentum equations can help with modelling wake mixing and wake interactions with downstream turbines. This requires sub-turbine scale numerical mesh resolution, which makes large array simulation computationally expensive. Wake interaction with downstream turbines depends on the level of wake recovery between turbine rows, which is driven by turbulent mixing between wakes and the neighbouring bypass flow, and the longitudinal spacing between turbine rows [116]. Opportunities for wake model validation are limited by available wake measurement data [131,132]. Large-eddy computational modelling has started to quantify the mean kinetic energy budget of tidal stream turbine wakes [133], with further research needed to quantify wake mixing losses.

(c) Technical resource estimates

Technical annual energy production (AEP) estimates of UK sites determine array specification by constraining the number of turbines to limit changes to the flow field, and to maintain economic viability [17]. Environmental and economic constraints are usually reserved for practical resource assessment [114], so estimates may be better described as quasi-practical. The assessment implements environmental constraints that limit changes to mid-range flow speeds to 10%, or a reduction in tidal amplitude of less than 0.1 m, whichever comes first as turbine drag is added to the two-dimensional hydrodynamic models. The rational for this approach is that ecological systems remain relatively unaffected by these small changes in flow speed and tidal range, since they are accustomed to high variability in local tidal stream flows. The validity of this approach is queried here, since the high variability may be what is preventing another species from out-competing those which are there. Economic constraints are implemented to maintain the cost of energy to within 80% of the energy that would be extracted if the surrounding flow field was unaffected by the added turbine drag. The aggregated UK quasi-practical AEP estimate, from 28 sites, is 29 TWh/year.

The estimate assumes that 15% of the total energy lost from the flow system is wasted as a result of support structure drag. This estimate is in close agreement with another based on the dual-rotor Seagen 1.2 MW device [115], that reports 18% of the total energy extracted from the flow arises from support structure drag when the turbine is operating at its rated speed. Subsequent research indicates that the support structure drag of more modern, single rotor, sea-bed mounted horizontal axis devices, which exhibit reduced exposed frontal area, is 5% of the total device drag, when operating at rated speed [111,134].

The UK study applies continuous drag across the array plan area to simulate turbine arrays, so does not resolve individual turbine wakes. The literature demonstrates a range of ways of accounting for the loss of generation arising from wake propagation on downstream turbines. The UK study assumes this generation reduction is 10% of the total energy that is extracted. This aligns with Blunden *et al.* [135], who implemented an attenuation factor that reduced the flow speed incident on downstream sub-arrays by 10%, based on learning from wind farm performance [136]. Three-dimensional modelling of the wake of a 1 MW turbine in the Fall of Warness, Scotland was validated against ADCP measurement at a single point approximately 3 diameters downstream of the turbine [131]. Results indicate that at peak upstream flow, of 2.7 $\mathrm{m\,s^{-1}}$ (i.e. when the wake extent is most extreme), the velocity deficit 15 diameters downstream of the rotor is approximately 0.3 $\mathrm{m\,s^{-1}}$, which represents a 30% reduction in the power available to a turbine at this downstream position, relative to the upstream turbine not being there. Results show that once the upstream flow speed has reduced to 1.5 $\mathrm{m\,s^{-1}}$, the flow 15 diameters downstream returned to approximately its upstream magnitude. Results from large-eddy-simulation show that the power of downstream turbines may even increase in staggered turbine layouts due to the positive local blockage effect (i.e. acceleration around the turbines) [137]. It is recommended that further wake measurements are collected to support further wake modelling validation.

The impact of relaxing economic constraints on the Pentland Firth's quasi-practical AEP was investigated, on the basis that the very large resource exhibited at the site enables economies of scale. This resulted in a 10 TWh/year increase in the national resource estimate, from 29 to 39 TWh/year. The impact of retiring the tidal range constraint on energy extraction at the tidal streaming sites was also investigated, on the basis that the tidal streaming sites exhibit unconstrained flow that is more representative of open sea. Removing the tidal range constraint at all 24 tidal streaming sites resulted in a further 10 TWh/year increase in the national quasi-practical AEP estimate, to 49 TWh/year.

The assessment reports high uncertainty in the level that economic and environmental constraints should be applied, and high sensitivity of quasi-practical resource estimates to these constraints. Modifying cost of energy and tidal range reduction constraints within their estimated maximum and minimum limits both have a +/−25% influence on the estimated practical resource magnitude. Recommendations for how to address uncertainty in environmental and economic constraints are provided in §§5 and 6, in relation to practical resource estimation, where they usually reside.

Subsequent technical resource assessment helps build confidence in the Pentland Firth's quasi-practical AEP estimate. This includes Adcock *et al.*'s [121] quasi-practical AEP assessment of the Pentland Firth, with economic constraints applied. The estimate, of 17 TWh/year, falls within 20% of The Carbon Trust estimate, of 21 TWh/year, and is based upon three rows of turbines spanning the entire width of the site. The turbines block 40% of the channel, and are represented as a line discontinuity in free surface elevation [120] in a validated ADCIRC depth averaged hydrodynamic model forced by M2 and S2 constituents. It is concluded that adding a fourth row of turbines results in an additional AEP of 2 TWh/year, and that this is unlikely to be economically viable as it provides a time averaged power of 0.75 $\mathrm{kW\,m^{-2}}$, which falls below the upper-bound performance of wind turbines, of around 1 $\mathrm{kW\,m^{-2}}$.

Campbell *et al.* [34] estimated the technical resource of French sites. Here we review results based on the most stringent, 'high', criteria used to set out turbine and array specification, which requires turbines to operate with a capacity factor of 0.3, with lateral and longitudinal spacing between turbines of 5 and 18 rotor diameters, respectively [34]. When the site selection criteria includes sites that exhibit mean current speed greater than 1.5 $\mathrm{m\,s^{-1}}$, the technically exploitable energy estimate is 13 TWh/year. Confidence in the technical resource estimates is low, since the study does not consider changes to the flow field as a result of turbine installations explicitly.

A similar approach was taken by Orhan *et al.* [69] to estimate the technical resource of the seven Indonesian Sunda Island chain sites, based on turbines with rotor diameter ranging between 1.5 and 20 m. As is the case in Campbell *et al.* [34], the study fails to consider changes to the flow field resulting from turbine installations. Instead it is argued that the modest turbine spacing assumed in the study prevents significant changes to the flow field. The technical resource at the seven sites is estimated to be 53 TWh/year, with 40% of the technical resource located in Alas Strait, and 14% at Lombok Strait.

The validity of the approach taken in the French and Indonesian studies to neglect turbine drag was interrogated based on hydrodynamic modelling of the Aderney Race [138]. Results show that the technical resource reduces by approximately 60% when turbine drag is simulated vs. not, based on an array with an installed capacity of 2.1 GW (i.e. similar to that considered by Campbell *et al.* [34] at the same site). Delft3D modelling of the Indonesian site of Larantuka Strait [139] has also demonstrated this point, where a 35 MW array causes changes in current speeds of up to 0.6 m s^{-1} 20 rotor diameters upstream/downstream of the array. In some array layouts the turbines were unable to reach rated power, and when a new row of turbines was added downstream of the existing array, there was a 5%–10% reduction in the performances of the rows located upstream. For this reason it is clear that turbine drag must be modelled when deriving technical resource.

Japanese technical resource estimates also exhibit low turbine performance. Waldman *et al.* [140] provided technical resource estimates for Naru, Tanoura and Takigawara Straits, located in the Goto Islands, Nagasaki Prefecture, a designated area for tidal energy development. The assessment implemented FVCOM three-dimensional hydrodynamic modelling forced by eight tidal constituents. Turbine drag was applied continuously across the majority of the width of the sites. The turbine drag was parameterized based on the OpenHydro device, with a rated power of 2 MW and a rotor diameter of 16 m. ‘High’ levels of turbine deployment were investigated, yielding technical resource estimates of 0.07, 0.05 and 0.07 TWh/year using 190, 130 and 182 turbines at Naru, Tanoura and Takigawara Straits, respectively. In all three straits the turbines operate with a capacity factor of just 0.02.

A follow on study of Naru Strait [141] considered modifications to the turbine specification and array layout considered by Waldman *et al.* [140] in an attempt to enhance capacity factor. Energy yield estimates were made based on hydrodynamic model outputs from the Waldman *et al.* study. The new study estimated that achieving a capacity factor of 0.3 required (i) the installed array capacity to be reduced from 380 to 45 MW to reduce flow retardation caused by array drag, (ii) a reduction in the rated power of the turbines from 2 MW to between 1 and 1.5 MW to prevent turbines from being over-engineered for the resource once flow retardation is considered, and (iii) an increase in the diameter of the rotors to between 25 and 38 m. The range of rated power and rotor diameter recommendations accounts for the spatial variability in depth and current speeds across the Naru Strait.

Canadian technical resource assessment focusses mainly on Minas Passage, given its significant theoretical resource. Walters *et al.* based their assessment on homogeneous arrays (i.e. arrays adopting a single turbine specification), with 30 m rotor diameter turbines simulated in depths greater than 50 m [123]. The lateral and longitudinal spacing between turbines was set to just 2 and 3 diameters, respectively, resulting in a significantly greater turbine density than is expected to be practical, based on guidelines [72]. The modelling yielded a technical resource estimate for Minas Passage of 24.5 TWh/year. This result is the total technical extracted power, which includes not only electricity generation, but also losses arising from support structure drag, added seabed drag and wake mixing, as opposed to technical AEP. This total technical resource estimate is 27% lower than that achieved by an array spanning the entire width of the site. Karsten *et al.* [142] also estimated the power generated by turbines in Minas Passage by implementing linear momentum actuator disc theory to parameterize turbine drag. The model was forced with M2 forcing only in this preliminary study, on the basis that the tides in the Bay of Fundy are dominated by the M2 signal. The model estimates a technical AEP of 17.5 TWh.

Two U.S national-scale technical resource estimates have been published, the first by the U.S Department of Energy [143], and the second by Kilcher *et al.* [144]. The latter states that the technical resource lies between 50–75% of the theoretical resource, giving a lower bound technical resource estimate of 223 TWh/year. As with the Canadian study, this definition of the technical resource is the total energy that is extracted from the flow, as opposed to technical AEP. The study provides no evidence to support the approach that technical resource is 50% of the theoretical resource, and conflicts with results from hydrodynamic modelling of UK sites [17], which concludes that the total technical energy extraction is 45%, 13% and 16% of the theoretical resource at hydraulic current, tidal streaming (also referred to as open sea sites) and resonant system sites, respectively.

Tidal streaming sites are defined as arising from the physical response to maintenance of the continuity equation, where acceleration occurs when flow is forced through a constriction [17]. The study acknowledges that in reality, the sites categorized as tidal streaming are more accurately described as open-sea sites, since they do not tend to exhibit the geometric constraints of a narrowing channel. Examples of these open sea sites are headland sites such as Portland Bill and the Mull of Galloway, and more generally coastal sites such as the Isle of Wight. This distinction between tidal streaming and open-ocean sites is important, and is explored by Garret *et al.* [145] and Shapiro *et al.* [146]. Results from analytical and three-dimensional hydrodynamic modelling show that the maximum extractable energy in a constrained channel may be up to three times lower than if the currents had not been disturbed by the turbines. In contrast, at the less constrained open-ocean sites, this can be as much as 14 times lower, as a result of the flow being able to more easily accelerate around an array in response to their added drag.

Hydraulic current sites exhibit flow from the pressure gradient created by a difference in water level between two bodies of water [17]. Examples of hydraulic currents include the Pentland Firth in Scotland UK, where the channel is flanked by mainland Scotland to the South, and the Orkney Isles to the North.

Estuarine/sea lough sites located in the Severn Estuary and Strangford Lough are classified as resonant systems [17]. In the classical definition, resonant systems require the natural period of the estuary/lough to match the tidal period, which results in an amplification of the tidal elevation and currents due to constructive interference between the incoming and reflected tidal wave. When there is a decrease in depth towards the head of the estuary, tidal waves behave as long waves, causing a slowing of the wave speed. This elevates the tidal height, and further increases current speed.

An important caveat to these site categories is that sites may be driven by a combination of mechanisms. In these cases the validity of resource estimates depends on how dominant one mechanism is over others. In addition, the level of re-direction of the flow as it responds to the added turbine drag is dependent on the width of the array relative to the width of the site, and/or the proximity of the array to coastline and shallow regions.

(d) Synthesis and recommendations

Technical resource estimates have been made at 249 out of the 426 sites identified in this review (58% of sites). 208 of the estimates are for sites in the U.S., followed by 28 in the UK, 6 in France and Indonesia, and 1 in Canada. Significant inconsistencies in the approach for estimating technical resource have been identified, and these inconsistencies prevent a meaningful cumulative global technical resource estimate, and like-for-like comparisons of technical resource estimates across sites that are derived from different studies [71].

A primary inconsistency is in the interpretation of the technical resource definition. Some Canadian and U.S studies estimate the total technical energy extraction, whilst the majority of others estimate technical AEP. U.S technical resource studies assume that 50% of the theoretical resource can be technically extracted [50], regardless of the site. Research shows that this is not the case, since it depends on the site specific force balance [17,130]. For this reason confidence in the U.S technical resource estimates is low. The relationships between theoretical, technical and practical is explored further in §6.

Secondly there is inconsistency in the interpretation of what constitutes a technical constraint, with UK studies implementing environmental and economic constraints that are more generally associated with the practical resource.

Thirdly, there is inconsistency in how turbine drag is modelled. It is clear that turbine drag will impact the surrounding flow field and in turn the available energy to arrays significantly. Wake measurement is critical in establishing the most suitable method for simulating turbine drag, and quantifying mixing losses, which are shown to be significant.

Fourth, there is inconsistency in the approaches taken to determine turbine and array specification, which the technical resource estimates are highly sensitive to. The majority of studies consider regular, homogeneous arrays that use a single turbine specification. This often leads to turbines being under or over-sized. Under-sizing turbine rated power and/or rotor diameter prevents turbines from generating high power during spring tides, leading to an under-estimation of technical resource. Over-sizing turbines prevents turbines from operating at their rated power, leading to unnecessarily high costs. Over-sizing of turbine rated power is common in studies that fail to model the effects of turbine drag on the surrounding flow field. Over-sizing of rotor diameter also limits the extent to which the array can span the width of a site. This is important because technical resource is sensitive to blockage [123,147].

It is argued here that turbines are not technically viable if they are not operating within their design window (i.e. across the inflow speeds and loading they are designed for), and that this should be considered when specifying appropriate turbine design in technical resource assessment. Heterogeneous array design can help address this, where sub-arrays of different rotor diameters and rated speeds are implemented, given the spatial variability in depths and flow speeds exhibited at sites [126,138,148].

It is not exactly clear what level of performance turbines are required to operate at, both presently and in the future, as the energy sector evolves. This is analogous to the challenges raised in §2 with respect to site selection, where it is unclear what current speed magnitude is required now/in the future for a site to be developed. It is therefore recommended that future technical resource assessment establishes the relationship between 'acceptable' turbine performance and technical resource, rather than deriving theoretical based on a single array design and performance. Data from operating tidal and wind turbines indicates that turbines typically operate with a capacity factor between 0.2–0.5, which may provide useful steer. This recommended method is set out in §6, with consideration also for practical constraints.

5. Practical resource

(a) Definitions

The National Academy's definition of practical resource is the portion of the technical resource that is available once all economic, environmental, regulatory and social constraints, which limit the installed capacity and array footprint, have been applied [114]. In general practical resource assessments quantify AEP, not total energy extraction.

Sustainable Energy Ireland's (SEI) definition limits the practical constraints to wave exposure, sea bed conditions, shipping lanes, military zones and disposal sites [81]. SEI considers two additional resource types; the 'accessible' resource is the practical resource limited by environmental constraints specific to each site; and the 'viable' resource is the accessible resource limited by commercial constraints including development costs and market reward. This definition has been adopted by O'Rourke *et al.* [82] and Segura *et al.* [149].

The accessible and viable resource categories introduced by SEI are not adopted here for three reasons. Firstly, site specific constraints should not just be limited to environmental considerations [114]. Secondly, commercial constraints such as development costs and reward are directly related to economic constraints, with no clear rational for why they should be separated. Finally, resource characterization should be kept as simple as possible to ease its adoption and limit ambiguity [150].

(b) Practical resource estimates

UK practical resource assessment has predominately focused on implementing practical constraints as exclusion zones to accommodate wind farm sites, oil and gas safety zones, aquaculture leases, and/or as restricted zones that consider shipping density, annual fishing value and dredging licences/applications [17]. Environmental and economic constraints that are more commonly associated with the practical resource were already accounted for in technical resource estimates from the study, as discussed in §4. The assessment concludes that only three constraint types potentially impede project development; fishing, shipping and designated conservation areas. Grid connection constraints were neglected and grid connection cost estimates only include the costs of connection to a shore based transformer/grid connection station. For this reason grid accessibility and associated grid connection costs is highlighted as an important constraint that requires further investigation.

The study estimates wide-ranging site-specific practical constraints, with practical resource estimates that are between 30 and 100% of a site's technical resource estimate. The UK's practical resource is estimated to be 34 TWh/year, once the environmental and economic constraints described in §4 at open sea and Pentland Firth sites are relaxed [111]. This is equivalent to 70% of the technical technical AEP estimate, and 11% of current UK annual electricity demand.

A recent practical resource assessment of the East Alderney Race, one of the largest French sites, also implemented exclusion zones to account for ports and oil and gas operations, for example [24,25]. The study estimated that a 0.4 GW capacity array could be practically deployed using 198 × 2 MW turbines with 20 m rotor diameter, operating with a capacity factor ranging between 0.24–0.27, resulting in an energy yield of approximately 0.85 TWh/year. The study failed to consider the impact of the added turbine drag on the surrounding flow field, with respect to the change in the available power to the array, and suitable turbine rating. The study also acknowledges that consideration of heterogeneous arrays would increase the practical resource, given the considerable spatial variability in current speeds and depths.

Additional national-scale French practical resource assessments are limited to a study conducted by the Agence de la Transition Écologique (ADEME), which focused on physical environment (type of seabed, distance to shore), restricted areas (protected areas, natural heritage) and navigation (shipping lanes, fishing/leisure activities) as practical constraints to tidal development [152]. The study fails to provide a description of its methodology for deriving practical resource, so is only discussed here to highlight similarities in the practical constraints it considered with other studies, and the limited nature of national-scale French practical resource assessment. The national-scale practical resource estimate, of 26 TWh/year, is double that of French technical resource estimates discussed in §4, which themselves are expected to be over-estimated. Clearly evidence of how this estimate was derived is needed before any credibility is given to it.

Karsten *et al.* [115] considered aspects of practical resource at six sites around Nova Scotia, Canada. The study imposed environmental constraints on energy extraction by implementing limits on the change in volume flux through the sites, which was simulated using two-dimensional hydrodynamic modelling. Limiting the reduction in flux as a result of turbine installations in Minas Passage to 10% and 5% of the ambient flow resulted in practical resource estimates of 30.7 and 17.5 TWh/year, respectively. The research assumes that 40% of the extracted energy can be converted to electricity, resulting in practical resource estimates of 12.3 and 7.0 TWh/year. This work was developed further through the implementation of three-dimensional numerical modelling of Minas Passage [142]. The model estimates that placing 2300 20 m diameter turbines in the Passage gives an AEP of over 17.5 TWh/year, whilst limiting the change in volume flux through the site to 2.5%. For context, this is equivalent to 33% of the sites theoretical resource estimate. When turbines are restricted to depths of between 30–70 m, results show that up to 11.4 TWh/year can be extracted. Further turbine deployment constraints to depths between 30 and 50 m reduces the maximum potential power further, to 2.6 TWh/year.

In general there is a lack of national-scale Chinese practical resource estimates, however several studies have investigated the environmental impacts of tidal stream energy development at site level in Zhoushan Archipelago. The studies show that large scale array installations can modify current speeds by up to $\pm 0.5\,\mathrm{m\,s^{-1}}$ [153–155]. It is estimated that the seabed shear stress could be reduced in the wake regions of a 170 MW array that extends over 10 km downstream, and that the salinity in the channel may be affected as a result [156,157]. Similar studies have considered environmental impacts of array development at Chengshan Cape [76,77,158]. The studies estimate that a 20 MW tidal stream turbine array would modify the free surface elevation by between 4 and 6 cm, and reduce current speeds in the wake of the array by around 0.8 m s^{-1}. The modelling estimates that the length of the array wake could extend 10 km downstream of the array.

Consideration of practical resource assessment in Indonesia has focused on Alas Strait [135], given its location far from major shipping lanes, proximity to grid and significant tidal resource. Other straits that meet these criteria are Lombok and Makassar Straits, however practical resource estimates are yet to be made. The study provides a practical resource estimate from a 520 MW array, based on results from the three-dimensional Princeton Ocean Model (POM), forced with eight tidal constituents. The model adopted a spatial resolution of up to approximately 1 km. Turbine placement was limited to a 35 km^2 region on the Western side of the strait, in depths between 25 and 80 m. The spatially varying bathymetry necessitated the use of rotors with diameters ranging between 14 and 25 m. The longitudinal spacing between turbines was set to between 19 and 33 rotor diameters, with higher spacing between larger rotors. The study did not implement turbine drag within the hydrodynamic model. Instead, the local onset flow speed to turbines in the wake of upstream turbines was modified based on an attenuation factor, based on experience from multi-row wind farms [136]. The estimated annual energy yield from the array is 0.64 TWh, with a capacity factor of 0.14. The low capacity factor arises from the selection of the turbine's rated power; set to 70% of the mean ambient spring maximum tide, before consideration of changes to the flow field.

(c) Synthesis and recommendations

Practical AEP estimates have been made at 35 sites, representing just 8% of those identified, with a focus mainly on UK sites [17]. Caution is recommended when interpreting practical resource estimates, since there is uncertainty in the appropriateness of the constraints that have been adopted. UK assessments choose environmental constraints based on mainly reasonable, but anecdotal rational, and it remains unclear what constitutes 'acceptable' environmental impact, and how this may change from site to site. Economic constraints were based on sector costs from nearly 15 years ago, which have changed significantly [111,159]. Practical resource is highly sensitive to the constraints that are imposed, with results estimating that modifying environmental and economic constraints within their maximum and minimum limits both have a $+/-$ 25% influence on the estimated practical resource magnitude.

For these reasons it is recommended that the choice of practical constraints is revisited. Environmental and economic constraints should be applied within practical resource assessment, not technical resource assessment, to align with The National Academy's definition. It is recommended that the sensitivity of practical resource to practical constraint levels is derived within practical resource assessment. Doing so makes it possible to establish the relationship between site selection parameters and the magnitude of the resource, and to re-evaluate the size of the practical resource as energy-wide sector costs and understanding into environmental impact evolve over time. The method for carrying this out is described in §6c.

6. Discussion

(a) Resource relationships/projections

Figure 12a shows the relationships between theoretical resource and quasi-practical AEP estimates of UK sites [17], where sites are categorized as tidal streaming, hydraulic current and resonant systems. To re-iterate, technical AEP estimates were derived with application of environmental and economic constraints, so are described here as 'quasi-practical' AEP. Tidal streaming sites are sub-categorized based on two geometric properties; (i) the level by which the flow is constrained by coastline, and the level by which the array fetch (i.e. the length of the array along the longitudinal axis parallel to the flow direction) limits the number of turbine rows that

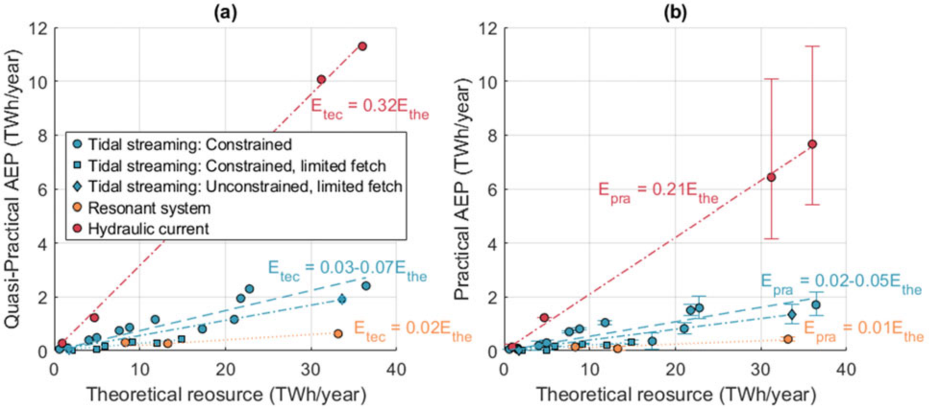

Figure 12. Relationship between theoretical resource and technical AEP at sites catagorized as tidal streaming, resonant system and hydraulic current, based on hydrodynamic modelling [17].

arrays can contain. Sites are described as constrained if the distance between the coastline and the array is less than one array width. The fetch of arrays is described as limited if it is shorter than the array width and restrcited by the site fetch.

The 21 sites characterized as 'tidal streaming' make up 80% of the total data set. In general, quasi-practical AEP lies between 3 and 7% of theoretical resource, depending on the extent of geometric constraints. The resonant system sites lie far from coastline, and exhibit limited fetch. These two features contribute to quasi-practical AEP that is 2% of theoretical resource. This is similar to unconstrained tidal streaming sites that also exhibit limited array fetch. Conversely, the hydraulic current sites are highly constrained by coastline either side of the arrays, and exhibit long fetch. These two geometric properties, combined with the pressure gradient that forces the flow, result in far higher quasi-practical AEP relative to theoretical resource, of over 30%.

The AEP estimates plotted in figure 12a have not been adjusted to account for the relaxation of the constraint on changes to the tidal range as a result of adding turbines, as described in §4. The relaxation of this constraint results in a 60% increase in the aggregated quasi-practical AEP of tidal streaming sites. For this reason the relationship between theoretical resource and quasi-practical and practical AEP of tidal streaming sites are likely to be conservative.

Clearly further research is needed to better understand any general relationships between resource types, given the limited number of estimates that are available. Nevertheless, figure 12a is informative because it suggests that widespread theoretical resource estimates, which are derived relatively easily, may provide insight into the magnitude of the quasi-practical resource, for which direct assessments are scarce, and more complex to derive.

Figure 12b shows the relationship between theoretical resource and practical AEP estimates from the same UK sites [17]. Practical constraints differ significantly from site to site, depending on the level of shipping, fishing and natural designation. Uncertainty bounds indicate the range of practical AEP estimates, based on site specific pessimistic to optimistic practical constraint levels. Designated conservation areas impose the most impactful practical constraint, reducing site specific practical AEP to just 5% of the quasi-practical AEP in the most extreme cases. Uncertainty in practical constraints is particularly high at the large hydraulic current sites.

The quasi-practical and practical AEP estimates presented in figure 12 are relevant to the specific set of constraints imposed in the UK resource assessment, such as the limit to the change in tidal range as a result of adding turbines to each site. Two points are important here; (i) quasi-practical and practical AEP are highly sensitive to the constraints that are imposed, and (ii) there is a high level of uncertainty surrounding appropriate constraints when deriving quasi-practical/practical AEP. Further research is needed to characterize technical and practical AEP sensitivity to the range of realistic constraints that may be imposed. This is explored further in §6c.

(b) National/regional contribution potential

To build on the quasi-practical resource estimates at UK sites, the relationships between theoretical and quasi-practical resource presented in figure 12a are used here to estimate the quasi-practical resource at the additional 51 sites, that to date, have only undergone theoretical resource assessment. This increases the number of sites with quasi-practical resource estimates from 39 to 90, equivalent to 21% of the 426 sites identified in this review.

Based on the scaling between theoretical and quasi-practical resource in figure 12a, of 0.32, 0.05 (taken as the average between 0.03 and 0.07) and 0.02 at hydraulic current, tidal streaming and resonant system sites respectively, the quasi-practical resource projection at the 90 sites is 108 TWh. This is equivalent to 41 GW of installed capacity, if turbines operate with a capacity factor of 0.3. This is distributed across the UK (25 TWh), France (1.5 TWh), Canada (18 TWh), USA (17 TWh), China (4.0 TWh) and New Zealand (42 TWh). It should be noted that technical resource estimates have been made at sites in Indonesia and Malaysia (totalling 52 TWh/year), but quasi-practical resource estimates could not be estimated in these cases, since no theoretical resource estimates exist to derive them from. Nevertheless they provide useful insight into the potential for tidal stream to play a significant role in these countries electricity supply.

Tidal stream resources in the UK, Indonesia and New Zealand show the greatest potential to contribute to national-scale electricity supply, where national quasi-practical or technical resource estimates are 16%, 17% and 93% of current national electricity production, respectively. National quasi-practical resource is a far lower proportion of electricity production in France (0.3-6.5%), Canada (3%), USA (0.4%) and China (0.1%). Factors causing this include a shortage of theoretical and quasi-practical resource estimates (less than 20% of sites in France and Canada, as shown in figure 11), and exceptionally high national electricity demand in Canada, USA and China. In these countries, regional-scale tidal stream electricity production may still be significant, since quasi-practical resource estimates are 6%, 200%, 243% and 103% of electricity production in Normandy (France), Nova Scotia (Canada), Alaska (USA) and Zhoushan (China), respectively.

The information presented in this review broadly supports the European Commission's projection of at least 8 GW of tidal stream capacity installed in Europe [15]. The UK's practical AEP estimate, of 34 TWh/year, is equivalent to an installed capacity of over 10 GW, based on capacity factor turbine performance of 0.3. Estimates in France are less certain, but the most prominent site of Raz Blanchard (East Alderney Race) has a projected quasi-practical capacity potential that exceeds 0.5 GW. 26 additional candidate sites have been identified in Norway and the Faroe Islands that have the potential to add to the European aggregate resource estimate.

Evidence is inconclusive on the validity of Ocean Energy System's projection of 120 GW global capacity. The aggregated quasi-practical resource projection is equivalent to 41 GW installed capacity, based on just 20% of the candidate sites that have been identified in this review. Clearly, the remaining 341 sites will contribute significantly to add to this global aggregate. However, there is high uncertainty in the practical constraints used to estimate this aggregated 41 GW potential. This is particularly true of grid constraints, which are largely neglected in practical resource assessment. Uniquely, Canadian resource assessment has started to investigate this point, and unsurprisingly concludes that when proximity to transmission grid, as well as port infrastructure, are considered, sites with excellent tidal stream resources become very challenging to develop [42]. The remoteness of tidal resources is notable around the world. Sites that contribute significantly to the aggregated global theoretical resource, such as the Pentland Firth in the UK, and Cook Inlet and Chatham Strait in the USA, are located far from major cities and suitable grid infrastructure for large scale tidal power transmission. It is recommended that grid and local demand increase (e.g. from the electrification of transport and heating) is considered in future practical resource assessment to help address this.

(c) Recommendations for future resource assessment

In general, technical/practical resource assessments are limited by their approach of deriving energy extraction based on a single, homogeneous turbine/array design, a single set of

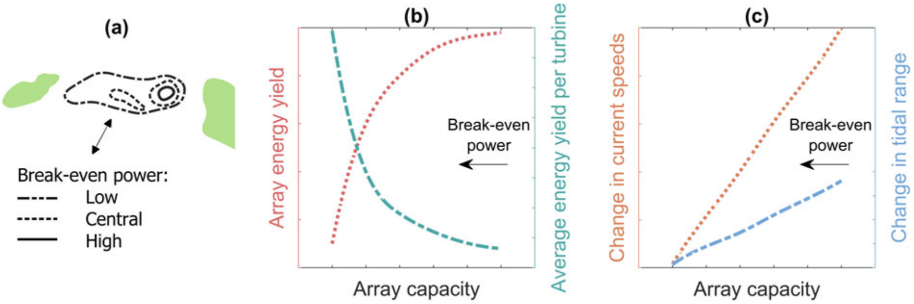

Figure 13. (a) Illustration of optimal array footprints for low, central and high break-even power based on adjoint array optimization in the Alderney Race [168], with arrows indicating ebb/flood current direction. (b) Relationship between array capacity and array/turbine energy yield, with break-even power increasing from right to left. (c) Relationship between array capacity and changes to current speeds and tidal range, with break-even power increasing from right to left.

practical constraints, and limited consideration regarding turbine/array energy performance. Consequently, resource estimates are only valid for the specific turbine/array design and practical constraints that are adopted. Often this approach yields very low turbine/array performance. Instead, resource assessment methods need to address the point that practical constraints and array performance requirements are not exactly known. They depend on a wide range of factors, and will differ depending on many project/sector related factors (e.g. cost of grid connection, competition from other generation projects, etc.). Further, they will evolve over time as the energy sector develops. For these reasons it is prudent that resource assessment establishes the sensitivity of technical/practical resource to these factors.

Adjoint optimization [160,161] helps to address many of these challenges, yet it has only been implemented in a small number of idealized and simplified site specific studies to date [162–169]. Array drag is implemented within hydrodynamic modelling to derive the changes to the surrounding flow field as a result of the added turbine drag, and energy yield of the first array design. Changes to the array design are then made to derive the functional gradient; the change in array performance with respect to changes in array design. The functional gradient informs subsequent improvement to the array design, which is then simulated in the hydrodynamic model to re-derive the flow field and array yield. This process is repeated until an optimal array design is established.

A framework for implementing the method is provided by Goss *et al.* [170], and forms the basis of the recommendations provided here. Figure 13 illustrates the reccommended approach, based on initial results focused on the Alderney Race [168]. Adjoint optimization of the array layout is implemented across a range of array sizes. The array size is constrained by setting a ‘break-even’ power, which is defined as the time-averaged power that the turbines must generate to be economically viable. The adjoint optimization establishes the array design that achieves the break-even power with greatest array yield. This process is repeated across a range of break-even power levels, to establish the sensitivity of array design and energy yield to break-even power, as illustrated in figure 13a,b.

Figure 13b shows that as the optimal array capacity increases, as a result of reducing break-even power, there is an increase in the energy yield of the array. There is a diminishing return however, as a result of new turbines being added in less energetic positions, and the added turbine drag impacting the available energy to the array, resulting in a reduction in the average energy yield per turbine. Figure 13a shows that the optimal expansion of the array leads to turbines spanning the site, to block the flow and help prevent flow diverting around the array.

Figure 13c illustrates the relationship between array capacity and changes to the current speeds and tidal range, based on UK resource assessment [17]. Establishing the sensitivity of energy yield to such environmental impacts is another important part of practical resource assessment that is, in general, neglected. Doing so allows the level of energy extraction to be re-assessed as understanding of acceptable changes in these, albeit broad environmental impacts, improve over time.

Adjoint turbine/array optimization provides multiple advancements on manual/un-coupled array optimisation approaches. Firstly, the inclusion of turbine drag within the hydrodynamic modelling means that changes to the surrounding flow field arising from the added array drag are updated at each iteration of the turbine/array optimization loop in order to inform the following array optimization iteration. Secondly, it can enable multi-criteria optimization, where for example, the addition of turbines is weighed up against cost of energy [168] and/or changes to the flow field in environmentally sensitive areas [166,167]. Thirdly, its computational expense is almost independent of the size of the array. Evidence shows that the method is capable of optimizing both the turbine specification and positions of a large array in less than 200 forward model and adjoint model runs [160]. Recommendations are made be Vennell *et al.* [126] that can help reduce computational expense significantly. A drawback of the adjoint method is that it can be difficult to establish if a local or global optimal array design has been derived, as is the case with optimization methods in general.

7. Conclusions

100 MW scale expansion of the tidal stream energy sector is planned over the next 5 years in the UK and France, which if delivered, will increase cumulative global installed capacity by 440%, to 188 MW. This would reflect similar progress to that made by the offshore wind sector 25 years ago. This review considers the future global contribution tidal stream may be able to make. It is motivated by projections that by 2050, Europe's tidal stream capacity could reach 8 GW [15], and global capacity could reach 120 GW [16], which are unsupported by site-specific assessment of the tidal stream resource itself.

This review identifies 426 candidate sites that exhibit potentially favourable conditions for tidal stream energy development across Europe, the Americas, Asia and Australasia. The literature exhibits high uncertainty over what constitutes 'suitable characteristics' for a site to be appropriate for further assessment, and adopts a wide range of site identification metrics (e.g. peak current speed, time averaged kinetic power, etc.). This means that sites that may be included in one assessment (e.g. US national assessments that use the least stringent criteria) would be discarded in others (e.g. more strict UK assessments). In general site identification is based on set levels of (say) time-averaged kinetic power, with no acknowledgement for the fact that a sites viability will evolve over time, since resource criteria such as time-averaged kinetic power are a proxy for cost of energy, and viable cost of energy is dependent on ever shifting drivers such as the cost of competing technologies. It is recommended that to account for uncertainty in what constitutes a suitable site, and its time dependency, site identification is undertaken under a range of (say) time-averaged kinetic power criteria, to derive its relationship with deployable area.

Theoretical resource estimates, which provide estimates of upper bound total energy extraction, have been made at 62% of the 426 identified sites, giving a cumulative global total of 1000 TWh/year. This cumulative theoretical resource is located across the UK (30 sites, 340 TWh/year), France (1 site, 16 TWh/year), Canada (3 sites, 64 TWh/year), USA (208 sites, 445 TWh/year), China (17 sites, 31 TWh/year) and New Zealand (2 sites, 132 TWh/year). 40% of this aggregated theoretical resource is located at just three sites; Cook Inlet (160 TWh/year) and Chatham Strait (105 TWh/year) in Alaska, USA, and Cook Strait in New Zealand (130 TWh/year).

Technical resource estimates have been made at 249 out of the 426 sites (58%). Inconsistencies in the interpretation of technical resource, and the methods used to estimate it, prevent a global aggregate estimate from being made. As an alternative, linear correlation between theoretical and technical resource estimates derived from UK sites are presented. The UK technical resource estimates impose environmental and economic constraints usually only considered in practical resource estimation, so are described here as quasi-practical resource estimates. Using these relationships, quasi-practical AEP is derived at sites that to date have only received theoretical resource estimates. This approach yields an aggregated quasi-practical AEP estimate of 108 TWh/year from the 90 sites with published theoretical resource estimates. This is equivalent to an installed capacity of 41 GW, from 21% of the candidate sites.

Practical AEP estimates have been made at just 31 sites, predominantly in the UK, with an estimated resource of 34 TWh/year. The study found practical constraints to be highly site specific and uncertain, resulting in pessimistic to optimistic practical AEP estimates that are up to 120% higher than, and 85% lower than, the baseline estimate in some cases.

The UK, Indonesia and New Zealand exhibit tidal stream resources with the greatest potential to contribute to national-scale electricity production, based on the ratio of national quasi-practical resource, to national electricity production. Resources in France, Canada, USA and China show potential to make significant regional-scale contributions. Many additional candidate sites without resource assessments have been identified, particularly in Japan, South Korea and the Philippines.

The information provided in this review broadly supports the European Commission's projected 8 GW of installed capacity in Europe [15], based on resource assessment of sites in the UK and France, and a further 26 sites identified in Norway and the Faroe Islands. Evidence is less conclusive when considering the validity of Ocean Energy System's global installed capacity projection, of 120 GW. Recommendations are provided to address this, through adjoint optimization of array design, within a framework that derives the sensitivity of the resource magnitude to current/future technical and practical constraint bands.

Data accessibility. Site specific theoretical resource data provided by the Carbon Trust is tabulated in supplementary material, Table 3.

The data are provided in the electronic supplementary material [171].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. D.S.C.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing—original draft, writing—review and editing; T.A.: investigation, writing—original draft, writing—review and editing; A.C.: investigation, writing—original draft, writing—review and editing; K.H.: investigation, writing—original draft, writing—review and editing; C.J.: investigation, writing—original draft, writing—review and editing; H.L.: investigation, writing—original draft, writing—review and editing; J.M.: investigation, supervision, writing—original draft, writing—review and editing; P.G.N.: investigation, writing—original draft, writing—review and editing; J.T.: investigation, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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