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# A review of global tidal stream energy resources

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**ABSTRACT**: This review identifies 426 sites with potentially suitable characteristics for tidal stream energy development, across nineteen 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 by filling a site with turbines. This includes not only the energy extracted directly for electricity production, but also the energy losses resulting from support structure drag, drive train losses and wake mixing. The aggregated theoretical resource estimate is 1,000 TWh/year, from 262 sites (62% of those identified), across six countries. A more informative, albeit less common, indicator of electricity generation potential, is provided by practical resource studies, that estimate annual electricity production once economic, environmental, regulatory and social constraints are taken into account. Practical resource assessments are limited mainly to UK sites, with an estimated resource of 34 TWh/year, equivalent to 10% of the theoretical resource estimate. Of the seven countries with sufficient resource information, sites in the UK, Indonesia and New Zealand show the greatest potential to make national-scale electricity supply contributions. Resource assessment in France, Canada, USA and China indicates regional-scale impact potential, with possible further resource that may be developed, depending on future resource assessment of an additional 80 sites. For countries limited to resource assessment of ambient flow characteristics only, sites in Norway, Faroe Islands, Japan, South Korea and the Philippines show the greatest energy potential. This review brings to light the inconsistent and wide ranging site selection criteria and practical constraints that are adopted in the literature. This is reflective of uncertainty in (i) what constitutes a suitable site, (ii) how site suitability evolves over time (e.g., with changing competing energy costs in the energy sector), and (iii) the level of energy that can practically be extracted. When these uncertainties are combined, along with uncertainty in resource data, and the magnitude of energy losses, reported P10 and P90 resource estimates can lie 43% below and 30% above the P50 value respectively. It is recommended that future resource assessment characterises how the resource magnitude is impacted by site selection criteria/practical constraint ranges, that acknowledge and reflect their time-dependency and uncertainty.

## 1. Introduction

The tidal stream energy sector has reached around 35 MW of global cumulative installed capacity to date, predominantly from installations in the UK (19 MW) and France (6.5 MW). The Faroe Islands, Netherlands, Canada, USA, China and Japan have begun testing tidal stream turbines in order to explore its utilisation. Future projects are contracted in the UK and France that, if delivered, would increase global cumulative installed capacity by 440%, to 188 MW, by 2029. Figure 1 shows the progression in cumulative installed capacity in countries around the world, as well as the aforementioned planned future build out. The global cumulative installed capacity, and the rate of future capacity build out, has reached similar levels to that of global offshore wind deployment around 2000. A detailed breakdown of tidal stream turbine installations to date is provided in Supplementary Materials.

Juxtaposed to this sector progress is a lack of clarity regarding the extent to which tidal stream energy can contribute to the net-zero carbon emissions transition in coastal nations. This is in part due to a lack of transparency on the reliability of tidal stream turbines that have been installed to date, as reflected in Tables 8 and 9 (Supplementary Materials), which raises questions regarding their reliability. Secondly, in general global/regional estimates of tidal stream capacity build out are limited to energy market studies, without detailed consideration for the resource itself. For example, the European Commission estimates that up to 8 GW of tidal stream energy may be installed in Europe by 2050, based on project pipelines currently being developed, and future installation projections based on current/expected build-out rate [16]. Ocean Energy Systems have developed an ocean energy roadmap that sets out 120 GW of tidal stream energy capacity installed globally by 2050 [17]. 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

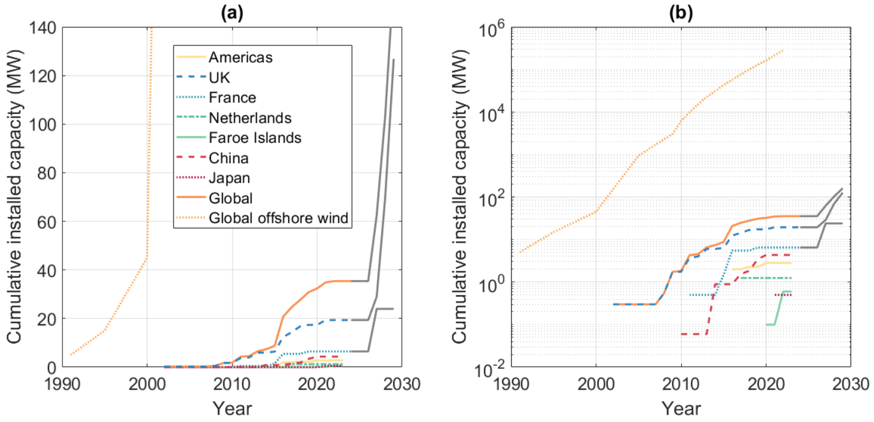


**Figure 1.** Increase in cumulative installed capacity of tidal stream between 2002 - 2029 [1–14], including future projects to be delivered between 2023 - 2029 that have successfully secured subsidy support (plotted grey). Figure 1b shows the cumulative global installed capacity of offshore wind to provide context [15]. The underlying installation information is provided in Supplementary Materials.

out), the cost of upgrades to/new infrastructure such as ports and manufacturing facilities, and regulation and legislation requirements. The projection is constrained by expected build-out rates, cost reduction as the sector develops, and the cost effectiveness of investment. The Eurpopean Commission/Ocean Energy System studies do not provide evidence that the projected installed capacities are underpinned by resource assessment of specific sites. It is likely for this reason that the studies do not provide detail on the specific locations that capacity would be built out.

Uncertainty and 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 mechanism requirements, (iii) investor confidence, and (iv) supply chain requirements to mobilise volume manufacturing. For this reason it is important that estimates of tidal stream energy potential are underpinned by both market studies and robust resource assessment.

This is addressed here through a review of the state of the art in tidal stream energy resource assessment. §2 provides a description of resource categorisation, to set out the different stages of assessment, which are discussed throughout the paper. §3 - 9 provide reviews of tidal resource studies for sites in the UK, France, Canada, USA, China, Japan and Indonesia respectively, in order to provide an evidence-led catalogue of site and country specific tidal stream resources. Countries have been selected for review based on the stage and rigour of resource assessments conducted, and the magnitude of resource estimates. Sites where further resource assessment is required are identified and discussed in §10. §11 provides a discussion that summarises findings, and provides recommendations for future work, and §12 summarises the main conclusions.

The review describes resource estimates in terms of annual energy, as opposed to power. This approach helps prevent ambiguity arising from the many different ways of describing power resource that are used in the literature, such as installed power capacity, time-averaged power and instantaneous power. Quoting resource in terms of annual energy also allows results to be contextualised through comparisons against national/regional energy demand.

## 2. Resource categorisation

## (a) Kinetic resource/Site characteristics

At its simplest level, tidal stream energy resource is characterised based on point measurements of depth, time-averaged/maximum current speeds and power density. In general single point resource measurements are suitable for estimating the energy yield of a single turbine, but fail to consider the spatial variability in the ambient resource, and the impacts turbines have on the flow field as a result of their added drag.

The International Electrotechnical Commission standards on resource assessment (TS62600-201) state that consideration of changes to the flow field are important when the installed capacity is greater than 10 MW, and/or the extracted energy is greater than 2% of the theoretical resource [18]. Other factors that are also important are the local and channel blockage ratios, which describe the ratio of the frontal projected area of a turbine, and array, to the site cross sectional area. The limit of power extraction by a single turbine in an idealised channel with uniform cross-sectional area, respectively, is proportional to $(1 - B)^{-2}$, where $B$ is the turbine blockage ratio [19]. The turbine's power performance is effected by the proximity of the rotor to the sea bed, free surface and lateral site boundaries, so the aspect ratio of the cross sectional area and the hub height of the turbine are also important [20]. Similarly, for single row turbine arrays, energy extraction is affected by the lateral spacing between rotors, where optimal lateral spacing results in an uplift in power performance because of reduced redirection of the flow around the turbines [21]. For multi-row turbine arrays, the longitudinal spacing between rows is also an important consideration, as wakes from upstream turbines can impinge on downstream turbines, thereby limiting downstream turbine power generation. Staggered turbine layouts can help enhance the power generation of downstream turbines when the downstream turbines are positioned in the accelerated bypass flow of upstream turbines [22]. In this paper these impacts on the flow from installing turbines are broadly referred to as changes to the surrounding flow field.

## (b) Theoretical resource

As turbines are added to a site, the energy extracted by the turbine array also increases, by virtue of the array's installed capacity increasing. The added drag from the turbines modifies the surrounding flow field, resulting in an increase in the free surface elevation upstream of the array, and a reduction downstream [23]. At some upper bound number of turbines, when evenly distributed across the entire width of a site, the energy that can be extracted reaches an upper limit, known as the theoretical resource. The addition of further turbines reduces energy extraction due to changes to the surrounding flow field, such as a reduction in the volume flux through the site, causing the available energy to the turbines to reduce. The theoretical resource quantifies this total, upper bound energy extraction. I.e., it quantifies not only the energy converted to electricity by the turbines (termed useful energy here on in), but also the turbine drive train losses, support structure drag losses and wake mixing losses, [24], as well as added seabed drag losses that may arise from flow acceleration underneath the turbine rotors [25]. The total energy extracted from the flow is the useful energy and these aggregated energy losses. The significant change in the flow field that arises as a result of extracting the theoretical resource means it would never be practical to extract this much energy in reality. Nevertheless theoretical resource is a useful, easily attainable indicator of a sites potential for tidal stream energy development. This is discussed further in §11.

For tidal channels, the theoretical resource is estimated to be between 20 and 24% of the product of peak tidal pressure head (from one end of the channel to the other), and peak undisturbed mass flux through the channel [26]. At this upper bound the current in the channel with turbines is reduced by around 40% of the undisturbed flow [27]. The theoretical resource is, in general, considerably less than the average kinetic power flux through the most constricted cross-section of a channel [26]. 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 [26]. 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 as ’the average annual power available at a site’ [28].

### (c) Technical resource

The National Academy defines the technical resource as the ‘portion of the theoretical resource that can be captured using a specific technology’ [28]. The technical resource considers turbine specification, such as rotor diameter, rated power, and cut-in/cut-out speeds. The introduction of a turbine rated power means that turbines limit energy extraction once the flow reaches/exceeds the rated speed of the turbine.

There are two main sources of ambiguity with this definition of technical resource. The first is that there is currently no clearly defined method for choosing suitable turbine design parameters (e.g., rated speed, rotor diamater), and array design parameters (e.g., number of turbines, turbine spacing and array footprint). The second stems from the word ‘captured’ in the National Academy’s definition of technical resource, which implies that technical resource quantifies the useful energy that is harnessed directly for electricity production, and not the total energy that is extracted as a result of installing turbines. This is not explicitly defined, which may have led some resource studies to favour quantifying the total extracted energy.

For example, The Carbon Trust’s UK resource study interprets the technical resource as the total energy that is extracted by specific technology, once economic and environmental constraints are imposed, to limit the number of turbines that are installed [29]. The study also considers cases where the cut in, cut out and rated power of the turbines is neglected [30]. The same study also considers another definition, which it calls the technical annual energy production (AEP). This is the useful energy that is harnessed for electricity production directly, once environmental and economic constraints on the number of installed turbines are imposed [29].

The different definitions of technical resource are discussed throughout the paper, with recommendations provided in Section 11 for how to consolidate the definition.

### (d) Practical resource

The National Academy’s definition of the practical resource is the portion of the technical resource available once all economic, environmental, regulatory and social constraints, which limit the installed capacity and array footprint, have been applied [28]. In general practical resource assessments quantify annual electricity production, 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 [31]. 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.

The accessible and viable resource categories introduced by SEI are not adopted here for three main reasons. Firstly, site specific constraints should not just be limited to environmental considerations [28]. 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 characterisation should be kept as simple as possible to ease its adoption and limit ambiguity [32].

## 3. UK and British Channel Islands

The latest UK-wide tidal stream energy resource assessment was commissioned by the Carbon Trust in 2011 [29]. This study, along with others, were reviewed in a 2021 review of UK tidal stream resource assessment [33]. The main findings from these works are provided here, along with subsequent resource assessment research.

## (a) Kinetic resource

The Carbon Trust study built parametric 2D hydrodynamic models to simulate the tidal flows at UK sites, with turbine drag added through an additional source term in the momentum equations. The models were forced by M2 and S2 constituents. The simplified geometry adopted in the parametric modelling approach was validated against more detailed, site specific modelling of Strangford Lough in Northern Ireland [30].

The study categorises the sites based on thee primary mechanism that drive the flow. At hydraulic current sites, the pressure gradient created by a difference in water level between two bodies of water drives the flow. Tidal streaming sites exhibit acceleration when flow is forced through a constriction as a result of continuity. Finally, resonant basins exhibit constructive interference between an incoming tidal wave and a reflected tidal wave, causing a standing wave.

28 sites were selected for assessment, based on criteria for achieving 'reasonable project economics', which required depth greater than 15 m, and time averaged power density exceeding 1.5 kW/m$^2$.The locations of the 28 sites, along with others that are reviewed here, are shown in Figure 2. Accompanying resource data for each site is summarised in Table 1.

## (b) Theoretical resource

The Carbon Trust study estimated the theoretical resource by simulating turbine drag with a locally enhanced bed-friction field, that is parameterised based on the turbine density and turbine thrust curve(s). The enhanced bed friction field spans the whole width of each site. The total theoretical resource from the 28 sites is 340 TWh/year. The study does not provide a breakdown of each sites theoretical resource estimate.

By far one of the largest UK resources is the Pentland Firth in Scotland. Draper et al. (2014) [34] estimated the Pentland Firth's theoretical resource using the DG-ADCIRC 2D hydrodynamic model [35], with M2 and S2 boundary forcings. The estimate, of 37 TWh/year, is equivalent to 11% of the Carbon Trust's UK estimate.

Coles et al. (2017) [36] adopted a similar method to estimate the theoretical resource of sites in the Channel Islands, including Alderney Race, using a Telemac 2D hydrodynamic model of the English Channel. The research reported theoretical estimates for Alderney Race, Casquets and Big Russel, of 49.2 TWh/year, 9.8 TWh/year and 2.0 TWh/year respectively, 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 49.2 TWh/year theoretical resource estimate is located outside of UK waters. This is discussed further with respect to technical resource.

## (c) Technical resource

The Carbon Trust study adopts two different definitions of technical resource. The first quantifies total energy extraction after environmental and economic constraints, that are normally associated with the practical resource, have been imposed. These constraints limit changes to mid-range flow speeds to less than 10%, or a reduction in tidal amplitude of less than 0.1 m, which ever comes first as turbine drag is increased. The rationale for this approach is that ecological systems encountered at suitable sites 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 study implements economic constraints so that the cost of energy that is extracted is within 80% of the energy that would be extracted if the surrounding flow field is unaffected by the added turbine drag. In cases where this constraint is exceeded, the packing density of turbines is reduced from its maximum limit of 2.5 and 10 rotor diameter spacing between rotors respectively. The cost of energy at shallow sites known to be under development (Kyle Rhea, Strangford Lough, Pentland Firth Shallow, Westray Firth and Alderney Race), are derived based on 1st generation technologies that were already largely proven at the time of the study in 2011. The costs at all remaining sites are derived based on 2nd generation technologies, that were derived based on a learning rate of around 12%.

Results demonstrate that at hydraulic current, tidal streaming and resonant basin sites, this technical resource is 45%, 13% and 16% of the theoretical resource respectively [30]. An important caveat to these findings is that in reality, sites may be driven by a combination of hydraulic current, tidal streaming and resonant basin mechanisms, so the validity of this result depends on how dominant one mechanism is over others.

The Carbon Trust study's alternative definition of technical resource, termed the technical annual energy production (AEP), is the energy that can be harnessed usefully for electricity production using envisaged technology, once the same environmental and economic constraints are applied. The study estimates that 15% of the total energy lost from the flow system is wasted as a result of support structure drag. It is estimated that the energy not captured by downstream turbines as a result of upstream turbine wake propagation is 10% of the total amount of the extracted energy. The technical AEP from the 28 sites is 29 TWh/year. A breakdown of technical AEP by site is provided in Table 1.

The impact of relaxing economic constraints at the Pentland Firth was investigated, on the basis that the very large resource exhibited in the Pentland Firth enables economies of scale. This resulted in a 10 TWh/year increase in the national technical resource estimate, from 29 TWh/year to 39 TWh/year. The study also investigated the impact of retiring the tidal range constraint on energy extraction at the tidal streaming sites, since these 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 technical resource estimate, to 49 TWh/year. The study does not provide a site-by site breakdown of this additional 10 TWh/year.

The study acknowledges the need for further work to test the robustness of technical AEP estimates given uncertainty in the modelling. Based on the uncertainty in economic and environmental constraints, and energy losses, P10 and P90 technical AEP estimates fall 43% below and 32% above the P50 estimate respectively.

Subsequent resource assessments also lie between the National Academy's definition of technical and practical resource. Adcock et al (2013) [37] modelled three rows of turbines spanning the entire width of the Pentland Firth using a validated ADCIRC depth averaged hydrodynamic model forced by M2 and S2 constituents. Turbines block 40% of the channel, and are represented as a line discontinuity in free surface elevation [38]. The study estimates the technical AEP to be approximately 17 TWh/year, which results in a reduction in maximum current speeds in the region of energy extraction of 30%. It is concluded that adding a fourth row of turbines results in an additional technical resource of 2 TWh/year, and that this is unlikely to be economically viable as it provides a time averaged power of 0.75 $kW/m^2$, which falls below the upper-bound performance of wind turbines, of around 1 $kW/m^2$. This technical AEP estimate is within 20% of The Carbon Trust estimate, of 21 TWh/year.

Coles et al. (2020) [23] investigated the technical AEP of a 3.3 GW array located in Alderney Race, that was originally considered by Bahaj et al. (2004) [39]. The research used validated Telemac 2D hydrodynamic modelling with 250 m resolution, and considered the impacts of turbine installation on changes to the flow field through the inclusion of a continuous array drag term in the momentum equation. The study estimated that the array would produce 3.2 TWh/year, with 1.4 TWh/year produced by turbines in Alderney territorial waters, based on M2 and S2 forcing. The study attempted to maximise the performance of turbines by considering heterogeneous array design, where a range of rotor diameters and rated power were utilised to account for the spatial variability in depth and ambient current speeds across the Race. The study did not consider the significant changes to the surrounding flow field as a result of introducing turbine drag when sizing rated power, resulting in the turbine's rated power being oversized. Consequently the capacity factor, which is the ratio of energy production to energy production from continuous rated power operation, of the array was 0.11. This performance brings into doubt the economic feasibility of such an array that uses horizontal axis turbines.

More recent resource assessment by Patel et al. (2024) [40] have considered heterogeneous array design based on the modified flow field for arrays in the Pentland Firth, yielding significantly improved capacity factors similar to those required for economic viability of the MeyGen array [41], of around 0.3. Array performance and the economic viability of arrays is discussed further in Section 11.

In general, technical resource estimates adopt the continuous drag approach to simulate turbine scale. This method does not resolve the sub-turbine scales, so is not capable of simulating individual turbine wakes. A shortfall of this approach is that the wake losses cannot be modelled explicitly. Alternative, discrete turbine representation requires sub-turbine scale mesh resolution, which can become prohibitively computationally expensive. This is discussed further in §11.

## (d) Practical resource

To estimate the UK practical resource, The Carbon Trust study investigated the impact of an additional 100 constraints. The constraints were treated either as exclusion zones (e.g. wind farm sites, oil and gas safety zones, aquaculture leases), or as restricted zones that consider aspects such as shipping density, annual fishing value and dredging licences/applications. The study concludes that only three constraint types potentially impede project development; fishing, shipping and designated conservation areas. In the case of Pentland Firth, it was assumed that shipping would cover 30% of the site. Grid connection constraints were neglected and grid connection cost estimates only include the costs of connection to a shore based transformer/grid connection station. Grid accessibility and associated costs is highlighted as an important constraint that should be investigated further.

At a site level, location-specific aggregated constraints on energy extraction vary widely; between 30 - 100%. The practical resource is estimated to be 34 TWh/year, once the environmental and economic constraints described above are relaxed [42]. This is equivalent to 10% of current UK annual electricity demand. The site specific practical resource estimates are summarised in Table 1.

The Carbon Trust study reports significant uncertainty in its resource estimates, with 'low' and 'high' resource estimates that are 24% lower, and 33% higher than the base estimate. The main source of uncertainty identified in the Carbon Trust study is from the parametric modelling approach. This is evident from subsequent studies that use higher fidelity, site-specific hydrodynamic modelling, and/or enhanced field measurements, which in some cases report different kinematic resource estimates. For example, Coles et al. (2017) [36] estimate that at Big Russel, the area that time-averaged power density exceeds 2.5 $kW/m^2$ is 14 $km^2$. This is 13 $km^2$ more than the Carbon Trust study estimate of area that exceeds 1.5 $kW/m^2$. Similar assessments of the Ramsey Sound, Isle of Wight and Portland Bill also derived different deployable areas, based on site-specific hydrodynamic modelling and geo-spatial analysis that brought together over 50 different datasets of practical constraints [43,44], including areas close to shipwrecks, ports, oil and gas operations, offshore wind farms, dredge spoil dumping sites, mineral/aggregate extraction and dumped munitions, as well as soft constraints that have the potential to prevent development. These include vessel traffic, fishing activity, marine protected areas, seabed sediment type, distance to shore, distance to grid and seabed gradient.

Contributions from 13 additional sites identified here have the potential to increase the national total considerably, subject to further investigation. These include Burra Sound, Hoy Sound, and Lashy Sound, which all exhibit maximum current speeds of 3 m/s or greater.

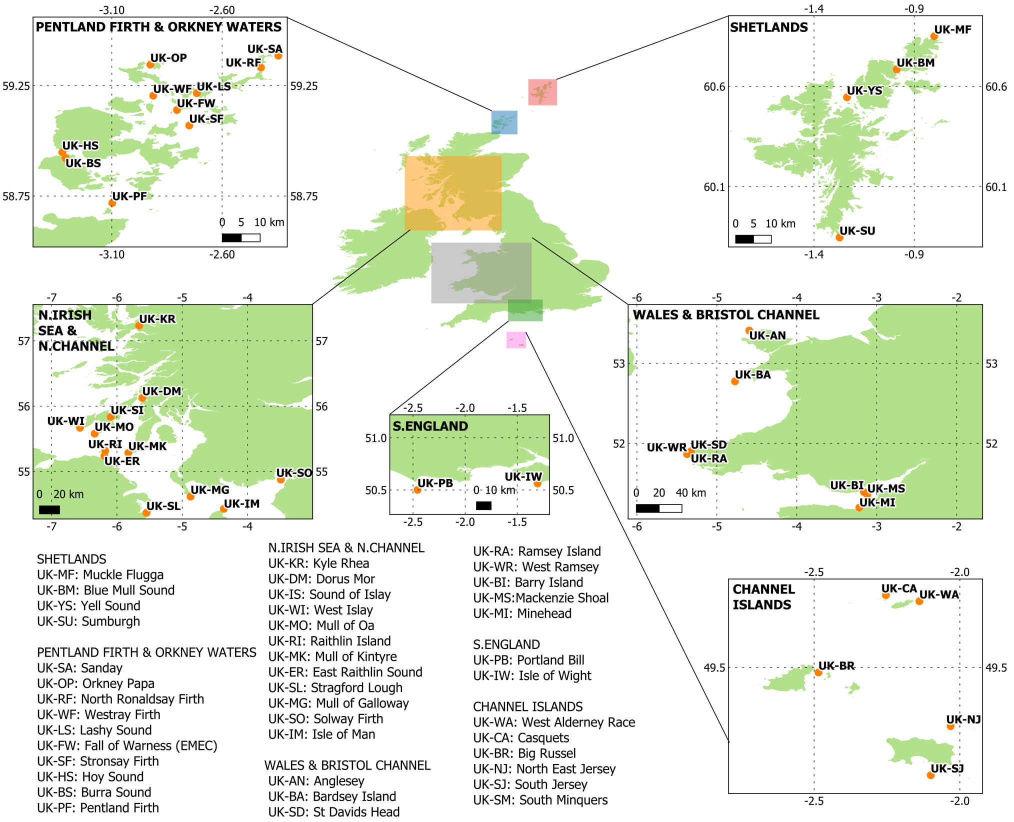


**Figure 2.** Overview of UK and British Channel Island tidal stream energy sites.

**Table 1.** Summary of kinetic, theoretical, technical and practical resource estimates of UK sites (excluding the Channel Island sites). Unless otherwise stated, data has been obtained from the Carbon Trust study [29].

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area (km$^2$) | Width (km) | Depth (m) | Flow vel. (m/s) | | Pow. den. (kW/m$^2$) | | Energy (TWh) | Energy (TWh) | Energy (TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Pent.Fir./Ork.Wat.** | | | | | | | | | | | | | |
| Orkney Papa | UK-OP | 59.3456 | -2.9256 | - | 2.5 | 30 | - | 2.9 [45] | - | - | - | - | - |
| N.Ronaldsay Firth | UK-RF | 59.3319 | -2.4238 | 17 | - | 17 | - | 2.4 | - | - | - | 0.4 | 0.4 |
| Westray Firth | UK-WF | 59.2049 | -2.9126 | 18 | - | 42 | - | 2.4-3.5 [46] | - | - | - | 0.9 | 1.3 |
| Stronsay Firth | UK-SF | 59.0697 | -2.7491 | - | - | - | - | 2 [46] | - | - | - | - | - |
| Hoy Sound | UK-HS | 58.9481 | -3.3250 | - | - | - | - | >4 [46] | - | - | - | - | - |
| Burra Sound | UK-BS | 58.9216 | -3.3103 | - | - | - | - | 3 [46] | - | - | - | - | - |
| Fall of Warness/Shapinsay Sound (EMEC) | UK-FW | 59.1398 | -2.8050 | - | - | - | - | >3.5 [46] | - | - | - | - | - |
| Lashy Sound (Eday) | UK-LS | 59.2161 | -2.7149 | - | - | - | - | >3 [46] | - | - | - | - | 0.1 [47] |
| Pentland Firth* | UK-PF | 58.7186 | -3.0984 | 260 | - | 30-62 | - | 3.1 - 4.7 [48] | - | - | 36.7 [34] | 17 [37]-21.3 | 11.3 |
| **N.Irish Sea/N.Cha.** | | | | | | | | | | | | | |
| Kyle Rhea | UK-KR | 57.2329 | -5.6598 | 1 | - | 34 | - | 3.8-4 [46] | - | - | - | 0.1 | 0.1 |
| Dorus Mor | UK-KR | 56.1266 | -5.612 | - | 0.8 | 22 | - | 4.1 [45] | - | - | - | 0.1 | 0.1 |
| West Islay | UK-WI | 55.6702 | -6.5655 | 93 | - | 31 | - | 2.4-4 [46] | - | - | - | 1.2 | 1.9 |
| Islay (Mull of OA) | UK-MO | 55.5805 | -6.3409 | 128 | - | 37 | - | 2.4-4 [46] | - | - | - | 0.9 | 1.5 |
| Sound of Islay | UK-SI | 55.8373 | -6.0943 | - | - | - | - | >2.5 [49] | - | - | - | - | - |
| Raithlin Island | UK-RI | 55.3161 | -6.179 | 4 | - | 102 | - | 2.3 - 3.0 [50] | - | - | - | 0.8 | 0.3 |
| E.Raithlin Sound | UK-ER | 55.2372 | -6.1922 | 2 | - | 45 | - | 2.2 - 3.0 [50] | - | - | - | 1.9 | 0.2 |
| Mull of Kintyre | UK-MK | 55.2856 | -5.8261 | 9 | - | 116 | - | 2.4 | - | - | - | 0.4 | 0.6 |
| Mull of Galloway | UK-MG | 54.6165 | -4.8717 | 9 | - | 29 | - | 2.3 | - | - | - | 0.3 | 0.5 |
| Strangford Lough | UK-SL | 54.3693 | -5.5476 | 3 | - | 35 | - | 3.5 | - | - | - | 0.3 | 0.1 |
| Isle of Man | UK-IM | 54.4307 | -4.3611 | - | - | - | - | - | - | - | - | 1.8 [51] | - |
| **Shetlands** | | | | | | | | | | | | | |
| Blue Mull Sound | UK-BM | 60.6846 | -0.9872 | 2 | - | 35 | - | 3.1 | - | - | - | 0.06 | 0.1 |
| Yell Sou. (W.Cha.) | UK-YS | 60.5453 | -1.2356 | 2 | - | 30 | - | 2.4 | - | - | - | - | - |
| **Wales/Bri.Cha.** | | | | | | | | | | | | | |
| Anglesey | UK-AN | 53.4119 | -4.5941 | 50 | - | 38 | - | 2.3 | - | - | - | 1.9 | 2.4 |
| Bardsey Island | UK-BA | 52.7769 | -4.7726 | 1 | - | 29 | - | 2.3 | - | - | - | 0.03 | 0.03 |
| West Ramsey | UK-WR | 51.8753 | -5.3257 | 18 | - | 42 | - | 2.4 | - | - | - | 0.9 | 0.7 |
| Ramsey Sound | UK-RA | 51.8719 | -5.3258 | - | 0.7 | 30 [43] | - | 5.0 [43] | - | - | - | 0.06 [43] | - |
| Barry Island | UK-BI | 51.3930 | -3.1601 | 9 | - | 26 | - | 2.3 | - | - | - | 0.3 | 0.2 |
| Mackenzie Shoal | UK-MS | 51.3527 | -3.1169 | 4 | - | 22 | - | 2.9 | - | - | - | 0.3 | 0.1 |
| Minehead | UK-MI | 51.1995 | -3.2160 | 17 | - | 30 | - | 2.3 | - | - | - | 0.6 | 0.4 |
| St Davids Head | UK-SD | 51.9033 | -5.3193 | - | - | 40 [43] | - | 5.0 [43] | - | - | - | - | - |
| West Ramsey Island | UK-WR | 51.8618 | -5.3712 | - | - | 25 [43] | - | 5.0 [43] | - | - | - | - | - |
| **S.England** | | | | | | | | | | | | | |
| Isle of Wight | UK-IW | 50.5632 | -1.3051 | 21 | - | 29 | - | 2.3 | - | - | - | 0.5 | 0.6 |
| Portland Bill | UK-PB | 50.5016 | -2.4567 | 1 | - | 29 | - | 2.2-3.6 [52] | - | - | - | 0.04 | 0.03 |
| **Cha.Isl.** | | | | | | | | | | | | | |
| W. Alderney Race | UK-AL | 49.7270 | -2.1390 | - | - | 31 | 2.7 [23] | 5 [23] | 13.5 [36] | - | 30.3 [36] | 1.3 [23] | 3.0 |
| Casquets | UK-CA | 49.7480 | -2.2540 | 77 | - | 21 | 2.2 | - | 3.5 [36] | - | 8.9 [36] | 2.5 [36] | 3.2 |
| Big Russel | UK-BR | 49.4830 | -2.4850 | 1 | - | 36 | 2.2 | - | 2.3 [36] | - | 1.8 [36] | 0.4 [36] | 0.1 |
| North East Jersey | UK-NJ | 49.2990 | -2.0320 | 35 | - | 21 | 2.4 | - | 2.3 [36] | - | - | 1.9 | 1.5 |
| South Jersey | UK-SJ | 49.1310 | -2.1000 | 60 | - | 20 | 2.4 | - | - | - | - | 3.1 | 2.5 |
| S.Minquiers | UK-SM | 48.9960 | -2.1260 | 11 | - | 16 | 2.3 | - | - | - | - | 0.5 | 0.4 |

## 4. France

### (a) Kinetic resource

Guillou et al. (2018) [53] identified potential sites in Western Brittany and the Channel Islands using a tidal current harmonic database, derived from the MARS 2D hydrodynamic model [54] [55]. The research used a resolution of up to 250 m in the regions of interest for energy extraction, and considered M2 and S2 current velocities. Sites were identified based on water depths greater than 25 m and depth-averaged peak spring current speeds in excess of 2 m/s. Based on this criteria, six sites were identified, which are listed in Table 2. The greatest kinetic resources are exhibited in the Alderney Race and the Raz de Barfleur off the Normandy coast, and the Fromveur Strait in Western Brittany.

Campbell et al. (2017) [56] quantified the kinetic resource at 20 sites within the Channel and Atlantic waters. The study also used outputs from the MARS 2D hydrodynamic model. Site selection was based on two criteria; current speeds greater than 1.5 m/s during mean spring tides, and water depth between 10-60 m. It was found that a total area of approximately 260 km$^2$ full-fills this criteria. The resource is located predominantly around the Cotentin Peninsula, Normandy, in the Alderney Race and the Raz de Barfluer, covering an area of 285 km$^2$. The study identifies lower flow sites around Brittany, such as Paimpol-Brehat. Less stringent current speed criteria were also considered that increase the area significantly, but are not discussed in this review since there is no evidence that they would ever be economically feasible at this stage.

Coles et al. [36] also investigated the kinetic resource in the Channel Islands, including East Alderney Race, and Raz Barfluer, reporting time-averaged power density of 13.5 kW/m$^2$ and 3.8 kW/m$^2$ respectively.

### (b) Technical resource

Campbell estimated the technical resource based on 'low', 'medium' and 'high' criteria. Here the discussion focusses on the 'high' criteria, which requires turbines to operate with a capacity factor of 0.4, and adopt lateral and longitudinal spacing between turbines of 5 and 18 rotor diameters respectively. These criteria are loosely in line with the performance of operating turbines [41], and the expected design of future arrays. When the site selection criteria includes sites that exhibit mean current speed greater than 1.5 m/s, the technically exploitable power estimate is 13 TWh/year. The study does not consider changes to the flow field as a result of turbine installations explicitly. The study reports potential errors in the current speeds derived from hydrodynamic modelling of up to 10%.

As discussed in Section 3, several studies consider the resource in the East Alderney Race, which lies in French territorial waters [23,29,39,57]. Coles et al. (2020) [23] used 2D hydrodynamic modelling to consider the energy yield of a large array, with consideration for changes to the flow field from turbine installations, resulting in a technical resource estimate in the East Race of 1.9 TWh/year. This is significantly less than the technical resource estimate by Campbell et al. (2017), of 6.0 TWh/year, which is likely to be a consequence of considering the impact of the added turbine drag on the technical resource. The importance of considering changes to the surrounding flow field as a result of turbine installations is discussed further in Section 11. The estimate considered co-development of tidal stream turbine arrays in the West Alderney Race, which has been shown to result in constructive interference in the region, because it helps prevent flow redirecting into a vacant West Race [36,58]. Coles et al. (2020) estimated that this level of energy extraction results in significant increases in instantaneous current speeds around the array, of up to 1 m/s, and a reduction in the time-averaged volume flux through Alderney Race of 8%.

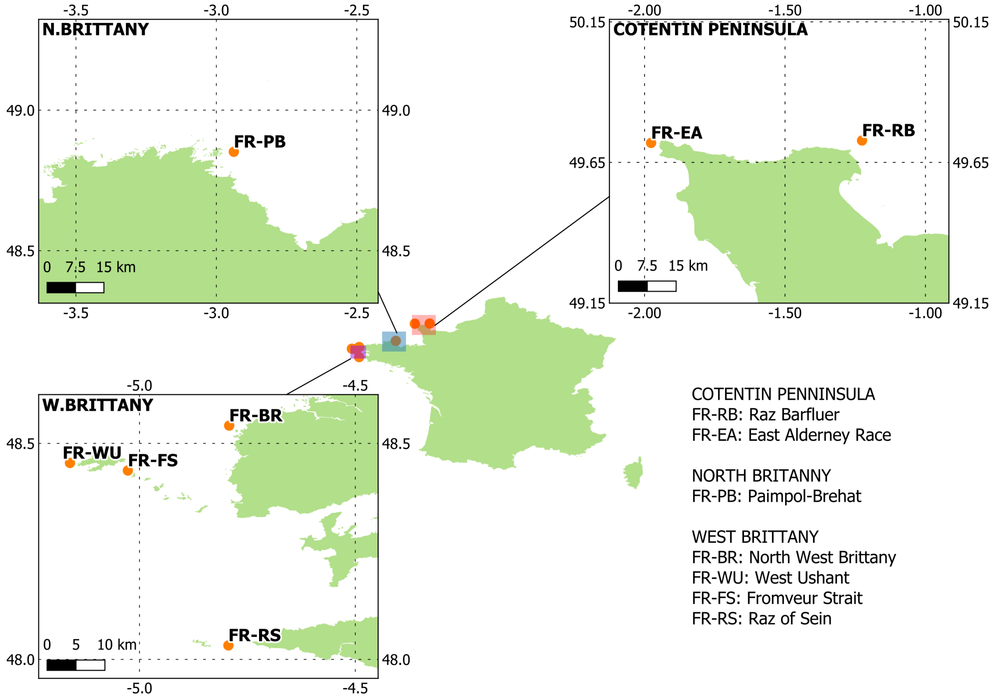


**Figure 3.** Overview of French tidal stream energy sites.

## (c) Practical resource

A practical resource estimate was undertaken in France's metropolitan coastal areas by the Agence de la Transition Écologique (ADEME) [59]. The study considered a range of practical constraints such as the physical environment (type of seabed, distance to shore), restricted areas (protected areas, natural heritage) and navigation (shipping lanes, fishing/leisure activities). Based on these constraints, the national scale practical resource is estimated to be 26.3 TWh/year. The study does not provide a description of the methodology it adopted, or a site-specific resource breakdown. For this reason it is not counted in the global practical resource tally presented in this paper.

The Offshore Renewable Energy Catapult have recently conducted an investigation of French practical resource for the East Alderney Race [43,44]. The study investigated the practical array deployment area based on the hard constraints that were considered for the UK sites such as limitations due to ports, and oil and gas operations. It is estimated that a 0.4 GW capacity array could be practically deployed using 198 x 2 MW turbines with 20 m rotor diameter. The study estimates that the turbines operate with a capacity factor ranging between 0.24 - 0.27, resulting in an energy yield of approximately 0.85 TWh/year. The array is estimated to achieve a baseline LCoE of 115 £/MWh, with pessimistic and optimistic estimates of around 100 £/MWh and 150 £/MWh respectively. These are likely to be an overestimate of energy yield and an underestimate of LCoE since changes to the flow field as a result of turbine installations was not considered. It is acknowledged that further regions of the East Alderney Race may be practically viable using a range of different turbine specifications given the considerable spatial variability in current speeds and depths. Further work is needed to explore this.

**Table 2.** Summary of kinetic, theoretical, technical and practical resource estimates of French and Channel Island sites. Unless otherwise stated, data has been obtained from the Guillou et al. (2018) study [53].

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area (km$^2$) | Width (km) | Depth (m) | Flow vel. (m/s) | | Pow. den. (kW/m$^2$) | | Energy (TWh) | Energy (TWh) | Energy (TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Cot. Peninsula** | | | | | | | | | | | | | |
| Raz de Barfleur | FR-RB | 49.7281 | -1.2260 | 114 [56] | - | 50 [36] | >1.5 [56] | - | 3 [36] | - | - | 9.9 [56] | - |
| E. Alderney Race | FR-EA | 49.7196 | -1.9769 | - | - | - | 3 [23] | 5 [23] | >13.5 [23] | - | - | 1.9 [23] | - |
| **North Brittany** | | | | | | | | | | | | | |
| Pai.Brehat | FR-PB | 48.852 | -2.938 | 18-545 [56] | - | - | >1 [56] | - | 1.1 | 1.8 | - | 14.3 [56] | - |
| **West Brittany** | | | | | | | | | | | | | |
| NW.Brittany | FR-BR | 48.5413 | -4.7923 | 53 | - | - | >1 [56] | - | - | - | - | 1.4 [56] | - |
| W.of Ushant | FR-WU | 48.4549 | -5.1611 | 40 | - | - | - | - | 1.4 | - | - | - | - |
| Fromveur Strait | FR-FS | 48.4373 | -5.027 | 17-39 [56] | - | - | - | - | 2.9 | 7.9 | - | 2.0 [56] | - |
| Raz of Sein | FR-RS | 48.0326 | -4.7941 | 15-108 [56] | - | - | - | - | 1.4 | 2.8 | - | 2.0 [56] | - |

# 5. Canada

## (a) Kinetic resource

In 2006 Canada's National Research Council published a report describing the national tidal stream energy resources [60]. The study estimated current speed, power density and kinetic power flux from hundreds of potential sites by referencing tide tables, nautical charts, and advice to mariners published by the Canadian Hydrographic Service, as well as numerical simulation output. A total of 191 sites with time-averaged kinetic power greater than 1 MW were identified. The total kinetic power across all sites was 42 GW. 89 sites were identified 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 are summarised in Table 3.

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, where current speeds exceed 5 m/s, was identified as the area with the greatest potential for large scale development in Canada. Cornett and Durand (2010) describe the development of a high-resolution 3-D model of tidal flows throughout the Bay of Fundy and its application to characterise the kinetic energy resource at several sites of interest, including Minas Passage, Passamaquoddy Bay, and Petit and Grand Passage [61]. The flows through Minas Passage are shown to be highly turbulent and strongly asymmetric. On the flood tide a large eddy forms along the southern shore at Cape Split, concentrating the main eastbound flow across the northern 3/4 of the passage, where depth-averaged flow velocities and power densities during an average spring tide exceed 4.5 m/s and 50 kW/m$^2$ respectively. On the ebb tide, westbound flow is more uniformly distributed across the 5 km wide channel, and peak velocities and energy densities are slightly lower, although still substantial.

Cousineau et al. (2021) [62] describe the development and application of a 2-D finite-element model to simulate tidal flows in a significant portion of the Canadian Arctic archipelago, and provide estimates of the tidal current energy resource near the northern communities of Cape Dorset, Igloolik, Iqualuit and Kuujjuaq. While the accuracy of the model and the resource estimates is generally limited by a paucity of detailed bathymetric data and good data for model calibration and validation, hot spots were identified near all four northern communities, including Kuujjuaq, where time-averaged current speed is around 1.75 m/s, maximum current speeds reach 6 m/s and depths range between 5 m to 30 m. However tidal stream development is likely to be challenging since there is typically ice cover for 8 months of the year.

Several studies implement high spatial resolution hydrodynamic modelling to improve the resource assessment in several regions, notably in the Bay of Fundy [63,64], the Pacific coast [65], the Salish Sea (near Vancouver) [66], Johnstone Strait (the channel between Vancouver Island and the mainland) [27], and the Eastern Arctic including Ungava Bay [62]. Kinetic resource estimates from these studies are summarised in Table 3.

## (b) Theoretical resource

Karsten et al. (2008) used a 2D numerical model to derive a theoretical resource estimate for Minas Passage in the Bay of Fundy, based on M2 harmonic constituent phase and amplitude forcing only, of 61 TWh/year [63]. Subsequent hydrodynamic modelling by Walters et al. (2013) re-estimated the theoretical resource of Minas Passage, using nine harmonic constituent phase and amplitude forcings, giving 53 TWh/year [67]. The main contributing factor that results in this 8 TWh/year reduction in theoretical resource estimate is the models enhanced coastline and bathymetry definition.

Sutherland et al. (2007) [27] used a 2-D finite-element model, in which turbines were simulated by increasing the sea bed drag, to investigate the theoretical resource at sites in and around Johnstone Strait on the West coast between mainland and Vancouver Island. The estimated theoretical resource in North-West Johnstone Strait, Discovery Passage and Cordero Channel is 13.1 TWh/year, 4.4 TWh/year and 2.6 TWh/year respectively.

Garrett and Cummins (2005) [26] describe the additional theoretical resource that arises from adding constituent forcings. This depends on the dynamic balance of the specific site. Studies of tidal streaming sites estimate the uplift in theorectical resource from adding S2 forcing to M2 is around 10% [36].

The combined theoretical resource estimates of Minas Passage, Masset Sound and Johnstone Strait is 63.6 TWh/year. 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. Whilst the additional 39 sites in Table 3 are expected to exhibit lower theoretical resource than those considered to date, their combined contribution is expected to be significant, pending further investigation.

## (c) Technical resource

Walters et al. (2013) went on to estimate the technical resource of Minas Passage, based on 30 m rotor diameter turbines simulated in depths greater than 50 m [67]. The lateral and longitudinal spacing between turbines was set to just 2 diameters and 3 diameters respectively, resulting in a significantly greater turbine density than is expected to be practical, based on guidelines [68]. The modelling yields a technical resource estimate for Minas Passage of 24.5 TWh/year. This is 27% lower than another scenario that considered an array that spans the entire width of the Passage. Note that the results report the total extracted power, which includes not only electricity generation, but also losses arising from support structure drag, added seabed drag and wake mixing. It is reported that there is little change in current speeds as a result of the turbines being installed, however no further quantitative information is provided.

## (d) Practical resource

Karsten et al. (2012) [24] estimated the practical resource of tidal currents at six sites around Nova Scotia using hydrodynamic modelling. The study considered environmental impacts on energy extraction by implementing constraints on the change in volume flux through the sites. Limiting the reduction in flow through the Passage as a result of turbine installations to 10% resulted in a practical resource estimate of 30.7 TWh/year. A 5% constraint on flow reduction resulted in a practical resource of 17.5 TWh/year. The research assumes that 40% of the extracted power can be converted to electricity, resulting in practical resource estimates of 12.3 TWh/year and 7.0 TWh/year based on the 10% and 5% flow reduction constraints respectively. The sensitivity of energy extraction to practical constraints is discussed further in Section 11. The theoretical resource estimates for Digby Gut, Petit Passage, Grand Passage, Great Bras d'Or Channel and Barra Strait all lie below 0.25 TWh/year when limiting changes in flow to 5%, as summarised in Table 3.

Karsten et al. (2013) [69] implemented a 3-D finite-volume numerical model of tidal flow to re-analyse the practical resource in Minas Passage. The model estimates that by placing 2300 20 m diameter turbines in the Passage, an energy yield of over 17.5 TWh/year is achievable, whilst limiting the change in volume flux through the site to 2.5%. 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 - 50 m reduces the maximum potential power significantly, to 2.6 TWh/year. The 11.4 TWh/year estimate is used in the global resource tally, since installations in 30 - 70 m depths are expected with future generations of turbine design.

Cousineau et al. (2018) [65] describe the development of a large (over 2.3 million nodes), high-resolution (up to 67 m), 2-D finite element model of the tidal flows along Canada's Pacific coast, including the Salish Sea, Johnstone Strait, Vancouver Island, and the Haida Gwaii archipelago. The model outputs were used in a web-based atlas and decision-support system created to facilitate tidal stream energy site selection in Western Canada [70]. The atlas was used to identify sites potentially suitable for tidal energy development, based on average depth between 10 - 60 m, median current speed greater than 1.5 m/s, and sites within 5 km, 10 km and 30 km of

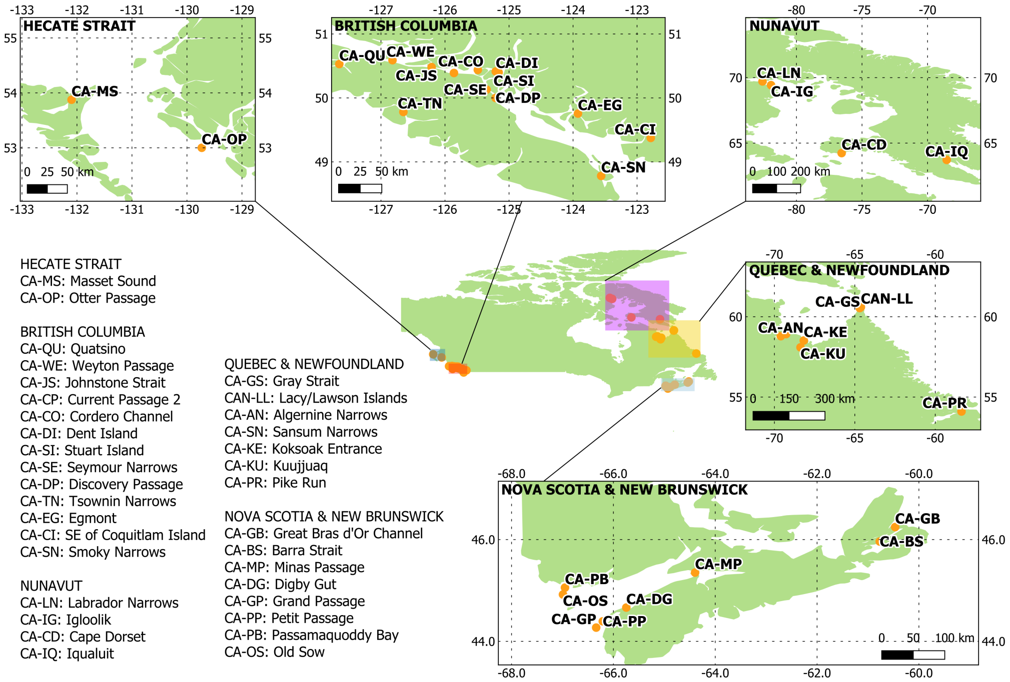


**Figure 4.** Overview of Canadian tidal stream energy sites.

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.

Based on the evidence presented here, the practical resource of Minas Passage is 11.4 TWh/year when energy extraction is constrained to the more conservative 5% changes in flow. This estimate disregards the contributions from Digby Gut, Petit Passage, Grand Passage, Great Bras d'Or Channel and Barra Strait), since energy extraction in Minas Passage will significantly reduce the available energy at these other sites located in the Bay of Fundy. Further assessment of the additional 28 sites reviewed here is needed to provide a national estimate.

**Table 3.** Summary of kinetic, theoretical, technical and practical resource estimates of Canada sites with a time averaged kinetic power greater than 1.5 kW/m$^2$ or a theoretical/technical resource estimate. Unless otherwise stated, data has been obtained from Cornett et al. (2006) [60].

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area (km$^2$) | Width (km) | Depth (m) | Flow vel. (m/s) | | Pow. den. (kW/m$^2$) | | Energy (TWh) | Energy (TWh) | Energy (TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Hecate Strait** | | | | | | | | | | | | | |
| Masset Sound | CA-MS | 53.875 | -132.098 | - | - | - | - | - | - | - | 0.7 [71] | - | - |
| Otter Passage | CA-OP | 53 | -129.73 | - | 0.6 | 50 | - | 3.1 | 1.9 | - | - | - | - |
| **British Columbia** | | | | | | | | | | | | | |
| Quatsino | CA-QU | 50.5300 | -127.6513 | 2 [65] | - | 20 [65] | 3.5 [65] | - | - | - | - | - | - |
| Weyton Passage | CA-WE | 50.59 | -126.82 | - | 1.5 | 75 | - | 3.1 | 1.7 | - | - | - | - |
| Johnstone Strait | CA-JS | 50.433 | -125.918 | - | - | - | - | - | - | - | 13.0 [27] | - | - |
| Current Passage 2 | CA-CP | 50.39 | -125.86 | - | 1.5 | 80 | - | 3.1 | 1.7 | - | - | - | - |
| Cordero Channel | CA-CO | 50.41 | -125.21 | - | 0.4 | 45 | - | 5.7 | 6.7 | - | 2.7 [27] | - | - |
| Dent Island | CA-DI | 50.4138 | -125.2072 | - | - | - | - | - | - | - | - | - | - |
| Stuart Island | CA-SI | 50.3991 | -125.1620 | 1 [65] | - | 50 | 4.0 [65] | - | - | - | - | - | - |
| Seymour Narroes | CA-SE | 50.13 | -125.35 | - | 0.8 | 41 | - | 8.2 | 18.2 | - | - | - | - |
| Discovery Passage | CA-DP | 50 | -125.21 | - | 1.5 | 42 | - | 3.6 | 3.7 | - | 3.9 [27] | - | - |
| Tsownin Narrows | CA-TN | 49.78 | -126.65 | - | 0.3 | 45 | - | 1.5 | 0.2 | - | - | 0.03 [24] | - |
| Egmont | CA-EG | 49.7550 | -123.9229 | 0.05 [65] | - | 10 [65] | 3.0 [65] | - | - | - | - | - | - |
| SE of Coquitlam Island | CA-CI | 49.3743 | -122.7854 | 0.05 [65] | - | 10 [65] | - | - | - | - | - | - | - |
| Smoky Narrows | CA-SN | 58.92 | -69.27 | - | 1.5 | 55 | - | 6.2 | 16.9 | - | - | - | - |
| **Nunavut** | | | | | | | | | | | | | |
| Labrador Narrows | CA-LN | 69.71 | -82.59 | - | 1.5 | 100 | - | 3.1 | 2.1 | - | - | - | - |
| Igloolik | CA-IG | 69.4247 | -81.9368 | - | - | - | - | - | - | - | - | - | - |
| Cape Dorset | CA-CD | 64.2364 | -76.5500 | - | - | - | - | - | - | - | - | - | - |
| Iqualuit | CA-IQ | 63.7136 | -68.5328 | - | - | - | - | - | - | - | - | - | - |
| **Quebec & Newfoundland** | | | | | | | | | | | | | |
| Gray Strait | CA-GS | 60.5408 | -64.69 | - | 6 | 550 | - | 3.1 | 2.1 | - | - | - | - |
| Lacy/Lawson Islands | CAN-LL | 60.6 | -64.62 | - | 2.8 | 80 | - | 3.6 | 3.4 | - | - | - | - |
| Algernine Narrows | CA-AN | 58.79 | -69.6 | - | 2 | 59 | - | 5.1 | 9.8 | - | - | - | - |
| Sansum Narrows | CA-SN | 48.78 | -123.56 | - | 0.6 | 40 | - | 1.5 | 0.2 | - | - | 0.1 [24] | - |
| Koksoak Entrance | CA-KE | 58.52 | -68.17 | - | 2 | 40 | - | 3.1 | 2.1 | - | - | - | - |
| Kuujjuaq | CA-KU | 58.0935 | -68.3757 | - | - | - | - | - | - | - | - | - | - |
| Pike Run | CA-PR | 54.1 | -58.36 | - | 0.6 | 45 | - | 3.1 | 1.6 | - | - | - | - |
| **Nova Scotia & New Brunswick** | | | | | | | | | | | | | |
| Great Bras d'Or Channel | CA-GB | 46.2459 | -60.4649 | - | - | - | - | - | - | - | - | 3.5 [24] | 0.004 [24] |
| Barra Strait | CA-BS | | | - | | | - | | | - | - | - | 0.002 [24] |
| Minas Passage | CA-MP | 45.3509 | -64.395 | - | - | 80 [61] | - | >4.0 [61] | - | - | 53.0 [24,67] | - | 11.4 [24] |
| Digby Gut | CA-DG | 44.663 | -65.746 | - | - | - | - | 4.5 | - | - | - | 236.5 [24] | 0.2 [24] |
| Grand Passage | CA-GP | 44.269 | -66.3376 | - | - | - | - | 1.5 [61] | 1.0 [61] | - | - | 31.5 [24] | 0.03 [24] |
| Petit Passage | CA-PP | 44.3927 | -66.2079 | - | - | - | - | 2.75 [61] | 2.3 [61] | - | - | 0.2 [24] | 0.07 [24] |
| Passamaquoddy Bay | CA-PB | 45.0553 | -66.9506 | - | - | - | - | 2.5 [61] | - | 2.25 [61] | - | - | - |
| Old Sow | CA-OS | 44.92 | -66.99 | - | 0.6 | 60 | - | 3.1 | 2.1 | - | - | - | - |

# 6. USA

## (a) Kinetic resource

The first national scale resource study in the United States (US) were provided by Haas et al. (2011) [72] and published by Defne et al. (2012) [73]. The assessment defined more than fifty distinct domains along the US coasts for numerical model simulations to predict tidal circulation under natural conditions. The hydrodynamic simulations were forced with the nine dominant tidal constituents; M2, S2, Q1, O1, K1, N2, K2, M4, and M6 for the East Coast. The West coast and Alaska models dropped the K2 and M6 constituent forcings. The models used a mesh resolution of up to 350 m in the regions of interest, which was chosen to achieve acceptable model accuracy and computational run time for this first national scale study. Model simulations produced 30 days of time series data for analysis which was used for the analysis.

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. Model validation shows that current speeds and tidal elevations are modelled within the accuracy tolerance of European Marine Energy Centre guidelines for stage 1 regional scale assessments, of within 30% [68]. Some significant bathymetric differences between the models and ADCP measurements of up to 30% were observed, which is likely to be as a result of the 350 m limit on the spatial resolution of the meshes, causing unresolved bathymetric features [74].

The resource assessment used the modelled tidal flows to determine the power density across each site. The total area over which time-averaged power density exceeds 0.5 $\mathrm{kW/m^2}$ within depth greater than 5 m is estimated to be over 9400 $\mathrm{km^2}$, 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.

Subsequent work led by the National Renewable Energy Laboratory's Tidal Gaps Analysis project [75] looked to reduce uncertainty in the 2011 US resource assessment results. The project collected data from eight new hydrodynamic models that incorporated model enhancements on the 2011 effort through 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. Examples of this subsequent work include assessments of Cook Inlet (Alaska) [76], the Western Passage (Maine) [77], the Salish Sea (Washington) [66], Cape Cod, (Massachusetts) [78], Portsmouth Harbor (New Hampshire) and the Florida Keys (Florida) [79], Cape May (New Jersey) [80], and Long Island Sound (New York) [75].

Gunawan et al. (2014) [81] undertook a resource assessment of the East River in New York using an Acoustic Doppler Velocimeter (ADV) deployment at a proposed turbine deployment location. The study found that the estimated power density at the specified location is an order of magnitude greater than the maximum power density estimated in the 2011 National study [72].

NREL found similar results at some sites when comparing power density estimates derived from publicly available NOAA velocity data with maximum power density estimates derived using the 2011 hydrodynamic models at 16 sites. The comparison shows that at 4 of the 16 sites, the 2011 maximum power density estimates are between 18-87% lower than those derived using the NOAA velocity data. This is particularly interesting given that the NOAA velocity data was not collected for the purposes of tidal stream energy resource assessment, so are not necessarily collected from the highest energy regions of the sites. Further investigation into uncertainty in the 2011 resource estimate is currently underway through NREL's Resource Characterization project [82].

## (b) Theoretical resource

The 2011/12 resource assessment also used the computed tidal flows to determine the tidal constituents for calculating the theoretical power of every estuary and bay in the United States using the method developed by Garrett and Cummins (2005) [26]. The total theoretical resource estimated from approximately 208 sites is 445 TWh/year.

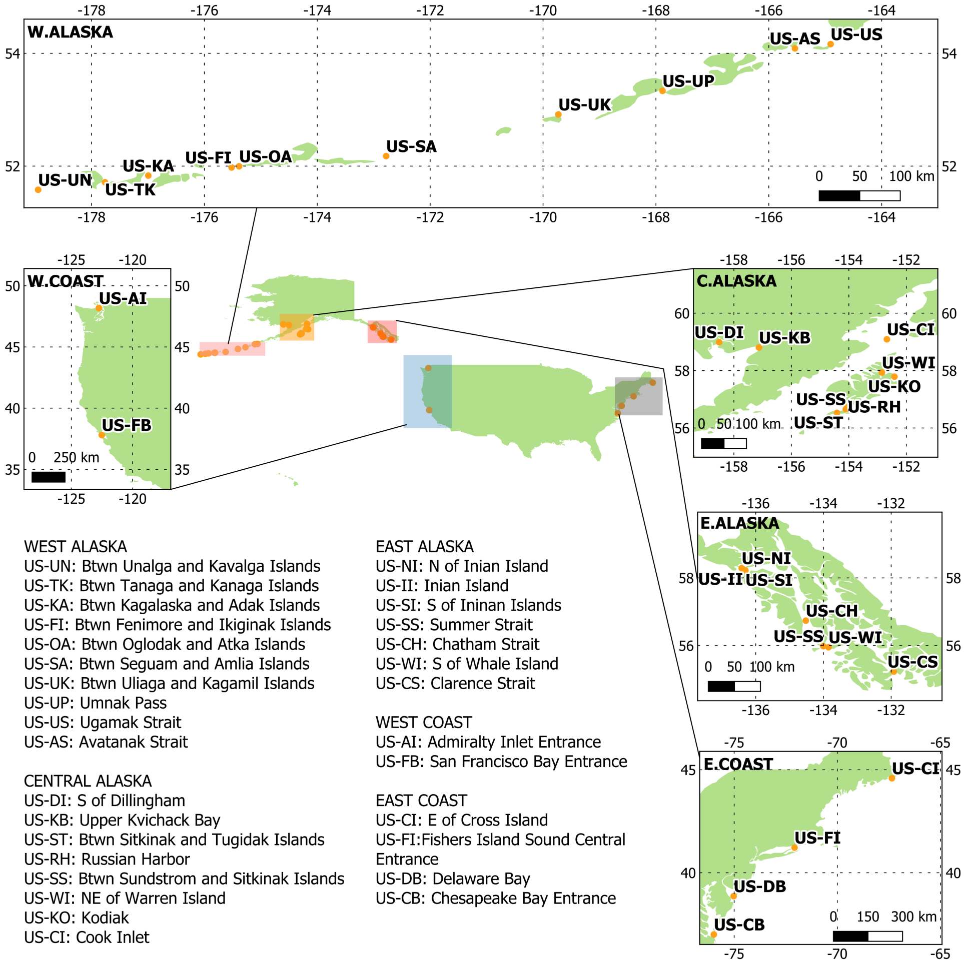
A partial list of site characteristics and the theoretical power estimated at US sites is provided in Table 4, which includes sites with an estimated theoretical resource greater than 1 TWh/year. The total theoretical energy resource for each state is also provided.

## (c) Technical resource

Two national scale technical resource estimates have been published, the first by the U.S Department of Energy [83], and the second by Kilcher et al. (2023) [75]. They state the technical resource to be between 50-75% of the theoretical resource, giving a lower bound estimate of 223 TWh/year. This estimate was made on the basis of estimated drive train losses, but does not provide further information regarding the breakdown of losses that are considered. This approach appears to assume the same number of turbines and array footprint as that needed to extract the theoretical resource. This approach is discussed further in Section 11 in the context of establishing a suitable method(s) for estimating technical resource.

## (d) Practical resource

Kilcher et al. (2016) considered practical aspects of tidal stream energy development through consideration of market size, shipping cost and energy price, alongside site characteristics including water depth [82]. A multi-criteria decision analysis framework was developed to generate an overall composite score that ranks potential tidal energy sites. A list of ranked hot-spot locations for long-term development (no cost of energy included) and short-term development (cost of energy included) was produced. The top 10 sites using the short-term scoring 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). The study did not go as far as deriving practical resource estimates.



WEST ALASKA
US-UN: Btwn Unalga and Kavalga Islands
US-TK: Btwn Tanaga and Kanaga Islands
US-KA: Btwn Kagalaska and Adak Islands
US-FI: Btwn Fenimore and Ikiginak Islands
US-OA: Btwn Oglodak and Atka Islands
US-SA: Btwn Seguam and Amlia Islands
US-UK: Btwn Uliaga and Kagamil Islands
US-UP: Umnak Pass
US-US: Ugamak Strait
US-AS: Avatanak Strait

CENTRAL ALASKA
US-DI: S of Dillingham
US-KB: Upper Kvichack Bay
US-ST: Btwn Sitkinak and Tugidak Islands
US-RH: Russian Harbor
US-SS: Btwn Sundstrom and Sitkinak Islands
US-WI: NE of Warren Island
US-KO: Kodiak
US-CI: Cook Inlet

EAST ALASKA
US-NI: N of Inian Island
US-II: Inian Island
US-SI: S of Ininan Islands
US-SS: Summer Strait
US-CH: Chatham Strait
US-WI: S of Whale Island
US-CS: Clarence Strait

WEST COAST
US-AI: Admiralty Inlet Entrance
US-FB: San Francisco Bay Entrance

EAST COAST
US-CI: E of Cross Island
US-FI:Fishers Island Sound Central Entrance
US-DB: Delaware Bay
US-CB: Chesapeake Bay Entrance

**Figure 5.** Overview of American tidal stream energy sites.

**Table 4.** Summary of kinetic, theoretical, technical and practical resource estimates of USA sites/States with a theoretical resource greater than 1 TWh/year. Unless otherwise stated, data has been obtained from Haas et al. (2011) [72].

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area ($km^2$) | Width (km) | Depth (m) | Flow vel. (m/s) | | Pow. den. ($kW/m^2$) | | Energy (TWh) | Energy (TWh) | Energy (TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Maine** | | | | | | | | | | | **5.9** | **3.0** | |
| E of Cross Island | US-CI | 44.5905 | -67.3551 | - | 7.0 | 29 | - | - | - | - | 2.4 | 1.2 | - |
| **New York** | | | | | | | - | - | - | - | **2.5** | **1.3** | |
| Fishers Island Sound Central Entrance | US-FI | 41.2234 | -72.0758 | - | 7.9 | 25 | - | - | - | - | 1.6 | 18.0 | - |
| **New Jersey** | | | | | | | | | | | **1.7** | **0.9** | |
| **Delaware** | | | | | | | | | | | **1.4** | **0.7** | |
| Delaware Bay | US-DB | 38.8664 | -75.0262 | - | 18.7 | 15 | - | - | - | - | 2.9 | 1.5 | - |
| **Virginia** | | | | | | | | | | | **1.2** | **0.6** | |
| Chesapeake Bay Entrance | US-CB | 37.0072 | -75.9869 | - | 17.5 | 12 | - | - | - | - | 1.1 | 0.6 | - |
| **South Carolina** | | | | | | | | | | | **3.4** | **1.7** | |
| **Georgia** | | | | | | | | | | | **1.9** | **1.0** | |
| **Florida** | | | | | | | | | | | **1.5** | **0.8** | |
| **California** | | | | | | | | | | | **1.8** | **0.9** | |
| San Francisco Bay Entrance | US-FB | 37.8037 | -122.5186 | - | 3.9 | 31 | | | 0.4 [75] | | 1.6 | 0.8 | - |
| **Oregon** | | | | | | | | | | | **1.0** | **0.5** | |
| **Washington** | | | | | | | | | | | **5.4** | **2.7** | |
| Admiralty Inlet Entrance | US-AI | 48.1775 | -122.7556 | - | 6.7 | 56 | | | | | 4.0 | 2.0 | - |
| **Alaska** | | | | | | | | | | | **416** | **208** | |
| Clarence Strait | US-CS | 55.2291 | 131.9197 | - | 10.2 | 301 | - | - | - | - | 36.0 | 18.0 | - |
| NE of Warren Island | US-WI | 55.9494 | 133.8482 | - | 3.4 | 87 | - | - | - | - | 4.7 | 2.4 | - |
| Summer Strait | US-SS | 55.9832 | 134.0028 | 21 | 19.8 | 132 | - | - | 0.5 - 1.5 | - | 23.4 | 11.7 | - |
| Chatham Strait | US-CH | 56.7374 | 134.5198 | - | 16.7 | 503 | - | - | - | - | 105.4 | 52.7 | - |
| S of Ininan Islands | US-SI | 58.2233 | -136.3034 | - | 1.7 | 42 | - | - | - | - | 2.4 | 1.2 | - |
| Inian Island | US-II | 58.2561 | -136.3736 | - | 0.8 | 40 | - | - | - | - | 1.5 | 1.3 | - |
| N of Inian Island | US-NI | 58.2898 | -136.4156 | - | 5.1 | 133 | - | - | - | - | 22.5 | 11.3 | - |
| Cook Inlet | US-CI | 59.0927 | -152.6733 | 5285 | 93.8 | 128 | - | - | 2.1 [75,82]-5.3 | - | 159.8 | 79.9 | - |
| S of Whale Island | US-WI | 57.9358 | -152.8482 | - | 1.0 | 25 | - | - | - | - | 1.9 | 1.0 | - |
| Russian Harbor | US-RH | 56.7391 | -154.0325 | - | 2.2 | 21 | - | - | - | - | 1.4 | 0.7 | - |
| Btwn Sundstrom and Sitkinak Islands | US-SS | 56.6576 | -154.1069 | - | 7.4 | 20 | - | - | - | - | 5.5 | 2.8 | - |
| Btwn Sitkinak and Tugidak Islands | US-ST | 56.5281 | -154.4119 | - | 6.1 | 4 | - | - | - | - | 2.9 | 1.4 | - |
| Avatanak Strait | US-AS | 54.0888 | -165.5386 | 73 | 5.8 | 54 | - | - | 0.9 | - | 2.2 | 1.1 | - |
| Ugamak Strait | US-US | 54.1637 | -164.9067 | 63 | 6.8 | 42 | - | - | 1.3 | - | 1.6 | 0.8 | - |
| Umnak Pass | US-UP | 53.3351 | -167.8847 | 97 | 5.9 | 49 | - | - | 1.3 | - | 2.4 | 1.2 | - |
| Btwn Uliaga and Kagamil Islands | US-UK | 52.9168 | -169.7292 | - | 5.9 | 22 | - | - | - | - | 1.8 | 0.9 | - |
| Btwn Seguam and Amlia Islands | US-SA | 52.1778 | -172.7808 | 180 | 26.8 | 95 | - | - | 0.5 - 0.8 | - | 10.2 | 5.1 | - |
| Btwn Oglodak and Atka Islands | US-OA | 51.9969 | -175.3859 | - | 7.0 | 33 | - | - | - | - | 2.4 | 1.2 | - |
| Btwn Fenimore and Ikiginak Islands | US-FI | 51.9762 | -175.5189 | 36 | 7.4 | 30 | - | - | 1.3 - 2.4 | - | 2.2 | 1.1 | - |
| Btwn Kagalaska and Adak Islands | US-KA | 51.8323 | -176.9941 | 1 | 8.7 | 57 | - | - | 0.8 | - | 3.7 | 1.9 | - |
| Btwn Tanaga and Kanaga Islands | US-TK | 51.7138 | -177.7614 | 36 | 7.6 | 25 | - | - | 0.9 | - | 1.2 | 0.6 | - |
| Btwn Unalga and Kavalga Islands | US-UN | 51.5810 | -178.9460 | - | 11.8 | 48 | - | - | - | - | 3.8 | 1.9 | - |
| Upper Kvichack Bay | US-KB | 58.8052 | -157.1269 | - | 9.2 | 2.8 | - | - | - | - | 1.7 | 0.9 | - |
| S of Dillingham | US-DI | 58.9905 | -158.5124 | - | 1.9 | 6.9 | - | - | - | - | 1.2 | 0.6 | - |

# 7. China

## (a) Kinetic resource

Three national scale assessments of the Chinese tidal stream energy resource have been conducted over the last 40 years. The first was jointly initiated by the Ministry of Water Conservancy and Electric Power and the State Oceanic Administration (SOA) in 1986 [84]. The study was based on field measurements, with no numerical modelling, and provides an estimate of the time-averaged kinetic power flux at approximately 130 sites of 14 GW. 79% of this kinetic power flux is located at sites in the East China Sea, with particularly energetic sites identified in the Zhoushan arcipeligo, located in the northeast of Zhejiang province. The area contains around 1400 islands, with time-averaged power density in the range of 15-30 kW/m$^2$ observed in Jintang Channel, Guishan Channel and Xihoumen Channels.

A second nation-wide study, conducted in 2004, which was also supported by the SOA, investigated the tidal stream energy resource at 99 sites in the Yellow Sea, East China Sea and South China Sea [85]. The study implemented hydrodynamic modelling using the Princeton Ocean Model (POM), along with over 17,000 days of field measurement data. The study re-estimated the time-averaged kinetic power flux at the selected sites, to 8.33 GW. In general the 2004 study downsized the estimate relative to the 1989 study in all Provinces, other than Jiangsu and Hainan. The main contributing factors of this reduction in resource estimate is consideration of fewer sites, and enhanced accuracy from more extensive field measurements and hydrodynamic modelling. Zhejiang remains the leading Province, with a time-averaged kinetic power flux estimate of 5.2 GW, equivalent to 60% of the resource over the 99 sites.

The third national study was initiated in 2010 under the support of the Ocean Energy Special Fund from SOA [86]. The study investigated the resource at 75 sites using the Finite Volume Community Ocean Model (FVCOM), and field measurements. It estimated a time averaged kinetic power flux from the 75 sites of 5.6 GW. The study also estimated the utilisation area based on power density exceeding a range of thresholds between 0.8 - 8 kW/m$^2$. It is estimated that Zhoushan Archipelago in Zhejiang Province, and Sansha Bay in Fujian Province, have areas where peak power density exceeds 8 kW/m$^2$ of 31.4 km$^2$ and 5.2 km$^2$ respectively. It is also estimated that Zhoushan Archipelago exhibits a 160 km$^2$ region where peak power density falls between 4 - 8 kW/m$^2$.

Subsequent field measurements and hydrodynamic modelling studies have characterised the kinetic resources at specific sites in further detail, with results from this work summarised in Table 5. 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 m/s, and maximum and average power density of 7 kW/m$^2$ and 2 kW/m$^2$ respectively [87–91].

Multiple studies have investigated sites in Zhoushan Archipelago. These include Guishan Channel, with an estimated maximum current speed of 4.5 m/s, and maximum power density of 22 kW/m$^2$ in depths ranging between 20 - 84 m [85,92]. Guanmen Channel has been identified as one of the most promising sites in China for tidal stream energy development. Several studies estimate peak current speeds of between 3.1-3.5 m/s, and a maximum power density of 16 kW/m$^2$ [85,92–94]. Xihoumen Channel exhibits an average and maximum depth of 37 m and 62 m respectively. Peak velocity and power density estimates of 3.6 m/s and 15.2 kW/m$^2$ have been reported [85,86,95]. Loutou Channel is 2.3 km wide, with depths greater than 100 m. It is estimated that maximum current speed and power density reach 2.5 m/s and 15.2 kW/m$^2$ respectively [85]. Many more sites in the Zhoushan Archipelago and across China exhibit promising kinetic resource characteristics, as summarised in Table 5.

## (b) Practical resource

Liu et al. (2021) [96] categorised sites based on their potential for large-scale development, based on practical considerations such as shipping routes, policy support and regulatory constraints.

Large-scale development is defined as any array over 50 MW capacity, in line with European Marine Energy Centre standards [68]. The Bohai/Yellow Sea region has favourable conditions for large scale development, in particular due to regulation that authorised the National Shallow Sea Comprehensive Testing Site (NSSCTS) to be built in nearby waters [97]. This is also true of the Zhoushan region, where the Zhejiang Zhoushan test site is operational.

Several studies have investigated the environmental impacts of tidal stream energy development at sites in Zhoushan Archipelago. The studies show that large scale array installations can modify current speeds by up to $\pm 0.5$ m/s [98–100]. 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 [101,102].

Similar studies have considered environmental impacts of array development at Chengshan Cape [88,89,103]. The studies estimate that a 20 MW tidal stream turbine array would modify the free surface elevation by between 4-6 cm, and reduce current speeds in the wake of the array by around 0.8 m/s. The modelling estimates that the length of the array wake could extend 10 km downstream of the array.

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, [96,104], regardless of the significant resources at the sites (Yangtze exhibits a maximum power density of 10 kW/m$^2$ [86]). Similarly, Jiaozhou Bay is an important shipping channel that will likely prevent, or at least limit, tidal stream energy development [96]. In Sansha Bay (Fujian Province) there are considerable marine aquaculture activities that are likely to limit tidal stream energy development [104], but estimating the extent to which this is the case requires further study.

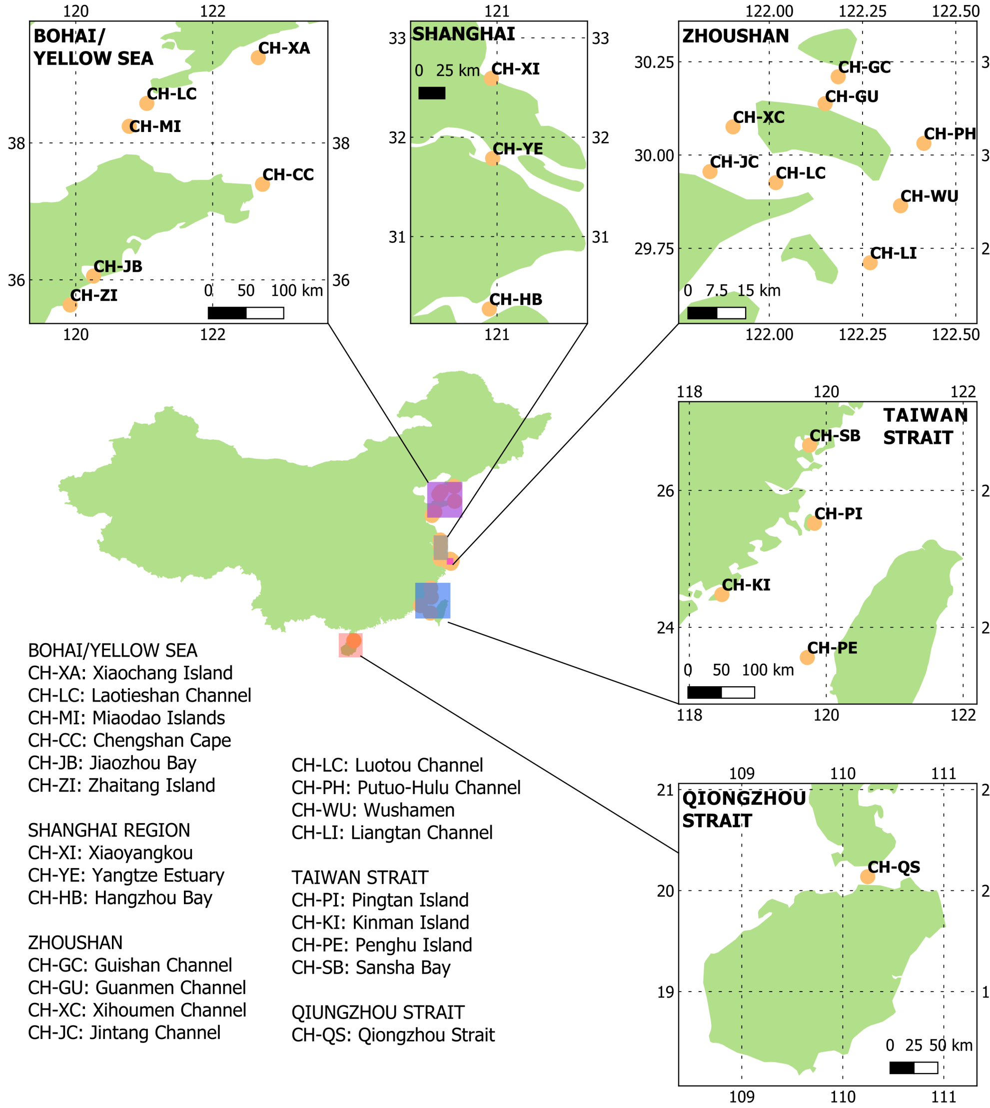


**Figure 6.** Overview of Chinese tidal stream energy sites.

**Table 5.** Summary of kinetic, theoretical, technical and practical resource estimates of China sites.

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area (km$^2$) | Width (km) | Depth (m) | Flow vel. (m/s) | | Pow. den. (kW/m$^2$) | | Energy (TWh) | Energy (TWh) | Energy (TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Bohai/Yellow Sea** | | | | | | | | | | | | | |
| Xiaochang Island | CH-XA | 39.2461 | 122.6657 | - | - | - | - | 1.7 | - | - | 0.1 | - | - |
| Laotieshan Channel | CH-LC | 38.578 | 121.0374 | - | 13 | 45 | - | 2.4 | - | 5.5 | 3.9 | - | - |
| Miaodao Islands | CH-MI | 38.2433 | 120.7805 | - | - | - | - | 2.5 | - | 2 | 1.8 | - | - |
| Chengshan Cape | CH-CC | 37.3977 | 122.7274 | 28 [86] | - | 60 | - | 2.5 | 2 | - | - | - | 0.2 |
| Jiaozhou Bay | CH-JB | 36.0566 | 120.2597 | 4.5 [86] | 28 | - | - | 2 | 0.3 | - | - | - | - |
| Zhaitang Island | CH-ZI | 35.6346 | 119.9176 | - | - | 40 | - | 2 | - | - | - | - | - |
| **Shanghai Region** | | | | | | | | | | | | | |
| Xiaoyangkou | CH-XI | 32.5917 | 120.9426 | - | - | 13 | - | 3 | - | - | 1.1 | - | - |
| Yangtze Estuary | CH-YE | 31.7872 | 120.9557 | 3263 [86]- | - | - | - | 2.8 | - | 10 | 0.8 | - | - |
| Hangzhou Bay | CH-HB | 30.272 | 120.922 | 486 [86] | - | 9 | - | 2.8 | - | 11.4 | 2.5 | - | - |
| **Zhoushan Archipelago** | | | | 7808 [86] | | | | | | | | | |
| Guishan Channel | CH-GC | 30.21 | 122.1847 | - | 1.8 | 52 | 2.1 | 4.5 | - | 22 | 5.7 | - | - |
| Guanmen Channel | CH-GU | 30.138 | 122.1497 | - | - | 45 | - | 3.5 | - | - | 1.7 | - | - |
| Xihoumen Channel | CH-XC | 30.0758 | 121.9028 | - | - | 37 | 1.9 | 3.6 | - | 15.2 | 2.1 | - | - |
| Jintang Channel | CH-JC | 29.9558 | 121.8411 | - | - | 75 | - | - | - | - | 1.8 | - | - |
| Luotou Channel | CH-LC | 29.9263 | 122.0175 | - | 2.3 | - | 1.2 | 2.5 | - | 15.2 | 2.1 | - | - |
| Putuo-Hulu Channel | CH-PH | 30.0315 | 122.4144 | - | 1.5 | 55 | - | - | - | - | 0.4 | - | - |
| Wushamen | CH-WU | 29.8643 | 122.3518 | - | - | - | - | - | - | - | 0.8 | - | - |
| Liangtan Channel | CH-LI | 29.7116 | 122.2705 | - | 1.5 | 30 | 1.8 | 3.4 | - | 15.2 | 1.6 | - | - |
| **Fujian Province** | | | | | | | | | | | | | |
| Pingtan Island | CH-PI | 25.5212 | 119.8276 | - | - | - | - | 2 | - | - | - | - | - |
| Sansha Bay | CH-SB | 26.6610 | 119.7563 | 266 [86] | - | - | - | 2.0 | - | 8.0 | - | - | - |
| **Qiongzhou Strait** | | | | | | | | | | | | | |
| Qiongzhou Strait | CH-QS | 20.138 | 110.246 | 1769 [86] | 44 | - | - | 4.6 | - | 5.9 | 3.4 | - | - |

## 8. Japan

### (a) Kinetic resource

The majority of the Japanese tidal stream resource identified to date is located in the South and West of the country, where sites exhibit mixed semi-diurnal tides [105]. 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, as shown in Figure 7. Elsewhere resources have been investigated at Tsugaru Strait, located between Hokkaido Island and Honshu Island in the North of the country.

Bricker et al. (2017) [105] investigated the feasibility of tidal current energy exploitation at 16 sites. Flow characteristics were derived based on hourly current speeds from hydrodynamic modelling undertaken by the Japan Coast Guard for Bisan Strait, Hayasui Strait, Obatake, Onomichi Strait, and Kurushima Straits [106], and peak current speeds at Naruto Strait, Akashi Strait, and Tomogashima Strait [106]. 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. (2002) [107]. 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 [108]. The algorithm assumes maximum spring flood current speed is 80% of the spring ebb current speed, and that neap current speeds are 60% of spring current speeds. Results obtained using this method showed reasonable agreement with current speeds obtained from numerical modelling. Adopting similar constraints to other studies, it is shown that 9 out of the 16 sites (Naruto, Kurushima, Kanmon, Akashi, Hayasaki, Hayasui, Kadako, Hirado and Obatake) exhibit maximum current speeds exceeding 2 m/s, and time-averaged kinetic power greater than 1.5 kW/m .

### (b) Technical resource

To date, the channels between the Goto Islands in Nagasaki Prefecture are the most studied since two of the channels, Tanoura Strait and Naru Strait, have been designated areas for tidal energy development by the Japanese Government. Waldman et al. (2017) [109] provided technical resource estimates for Naru, Tanoura and Takigawara Straits, based on FVCOM 3D hydrodynamic modelling forced by eight tidal constituents. Turbine drag was applied continuously across the majority of the width of the sites, with a thrust coefficient of 0.85, based on experiments by Bahaj et al. (2007) [110]. The turbine drag was parameterised based on the OpenHydro device, which has 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 TWh/year, 0.05 TWh/year 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, which is addressed in follow up work reviewed in Section 8(c).

### (c) Practical resource

A follow on study of Naru Strait [111] considered modifications to the turbine specification and array layout considered by Waldman et al. 2017 [109] in an attempt to enhance capacity factor above the prohibitively low 0.02 achieved in the original work. Energy yield estimates were made based on hydrodynamic model outputs from the Waldman et al. (2017) study, which considers changes to the flow field as a result of turbine installations. The study estimated achieving a capacity factor of 0.3 required (i) the installed array capacity to be reduced from 380 MW 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 1-1.5 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 - 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. The 45 MW array is estimated to generate 0.1 TWh/year. Other than economic constraints on energy yield, additional practical constraints that may reduce this practical resource estimate of Naru Strait were not considered.

Bricker et al. (2017) [105] considered various practical constraints to the development at sites. Site selection required less than 35 km proximity to a city with a population larger than 100,000 people, to help address transmission challenges when developing remotely located tidal resources. It is important to acknowledge that tidal stream energy development proximate to demand centres may result in marine spatial planning challenges due to high levels of maritime traffic on route to/from major ports. Kobe, Osaka and Hiroshima are examples of this.

The study estimates the annual energy yield from single devices based on two different turbine specifications. The first turbine specification is based on the Marine Current Turbine Seagen device, with two 18 m rotor diameter rotors, each with a rated power of 0.6 MW. The second is based on the Verdant Power Kinetic Hydropower System (KHPS) turbine with a rotor diameter of 5 m, and a rated power of 0.04 MW. 7 out of the 16 sites achieve a capacity factor greater than 0.3 with either/both the Seagen and Verdant turbines, which may deliver economic viability, based on the assessment presented in The Carbon Trust UK study [29]. In some cases, capacity factor exceeds 0.7. In these cases it is likely that the rated power of the turbine is undersized, which limits its annual energy yield potential [112].

The economic viability of tidal stream development across Japan was assessed by carrying out a life cycle cost analysis that estimated the price of electricity needed for tidal stream turbine installations to break even over 25 years. The analysis is based on the method developed by Dunnett et al., (2009) [113]. The study assumed a capital and installation cost of a Seagen device of ¥295,000 ¥/kW (equivalent to 1850 $/kW) and 42,480,000 ¥(equivalent to 270,000 $) respectively [108]. The annual operations and maintenance cost of the Seagen device were assumed to be 4% of its capital costs. This is higher than the reported CapEx/OpEx split reported for the MeyGen Phase 1A array, where annual OpEx is less than 3% of CapEx [41]. The study also undertook the same life cycle cost analysis based on Verdant turbines. In this case a combined capital and installation cost of 283,200 ¥/kW was used. Figures are based on the value of the Yen in 2017, when the conversion from US dollars to Yen was 112, as opposed to 160 in 2024. In both turbine cases it was assumed that the export cable length is equal to the width of the channel, and that the onshore cable is 5 km in length, since each site considered is proximate to large demand centres. Results derived using a 10% annual discount rate with the Seagen device identified 7 sites that require a price of electricity that is below the daytime price in Japan, of 30 ¥/kWh, at the time of publication in 2017. The sites identified are Naruto Strait, Kurushima Strait, Kanmon Strait, Akashi Strait, Hayasaki, Hirado Strait and Obatake. The sites that require an electricity price greater than 30 ¥/kWh are Hayasui Strait and Kudako Strait. To enhance the accuracy of the life cycle cost analysis, aspects such as learning rate, array scale economies of volume and changes to the flow field as a result of turbine installations should be included.

A subsequent study used results from an FVCOM numerical model to derive energy yield at 17 sites across Western Japan [114]. The study considered 30 MW arrays at each site. A range of different turbine specifications were considered for each array, with rotor diameters ranging between 8.5 - 38 m, rated power ranging between 0.1 - 2 MW and power coefficient ranging between 0.36 - 0.45. Based on a simulation period of 3 months, 11 of the 17 sites achieved a capacity factor exceeding 0.3 using at least one of the five turbine specifications, although changes to the flow field as a result of turbine installations were not simulated, so the capacity factors are expected to be overestimated. The 11 sites are Tanoura, Naru, Takigawara and Wakamatsu Straits in the Goto region, Hayasaki, Hirado, Kurono and Nagashima Straits in West Kyushu, Naruto Strait by Awaji island, and Heyasui and Onomichi Straits in the Seto Inland Sea (between Honshu and Shikoku).

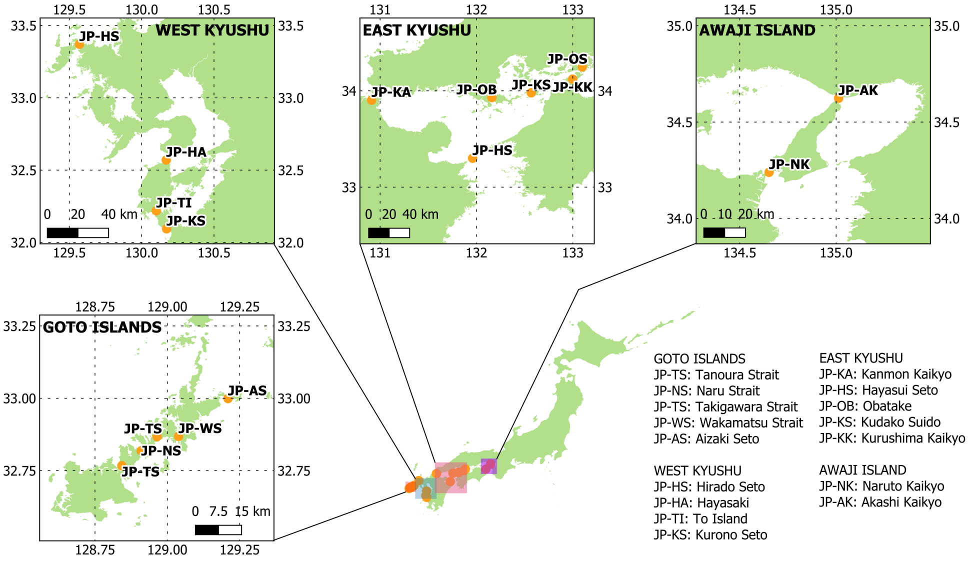


**Figure 7.** Overview of Japan’s tidal stream energy sites.

**Table 6.** Summary of kinetic, theoretical, technical and practical resource estimates of sites in Japan sites.

| Site | ID | Lat | Lon | Kinematic |  |  |  |  |  |  | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Area ($km^2$) | Width (km) | Depth (m) | Flow vel. (m/s) |  | Pow. den. ($kW/m^2$) |  | Energy (TWh) | Energy (TWh) | Energy (TWh) |
|  |  |  |  |  |  |  | Mean | Max | Mean | Max |  |  |  |
| **Goto Islands** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Tanoura Strait | JP-TS | 32.7669 | 128.8429 | - | - | - | - | - | - | - | - | - | - |
| Naru Strait | PP-NS | 32.8186 | 128.91 | 3.65 | - | 40 | 1.15 | - | - | - | - | 0.1 [48] | - |
| Takigawara Strait | JP-TS | 32.8673 | 128.9648 | - | - | - | - | - | - | - | - | - | - |
| Wakamatsu Strait | JP-WS | 32.8684 | 129.0390 | - | - | - | - | - | - | - | - | - | - |
| Aizaki Strait | JP-AS | 32.9989 | 129.2098 | - | - | - | - | - | - | - | - | - | - |
| **W.Kyushu** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Hirado Seto | JP-HS | 33.37 | 129.57 | - | 0.2 | 35 | - | 3.6 | 5.8 | - | - | - | - |
| Hayasaki | JP-HA | 32.57 | 130.17 | - | 3.5 | 80 | - | 2.8 | 2.7 | - | - | - | - |
| Nagashima Strait | JP-NS | 32.2193 | 130.1013 | - | - | - | - | - | - | - | - | - | - |
| Kurono Island | JP-KI | 32.0944 | 130.1724 | - | - | - | - | - | - | - | - | - | - |
| **E.Kyushu/Inland Sea** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Kanmon Kaikyo | JP-KA | 33.9034 | 130.9121 | - | 1 | 15 | - | 3.5 | 5.3 | - | - | - | - |
| Hayasui Seto | JP-HS | 33.3 | 131.96 | - | 9 | 150 | - | 3 | 3.3 | - | - | - | - |
| Obatake | JP-OB | - | - | - | - | - | - | 3.2 | 4.2 | - | - | - | - |
| Kudako Suido | JP-KS | 33.98 | 132.569 | - | - | - | - | 2.4 | 1.6 | - | - | - | - |
| Kurushima Kaikyo | JP-KK | 34.1215 | 132.9985 | - | 0.4 | 30 | - | 4.1 | 8.6 | - | - | - | - |
| Onomichi Suido | JP-OS | 34.2474 | 133.0985 | - |  |  | - |  |  | - |  | - | - |
| Heyasui Strait | JP-HS | 33.3154 | 131.9792 | - |  |  | - |  |  | - |  | - | - |
| **Awaji Island** |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Naruto Kaikyo | JP-NK | 34.2394 | 134.6522 | - | 1 | 25 | - | 5.1 | 16.3 | - | - | - | - |
| Akashi Kaikyo | JP-AK | 34.6237 | 135.013 | - | 3.5 | 50 | - | 3 | 3.3 | - | - | - | - |

# 9. Indonesia

## (a) Kinetic resource

Like Japan, Indonesia is an archipelagic country with a vast coastline. In addition to tidally generated flows, the region exhibits the 'Indonesian through flow', an ocean current system driven predominantly by regional wind patterns that creates a pressure difference between the Pacific and Indian Oceans [115].

The twelve sites identified in Table 7 generally exhibit maximum flow speeds greater than 1.8 m/s. Orhan et al. 2016 [116] considered the resource of the seven Sunda Island chain sites, of Alas, Badung, Bali, Boleng, Larantuka, Lombok and Sunda Straits. Tidal flows were simulated using Delft3D, with up to 20 m and 3 m horizontal and vertical resolution respectively. The model was forced by eleven harmonic constituents. Meteorological forcings (temperature, atmospheric pressure and wind) were also included in the model. The study estimated that the potential utilisation area of regions with an average kinetic power density greater than 0.5 kW/m$^2$, and depth greater than 7.5 m, is 1040 km$^2$. This utilisation area reduces to 238 km$^2$ when the average kinetic power density requirement is increased to 1 kW/m$^2$. Kinetic resource data is provided in Table 7. Sites that exhibit the highest maximum current speeds are Alas Strait (3.9 m/s) and Larantuka Strait (4.0 m/s).

## (b) Theoretical resource

Firdaus et al. (2019) [117] used the ADvanced CIRCulation Model (ADCIRC) to estimate the theoretical resource of Badung, Toyopakeh and Lombok Straits, located South/East of the island of Bali in the Sunda Island chain. The model was validated against tidal elevations, co-tidal charts and ADCP current measurements. 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 installations [118] from a fence of turbines spanning the entire width of the three Straits. The study estimated the theoretical resource of Badung, Toyopakeh and Lombok Straits to be 2.2 TWh, 0.2 TWh and 15.6 TWh respectively.

## (c) Technical resource

Orhan et al. 2016 [116] estimated the technical resource of the seven Sunda Island chain sites, based on turbines with rotor diameter ranging between 1.5-20 m. The study fails to consider the 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, however it is unclear what turbine spacing was implemented. This approach is likely to over-estimate the resource, since similar resource assessments in the Alderney Race presented in Section 4(b) show significant changes in the flow field arise from turbine installations, resulting in a reduction in energy extraction relative to estimates derived without considering the effects of added turbine drag. This is discussed further in Section 11. The technical resource at the seven sites is estimated to be 53 TWh/year, with 40% of the technical resource located in Alas Strait. Lombok Strait is estimated to have a technical resource of 7.6 TWh. This is 48% of the theoretical resource estimated by Firdaus et al. [117]. This relationship between the theoretical and technical resource shows close alignment with that found in USA resource studies [75], however it is likley to be coincidental given that technical resource estimates do not include the impacts of turbine drag.

Orhan et al. 2020 [119] implemented an updated Delft3D model to estimate the energy yield of a 35 MW array within Larantuka Strait. Individual momentum sinks discretely simulate each turbine's drag and the effects on the surrounding flow field. Model validation was limited to model vs. field data comparisons of water level at a single location within the Strait. The introduction of the 35 MW array led to changes in current speeds of up to 0.6 m/s 20 rotor diameters upstream/downstream of the array. The study acknowledges the concern arising from these flow speed changes related to erosion. The estimated capacity factor of the array is 0.33 over a single spring tidal cycle. Inevitably capacity factor will worsen when neap tides are also considered.

## (d) Practical resource

Blunden et al. [120] estimated the practical resource from a 520 MW array located in the narrowest section of Alas Strait. Alas Strait was chosen for the study based on its practical credentials of not containing a major shipping lane, and its proximity to existing electricity grid. Other straits that meet these criteria are Lombok and Makassar Straits. The study used the 3D 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 25-80 m. The spatially varying bathymetry necessitated the use of rotors with diameters ranging between 14-25 m. The longitudinal spacing between turbines was set to between 19-33 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 [121]. This approach does not include the impact of array-scale drag on the surrounding flow field, which in general, results in an increase in free surface elevation, and reduction in current speeds, upstream of the array. The estimated annual energy yield from the array was estimated to be 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.

Orhan et al. (2016) [116] considered conflicting uses of the marine environment in future site identification activities. Uses include fishing, shipping, offshore wind, and habitat protection. 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 [122]. The intersectorial 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.

**Table 7.** Summary of kinetic, theoretical, technical and practical resource estimates of Indonesian sites.

| Site | ID | Lat | Lon | Kinematic | | | | | | | Theoretical | Technical | Practical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Area(km$^2$) | Width(km) | Depth(m) | Flow vel. (m/s) | | PD (kW/m$^2$) | | Energy(TWh) | Energy(TWh) | Energy(TWh) |
| | | | | | | | Mean | Max | Mean | Max | | | |
| **Sunda Strait** | | | | | | | | | | | | | |
| Sunda Stait | IN-SS | -5.9090 | 105.8580 | 145 [116] | - | - | - | 2.1 [116] | - | 1.6 [116] | - | 2.9 [116] | - |
| **Sunda Islands** | | | | | | | | | | | | | |
| Bali Stait | IN-BA | -8.1074 | 114.4220 | 104 [116] | - | - | - | 3.2 [116] | - | 14.8 [116] | - | 9.2 [116] | - |
| Badung Strait | IN-BS | -8.6560 | 115.4153 | 162 [116] | - | - | - | 2.2 [116] | - | 1.5 [116] | 2.2 [117] | 4.8 [116] | 0.6 [120] |
| Toyopakeh Stait | IN-TS | -8.6855 | 115.4682 | - | - | - | - | - | - | - | 0.2 [117] | - | - |
| Lombok Stait | IN-LO | -8.7714 | 115.7151 | 114 [116] | - | - | - | 3.3 [116] | - | 2.4 [116] | 15.6 [117] | 7.6 [116] | - |
| Alas Strait | IN-AS | -8.6000 | 116.7000 | 403 [116] | - | - | - | 3.9 [116] | - | 3.1 [116] | - | 19.8 [116] | 0.6 [120] |
| Molo Stait | IN-MO | -8.6322 | 119.8087 | - | - | 15-30 | - | 1.8 (Neap) [122] | - | - | - | - | - |
| Larantuka Stait | IN-LS | -8.3281 | 123.0193 | 6 [116] | - | - | - | 4.0 [116] | - | 10.2 [116] | - | 2.6 [116] | - |
| Boleng Stait | IN-BO | -8.2923 | 123.3404 | 106 [116] | 2-4 [122] | - | - | - | - | 3.5 [116] | - | 6.4 [116] | - |
| Pantar Stait | IN-PS | -8.2571 | 124.3478 | - | 0.9-3.5 [123] | - | - | 2.9 [123] | - | - | - | - | - |
| **Waigeo** | | | | | | | | | | | | | |
| Mansuar Stait | IN-MS | -0.5675 | 130.6137 | - | - | - | - | 1.8 [122] | - | - | - | - | - |
| **Molucco Strait** | | | | | | | | | | | | | |
| Capululu Stait | IN-CS | -1.8585 | 125.3225 | - | - | - | 1.7 [124] | - | - | - | - | - | - |

## 10. Additional resource

This review has focused on countries that, based on the literature to date, 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 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.

### (a) Europe/North Atlantic

Sustainable Energy Ireland estimates the kinetic flux through Irish sites based on 2D hydrodynamic modelling [31]. 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 [125].

The Hammerfest HS300 turbine was tested in Norwegian waters in 2003 [2]. Significant progress has been made to characterise the kinetic resource at a total of 104 Norwegian sites through hydrodynamic modelling by the University of Bergen [126], the University of Oslo [127,128] and later a review/analysis by Grabbe et al. (2009) [129]. The studies identified 28 sites with mean maximum spring speeds greater than 3 m/s [126,129–133]. 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.

The Faroe Islands is currently undertaking testing of the Minesto Dragon kite [14]. Detailed hydrodynamic modelling of the whole archipelago has identified areas totalling 35 km$^2$ where peak current speeds exceed 2.5 m/s, and a kinetic energy flux of 17.5 TWh/year from 13 sites [134].

The Netherlands is home to the Dutch Marine Energy Center (DMEC) [14]. The first national scale tidal stream energy resource assessment was carried out by Alday et al. (2024) [135]. Based on results from hydrodynamic modelling with 500 m resolution along coastlines, the study concludes that the resource is relatively low energy, and shallow.

### (b) South America

In Chile, maximum current speeds of 4 m/s and 4.5 m/s have been reported in Chacao Channel [136] and the Strait of Megellan [137] 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 [138]. 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 [136].

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. (2015) [139]. Marta-Almeida et al. (2017) implemented hydrodynamic modelling to estimate peak power density in Baía de Todos os Santos (near Salvador), of 2.5 kW/m$^2$ [140]. The Rio Grande do Sul exhibits peak current speeds of over 1.5 m/s, with flow speeds further enhanced in some coastal areas [141].

In Argentina, maximum current speeds of 3 m/s and 2.5 m/s have been reported at San José Gulf inlet and Leones Island respectively, based on data collected from nautical charts and in situ measurements [142].

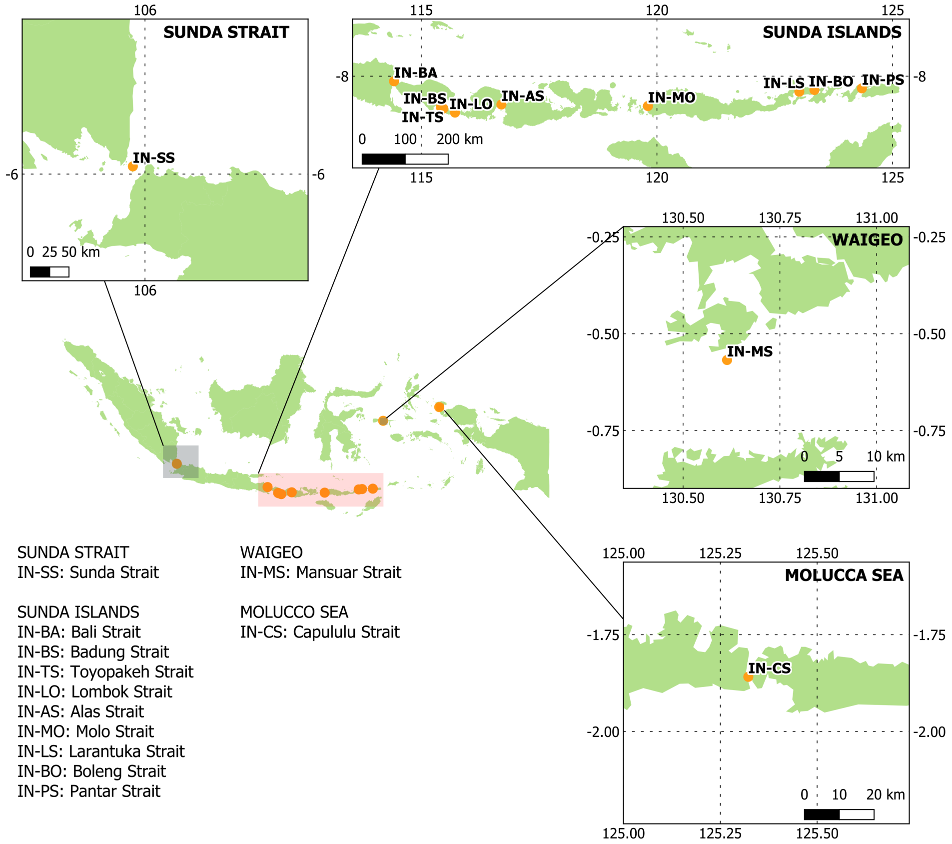


**Figure 8.** Overview of Indonesian tidal stream energy sites.

## (c) Asia

In South Korea, 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 [143,144]. Byun et al. (2013 [145] used in-situ measurements obtained from 264 locations spanning from the North-West to the South-East coastlines to characterise the kinetic resource. Particularly high current speeds ranging between 2 - 6.5 m/s 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. 3D hydrodynamic modelling by Hwang et al., (2019) [143] 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 1.25 m/s and 2.43 m/s respectively. Estimates of the theoretical and technical resources in South Korea are based on time averaged kinetic power through the swept area of turbines, without consideration for changes to the flow field as a result of turbine installations [143]. For this reason theoretical and technical estimates bear no link to the accepted theoretical and technical resource definitions that are adopted in this paper.

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 [146], Liloan Port, Hilutungan Channel, Surigao Strait and Banug Strait [147], and Verde Island Passage [148].

Malaysia has a substantial coastline, with most focus on sites in the Malacca Strait between Malaysia and the Indonesian island of Sumatra [149,150]. Bonar et al. (2018) [151] conducted numerical modelling of eight sites in the Malacca Strait, and provides a technical resource estimate of approximately 1 TWh/year. The study concludes that the resource is too small to ever play a substantial role in meeting the country's 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. (2010) [152] used outputs from the Princeton Ocean Model (POM) to also identify a further 8 sites in the South Chinese Sea, around the North and East of Borneo, where maximum current speeds exceed 2 m/s, namely Kapar, Pulau Jambongan, Semporno, Barangbongan, Kuching, Kota Belud and Sibu. Rahim et al. (2023) [150] 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 m/s in Khambhat, Kutch, South Gujurat and Sunderbans regions [153].

### (d) Australasia

Research into the tidal stream energy resource in New Zealand has focused predominantly on the energetic sites of Kaipara Harbour in the North West, Cook Strait that separates the North and South Islands, and Foveraux Strait/Stewart Island at the Southern end of the country [154]. Cook Strait has a very large estimated theoretical resource of 131 TWh/year [155]. Deep water is acknowledged to be a key challenge for large scale development in Cook Strait, which exceeds 150 m over the majority of its narrowest section [156]. A follow on study that limited turbine deployment to depths less than 100 m estimated that a 95 MW array may be viable in Cook Strait if turbine manufacturing costs fall, or energy prices increase, by approximately 25%, on 2020 levels. The same study provided a 1-2 TWh/year theoretical resource estimate for Kaipara Harbour. For context New Zealand's electricity demand is approximately 45 TWh/year.

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 $\text{km}^2$), Banks Strait between Australia and Tasmania (67 $\text{km}^2$), and Clarence Strait located in the Northern Territory (<1 $\text{km}^2$) [12]. The evaluation considered resource, distance to infrastructure and population, and constraints set by bathymetry, marine users and conservation areas. Further work is needed to estimate the energy resources at the sites.

## 11. Discussion and recommendations

### (a) Site characteristics

Figure 9 provides a summary of the site and theoretical resource data presented in this review. Figure 9a-c shows the range of maximum current speed, depth and site width, across sites in each country, respectively. The site characteristics are quantified in terms of median, 25th/75th percentile, extreme values and outlier values.

Figure 9a demonstrates that the majority of sites exhibit maximum current speeds ranging between 2 - 5 m/s. Sites with maximum current speeds between 1.5 - 2 m/s are located in Norway and USA. It is important to acknowledge that the site selection criteria varies widely across the studies. Sites are selected in the UK, USA, China and Indonesia based on minimum time averaged power density, of between 0.5-1.5 $\text{kW/m}^2$ [29,72,86,116]. Other studies specific to France disregard sites with peak current speeds lower than between 1.5-2 m/s [53,56]. Cousineau et al. (2018) considered Canadian sites with median current speeds that exceed 1.5 m/s [65]. Haas et al. (2011) [72] selected USA sites with a time averaged current speed greater than 1 m/s. The selection of sites in the USA, China and Indonesia has been based on time averaged power density that exceeds 0.5 kW/m$^2$, whilst in the UK, the Carbon Trust's study requires time averaged power density to exceed 1.5 kW/m$^2$. Cornett et al. (2006) select Canadian sites that exhibit a time averaged kinetic power flux that exceeds 1 MW. This inconsistency in site selection criteria skews the data presented in Figure 9 and prevents like-for-like comparisons of tidal stream resource across studies, sites, and countries. Recommendations for addressing this, along with other sources of inconsistent site selection, are provided below.

Inconsistencies in the depth criteria for site selection are also evident in the literature. The minimum depth requirement ranges from 5 m in the USA [72] to greater than 25 m in France [53]. Other studies also implement upper limits on depth of 60 m for French [56] and Canadian sites [65]. Figure 9b illustrates that in general, the average depth of sites varies between 15 - 100 m. There are exceptions to this in the USA, Canada, and Indonesia, where deeper sites of up to 400-550 m have been assessed. It is unclear at this stage of the sectors development whether such deep waters are technically viable for floating tidal stream turbine deployment.

It is recommended that a clear and consistent site selection approach is developed. Importantly, site selection should reflect the rapidly evolving landscape of the energy sector, for which site selection must be based upon. For example, the levelised cost of tidal stream energy is projected to reduce from around 200 £/MWh to 150 £/MWh for projects commissioned in 2025 and 2030 respectively [33]. In contrast, the LCoE of competing technologies are either expected to fall by a slower rate (e.g., offshore wind: 11% reduction from 44 £/MWh to 39 £/MWh), or increase (e.g., combined cycle gas turbines: 22% increase from 114 £/MWh to 139 £/MWh) over the same time period [157]. This example highlights that historic/current site selection criteria is unlikely to be valid in the context of the future energy sector.

To help address these uncertainties in future site selection criteria, it is recommended that site selection should not be fixed by rigid criteria that quickly become outdated. Instead, there is a need to characterise how the number of sites and the size of the resource is impacted by site selection criteria and practical constraint ranges that reflect current and expected future energy sector evolution, and its uncertainty. This means quantifying the size of the resource based on a range of, for example, minimum time-averaged current speed criteria, as this is a driver for the economic viability of a project. Doing so makes it possible to establish the relationship between site selection parameters and the magnitude of the resource, making it possible to re-evaluate the size of the practical resource as energy-wide sector costs evolve over time. This is discussed further in §11(d).

It is also important to highlight that the data presented in Figures 9a-b only provide a limited representation of maximum current speed and depth across sites, as the spatial variability in these site characteristics is significant.

Figure 9c shows the significant variability in width of sites, of between 0.01-100 km. In general site width is measured at the narrowest section of each site, where current speeds are, in general, greatest. This may make the narrowest section the most likely location to position turbines, however many practical constraints must be considered before the development area can be determined.

## (b) Theoretical resource

Figure 9d summarises the cumulative theoretical resource, and the proportion of sites with a theoretical resource estimate, when the data is aggregated by country. Of the 426 sites identified as exhibiting potentially viable conditions for tidal stream development in this review, theoretical resource estimates have been conducted at 262 sites (62% of sites). The total estimated theoretical resource from the 262 sites, across six countries, is 1000 TWh/year. The countries with the greatest estimated theoretical resource contributions are the USA (445 TWh/year from 208 sites), the UK (340 TWh/year from 31 sites) and New Zealand (132 TWh/year from 2 sites). The remaining three countries with theoretical resource estimates are Canada (64 TWh/year from 3 sites), China

(31 TWh/year from 17 sites) and France (16 TWh/year from 1 site). 28% of this aggregated theoretical resource is located at just three sites; the Pentland Firth in Scotland, UK, and Cook Inlet and Chatham Strait in Alaska, USA.

A further 82 sites have been identified in these six countries where theoretical resource estimates have yet to be made. No theoretical resource estimates have been made in the remaining thirteen countries across Europe, South America, Asia and Australia either, which have a further 114 sites identified as potentially suitable for development. Discussion around the significance of the magnitude of the resources relative to national and regional electricity demand is provides in §11(e).

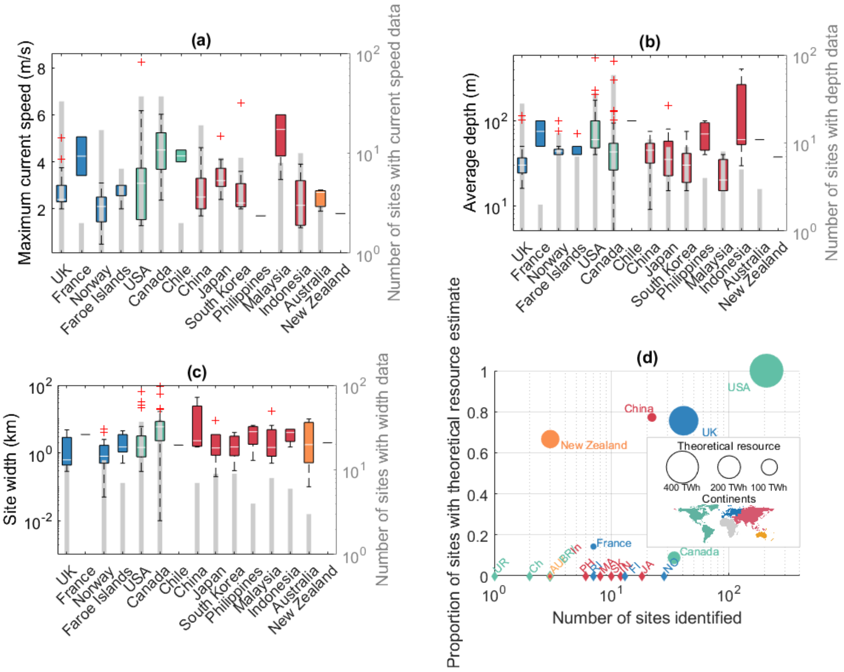


**Figure 9.** Summary of (a) maximum current speed data, (b) average depth , (c) site width, and (d) national theoretical resource estimates by country. Box plots (a-c) show median (white horizontal lines), 25th - 75th percentile range (boxes)and extreme values (crosses). Grey bars show the number of sites that that the data is based upon. 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.

## (c) Technical resource

Technical resource estimates have been made at 249 out of the 426 sites (58% of sites). Of the technical resource studies identified, inconsistent methods have been adopted for deriving it. This prevents (i) meaningful cumulative technical resource estimates from being made, and (ii) like-for-like comparisons of estimated technical resource across sites/countries [96].

Technical resource estimation is based on the energy that can be extracted by specific turbine design. The choice of rotor diameter(s) places a constraint on the depth that turbines can be installed. This contradicts a simpler definition of technical resource; the proportion of the theoretical resource that can be used for electricity generation, because the theoretical resource is grounded in the assumption that turbines span the entire width of a site. Results from theoretical modelling show that array footprint and blockage ratio constraints impact the level of energy extraction and volume flux significantly [19,20,118,158]. For example, hydrodynamic modelling of Minas Passage by Walters et al. (2013) [67] found that limiting turbines to depths greater than 50 m led to a 27% reduction in theoretical resource, relative to an idealised array spanning the entire width of the channel. To ensure consistency in future technical resource estimation, it is recommended that resource assessment standards are developed to define a procedure for selecting turbine specification, and in turn, setting a depth constraint on array footprint.

Many studies choose the rated speed of turbines based on the ambient flow field. The problem with this approach is that turbine installations reduce the current speeds upstream of the turbines, limiting the amount of time the turbines operate at their rated power. It is argued here that turbines are not 'technically viable' if they are not operating within their design window, and that this should be considered when specifying appropriate turbine design in technical resource assessment. Data from operating tidal and wind turbines suggests that to achieve economic viability, conventional horizontal axis tidal stream turbines should operate with a capacity factor of around 0.3 [41], which may provide useful steer. Some UK studies consider a range of turbine specifications (i.e., swept area and rated speed) to account for spatial variability in depth and current speed [23,29,40]. It is recommended that future technical resource assessments adopt this heterogeneous array design approach, to size turbines appropriately to the local resource.

In studies that estimate technical resource as the annual electricity production from the same array that is needed to extract the theoretical resource (e.g., [75]), the estimated technical resource is generally estimated to be between 40-50% of the theoretical resource [24,75], although evidence for how this conversion has been derived is limited. On this, a shortfall of implementing a continuous drag field to simulate turbine array drag, as most array scale resource assessments do, is that sub-turbine scale flow features, such as individual turbine wakes, are not resolved. This prevents wake losses from being modelled, and estimated. This is an important uncertainty that future research needs to address to build confidence in technical and practical AEP estimations. Preliminary research quantifying energy losses based on an isolated, idealised, dual rotor Seagen 1.2 MW turbine operating at the Betz limit at rated speed concludes that 16% of the extracted power is lost to turbine inefficiencies (i.e., drive-train losses), 18% is lost to support structure drag, and 27% is lost in wake mixing, leaving around 40% for electricity generation [24]. This estimate is device specific, since, for example, the drag from a supporting pile is likely to be different to the drag created by a floating support structure, or gravity-based structure. For idealised arrays of turbines, research indicates that the magnitude of the wake losses is inversely proportional to the blockage ratio, since higher blockage limits the amount of bypass flow accelerating around the turbines, and reduces mixing with the turbine wakes [21]. Research characterising wakes through in-situ measurements acquired using Acoustic Doppler Current Profilers (ADCPs) and aerial drones has now started [159,160], which is vital for validation of array modelling and wake loss quantification.

## (d) Practical resource

Practical AEP estimates have been made at just 31 sites, representing 7% of those identified, mainly focusing on UK sites [29]. Caution is recommended when interpreting the UK practical resource estimates, since there is uncertainty in the appropriateness of the constraints that were adopted. Environmental constraints were chosen based on anecdotal rational, and economic constraints are based on sector costs at the time of the report in 2011, which have changed significantly since this time [33,161].

For these reasons it is recommended that the choice of practical constraints is revisited. As with site selection criteria discussed in §11(a), it is important to acknowledge that many practical constraints are uncertain, and time-dependent. For example, on constraint uncertainty, The Carbon Trust state that 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. On the time-dependency of practical constraints, economic performance indicators such as levelised cost of energy are driven by many time dependent factors such as the cost of competing power generation technologies relative to tidal stream, and the availability of economic support (e.g., subsidies, grants) [161]. On environmental constraints, there is high uncertainty in what constitutes acceptable, site specific environmental impact. For these reasons environmental constraints are poorly defined and must develop over time as understanding improves, which necessarily must happen alongside stage-gated, go no-go array development. Practical resource studies that derive the resource based on a single set (i.e., time-frozen) of practical constraints, which is common in the literature, are highly likely to become outdated quickly.

It is recommended that future resource assessment characterises the sensitivity of energy extraction magnitude to practical constraints. To inform this approach, learning may be taken from resource assessment studies reviewed here. Figure 10a shows the relationship between the change in volume flux as a result of adding turbines across the width of a site, and the extracted power as a proportion of the theoretical resource, based on results from studies of sites across the UK, France and Canada. Results show that the theoretical resource is achieved 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, much lower changes in volume flux, of between 5-10% of the volume flux without turbines, still results in significant total energy extraction of between 20-40% of the theoretical resource. The fact that the relationship between $Q/Q_0$ and $P/P_{max}$ is consistent across sites helps infer what the limit on practical resource is, for any given change in volume flux.

Figure 10b illustrates the relationship between the change in current speed and tidal range resulting from turbine installations, and energy extraction, based on hydrodynamic modelling of UK tidal streaming sites [29]. In this example energy extraction is constrained by a limit imposed on current speed change, which is reached before the tidal range change constraint when turbines are installed in a channel. Importantly, deriving this site-specific relationship between the change in current speed/ tidal range and energy extraction is critical becuase it allows the level of energy extraction to be re-assessed as understanding of acceptable changes in these, albeit broad, environmental impacts improves over time.

Figure 10c illustrates the relationship between an array's installed capacity and energy extraction, based on results derived by Goss et al. (2020) [162]. It is recommended that resource assessment derives this relationship in order to help assess the economic viability of the array design. A useful indicator of economic viability of arrays using large scale (multi-MW), horizontal axis turbines is capacity factor, with reported contractual values from the MeyGen array of around 0.3. In the absence of any evidence to suggest otherwise, this real-world data is useful in that it implies that performance significantly below this level, for this particular commonly adopted type of turbine, is unlikely to be economically viable. This helps address a key limitation of several studies reviewed here; that the capacity factor of arrays falls to low levels, below 20%, which is highly unlikely to achieve economic viability based on the performance requirement for horizontal axis turbines that the modelling is based upon [41].

The UK's site specific practical AEP estimates lie between 30-100% of the technical AEP estimates. The aggregated practical AEP that is 10% of the aggregated theoretical AEP. Applying a simple linear regression to the technical and practical AEP datasets yields an $r^2$ coefficient of determination equal to 0.9. This implies that, based on the results derived by The Carbon Trust, whilst practical constraints can vary from site to site significantly, the impact of practical constraints in reducing the AEP from its technical to practical level may be similar across most sites. This has potentially impactful consequences because it means that with knowledge of the aggregated technical AEP at sites, it becomes possible to infer the aggregated practical AEP, when a statistically robust number of sites are considered. It is recommended that further work is conducted to test this hypothesis, given that it is based on a limited number of sites, with high uncertainty in the constraints that have been imposed to derive technical and practical AEP.

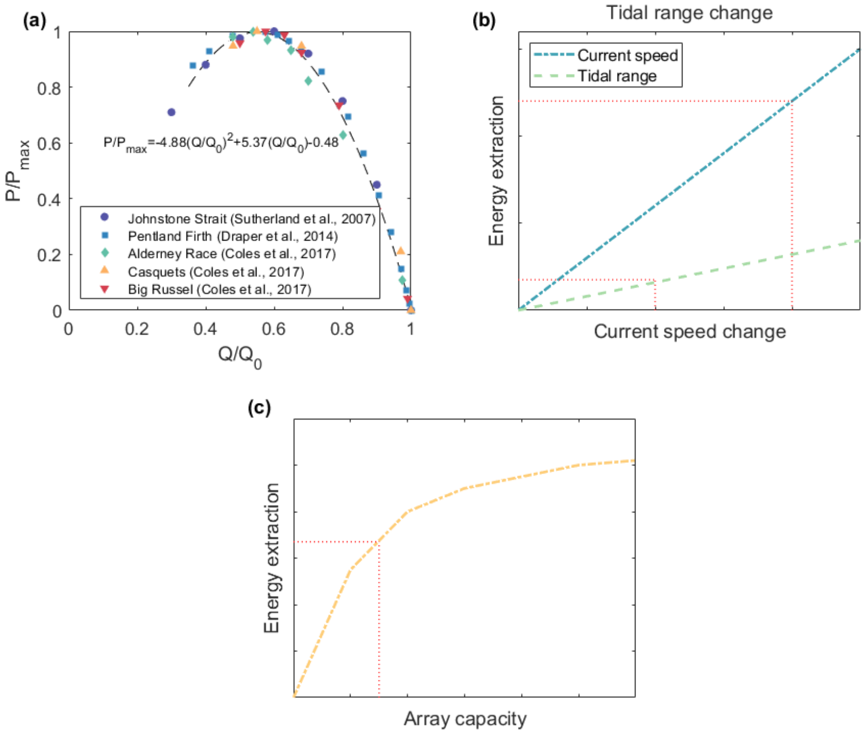


**Figure 10.** (a) Comparison of hydrodynamic modelling that relates the change in volume flux to time-averaged extracted power as a proportion of theoretical resource, (b) Relationship between changes to current speed and tidal range, and the energy extracted from a tidal streaming site [29], (c) Relationship between array capacity and energy extraction. Red lines indicate user-defined environmental and array capacity (i.e., capacity factor) constraints that limit energy extraction.

The same extends to establishing the correlation between theoretical resource and technical AEP, which has not yet been carried out. This is potentially of greater use, since neither resource requires assumptions regarding spatial constraints (e.g., other marine users). If a statistically robust correlation exists, the relatively simple derivation of theoretical resource can help rapidly infer an initial estimation of technical resource.

## (e) National/regional contribution potential

To help establish the potential for tidal stream to contribute to de-carbonisation of electricity generation, we introduce a new metric, termed the resource-demand ratio $\Phi$, which is the ratio of tidal stream energy resource to annual electricity demand. Upper-case $\Phi$ indicates a national scale resource-demand ratio, whilst lower-case $\phi$ indicates a regional equivalent. Subscripts 1,2 and 3 indicate whether the tidal stream resource is a theoretical, technical or practical estimate. Technical and practical estimates are based on AEP.

Results indicate that tidal stream resources in the UK, Indonesia and New Zealand have potential to contribute significantly to electricity supply at national scale. Theoretical resource estimates for UK and New Zealand sites yield $\Phi_1$ of 1.0 and 2.9 respectively. Technical resource estimates of UK and Indonesian sites yield $\Phi_2$ of 0.16 and 0.2 respectively. Finally, practical resource estimates of UK sites yields $\Phi_3$=0.11

Tidal resources in France, Canada, USA and China exhibit potential to contribute to electricity supply at regional level, with $\phi_1$ of 0.6, 5.4, 53.0 and 15.4 based on tidal stream resource and electricity demand in Normandy, Nova Scotia, Alaska and Zhoushan archipelago respectively.

Further research is clearly needed to understand the potential role(s) of tidal stream to integrate with energy systems, and future co-development of transmission grid and/or demand increase (e.g., from digitisation such as demand centres and the electrification of transport and heating) to absorb excess tidal stream power.

## 12. Conclusions

The tidal stream sector is planning rapid, mega-watt scale expansion, mainly in the UK and France, which if delivered, will increase cumulative installed capacity by 440% by 2029, to 188 MW. Juxtaposed to this progress is uncertainty regarding tidal stream's potential to contribute significantly to the long-term net-zero transition. To help address this, this review critically assesses research in resource assessment.

426 sites are identified that exhibit potentially favourable characteristics for tidal stream energy development across Europe, the Americas, Asia and Australisia. Theoretical resource estimates have been made at 62% of the sites, with a cumulative total of 1000 TWh/year. This cumulative theoretical resource is located across the UK (41 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). 28% of this aggregated theoretical resource is located at just three sites; the Pentland Firth in Scotland, UK, and Cook Inlet and Chatham Strait in Alaska, Canada. Within these 6 countries, 82 sites lack theoretical resource estimates.

A further 92 sites have been identified as potentially suitable for tidal stream energy development in other countries, namely the Republic of Ireland (7 sites), Norway (28 sites), Faroe Islands (13 sites), Chile (2 sites), Uruguay (1 site), Brazil (3 sites), South Korea (10 sites), Philippines (6 sites), Malaysia (16 sites), India (3 sites) and Australia (3 sites), based on albeit limited ambient flow data.

In general, studies adopt inconsistent site selection criteria. This is reflective of (i) the uncertainty in what constitutes a 'suitable site', and (ii) the time-dependent nature of site selection criteria that needs to account for the changing energy landscape. It is recommended that a consistent, time-dependent site selection method is developed to address this, that also acknowledges uncertainty bounds in resource assessment methods.

Technical resource estimates have been made at 249 out of the 426 sites, with an aggregated global estimate of 369 TWh/year, the majority of which is located in the USA, Indonesia and the UK. Caution is recommended when interpreting technical resource estimates, since studies adopt inconsistent approaches for quantifying it. There is a need to clarify the method for quantifying technical resource to address ambiguity in (i) the difference between total energy extraction and annual energy production (AEP), (ii) how to specify turbines and array layout, and (iii) validation of the extracted energy that can usefully be used for electricity production, relative to energy losses that arise from support structure drag and wake mixing, with the latter often not modelled in regional scale hydrodynamic modelling.

Practical resource estimates have been made at 31 sites, predominantly in the UK, with an estimated resource of 34 TWh/year. As with site selection, practical constraints on energy extraction are uncertain, and time-dependent. If a resource assessment quantifies resource based on rigid, time-frozen constraints, as is often the case in the literature, results quickly become outdated. Recommendations are made to help address this by characterising the sensitivity of the resource magnitude to constraint ranges that reflect their uncertainty and time-dependency.

Results presented in this review indicate that of the seven countries with theoretical/technical resource estimates, the UK, Indonesia and New Zealand have tidal stream resources that show the greatest potential to contribute to national scale electricity production. Resources in France, Canada, USA, China and Indonesia show potential to make regional scale contributions. Ambient flow data indicates that Norway, Faroe Islands, Japan, South Korea and the Philippines have potentially significant resource that also requires further investigation.

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## 13. Supplementary Material

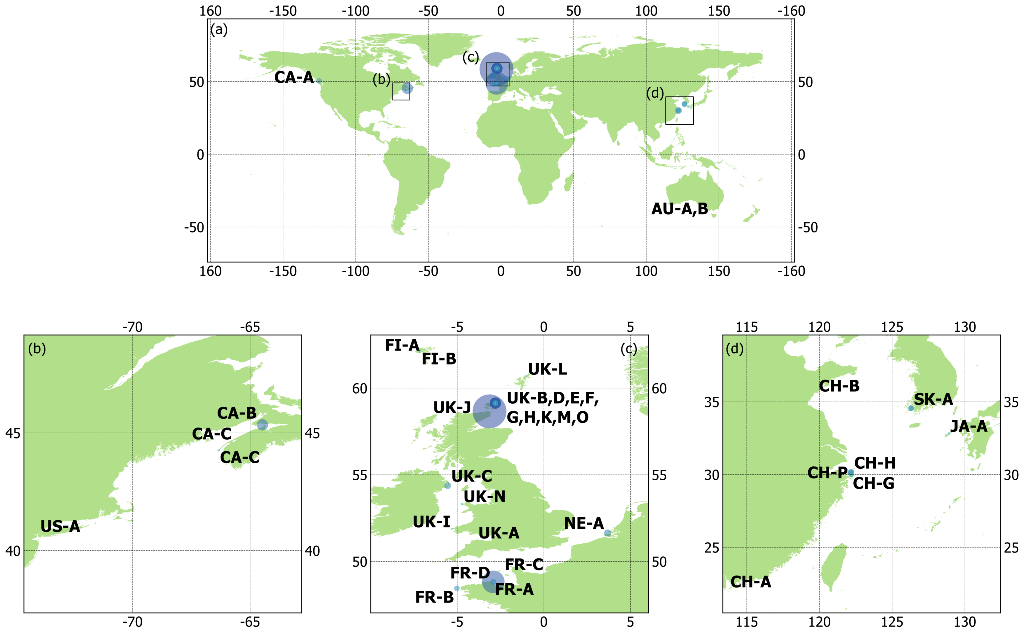

**Figure 11.** Overview of tidal stream energy installations to date. Marker size is indicative of installed capacity. Marker labels are linked to project information in Tables 1 and 2.

**Table 8.** Summary of $>$0.1 MW tidal stream turbine installations in the Americas and Europe. Capacity factors estimated based on the energy yield achieved over the following periods; $^{\dagger}$SR2000: October 2016 - September 2018, $^{\ddagger}$MeyGen 1A: December 2016 - February 2023, $^{\perp}$Alstom DeepGen: January 2013 - December 2014, $^{\top}$MCT SeaGen: July 2008 - July 2019, $^{\wr}$Verdent Gen5: 9 month period (dates not available), $^{\sqcap}$Andritz Hydro Hammerfest HS300: 2003 - 2007 and 2009 - 2011 [163]. 'N/A' indicates fields where data has not been available.

| Project/site | ID | Developer | Turbine model(s) | Rotors | Start of operation | Installed capacity | Active | Energy yield | Capacity factor |
|---|---|---|---|---|---|---|---|---|---|
| **Americas** | | | | | | | | | |
| Pempa'q Instream, Grand Passage [11] | CA-D | Sustainable Marine Energy/Schottel | PLAT-I 6.40 | 6 | 2020 | 0.42 MW | Yes | N/A | N/A |
| The RITE Project, East River [11] | US-A | Verdant Power | Gen5 | 3 | 2020 | 0.11 MW | Yes | 0.3 GWh | $0.42^{\wr}$ |
| Digby Neck [9] | CA-C | Sustainable Marine Energy/Schottel | PLAT-I 4.63 | 4 | 2018 | 0.28 MW | Yes | N/A | N/A |
| FORCE, Minas Passage [7] | CA-B | OpenHydro | N/A | 1 | 2016 | 2.00 MW | No | N/A | N/A |
| Dent Island [7] | CA-A | Water Wall Turbine Inc. | N/A | 1 | 2016 | 1.00 MW | Yes | N/A | N/A |
| **UK** | | | | | | | | | |
| Bluemull Sound, Shetland [7] | UK-L | Nova Innovation | M100-D | 1 | 2023 | 0.10 MW | Yes | N/A | N/A |
| EMEC, Fall of Warness [11] | UK-O | Orbital Marine Power | O2 | 2 | 2021 | 2.00 MW | Yes | N/A | N/A |
| Bluemull Sound, Shetland [7] | UK-L | Nova Innovation | M100-D | 1 | 2020 | 0.10 MW | Yes | N/A | N/A |
| Holyhead Deep [9] | UK-N | Minesto | DG500 | 1 | 2019 | 0.50 MW | Yes | N/A | N/A |
| EMEC, Fall of Warness [11] | UK-M | Magallanes | ATIR | 2 | 2019 | 2.00 MW | Yes | N/A | N/A |
| Bluemull Sound, Shetland [7] | UK-L | Nova Innovation | M100-D | 3 | 2017 | 0.30 MW | Yes | N/A | N/A |
| EMEC, Fall of Warness [7] | UK-K | Orbital Marine Power | SR2000 | 2 | 2016 | 2.00 MW | No | 3.3 GWh | $0.10^{\dagger}$ |
| MeyGen 1A, Inner Sound [7] | UK-J | MeyGen | HS1500, AR1500 | 4 | 2016 | 6.00 MW | Yes | 50.0 GWh | $0.15^{\ddagger}$ |
| Ramsey Sound [5] | UK-I | Tidal Energy Ltd | Deltastream | 1 | 2015 | 0.40 MW | No | N/A | N/A |
| EMEC, Fall of Warness [4] | UK-H | Alstom | Deepgen | 1 | 2013 | 1.00 MW | No | 1.2 GWh | $0.07^{\perp}$ |
| EMEC, Fall of Warness [3] | UK-G | Voith Hydro | HyTide 1000 | 1 | 2013 | 1.00 MW | No | N/A | N/A |
| EMEC, Fall of Warness [3] | UK-F | Orbital Marine Power | SR250 | 2 | 2012 | 0.25 MW | No | N/A | N/A |
| EMEC, Fall of Warness [1] | UK-E | Atlantis Resources | AR1000 | 1 | 2011 | 1.00 MW | No | N/A | N/A |
| EMEC, Fall of Warness [1] | UK-D | Andritz Hydro Hammerfest | HS1000 | 1 | 2011 | 1.00 MW | No | N/A | N/A |
| Strangford Lough | UK-C | Marine Current Turbines | SeaGen | 2 | 2009 | 1.20 MW | No | 11.6 GWh | $0.10^{\top}$ |
| EMEC, Fall of Warness | UK-B | OpenHydro | N/A | 1 | 2008 | 0.25 MW | No | N/A | N/A |
| Lynmouth [164] | UK-A | Marine Current Turbines | N/A | 1 | 2002 | 0.30 MW | No | N/A | N/A |
| **France** | | | | | | | | | |
| Paimpol-Brehat [10,165] | FR-C | Hydroquest | OceanQuest | 4 | 2019 | 1.00 MW | No | N/A | N/A |
| Fromveur Passage [6] | FR-B | Sabella | D10 | 1 | 2015 | 1.00 MW | N/A | N/A | N/A |
| Paimpol-Brehat [1] | FR-A | OpenHydro | N/A | 1 | 2011 | 0.50 MW | No | N/A | N/A |
| **Netherlands** | | | | | | | | | |
| Eastern Scheldt [8] | NE-A | Tocardo | T-2 | 5 | 2017 | 1.25 MW | Yes | N/A | N/A |
| **Faroe Islands** | | | | | | | | | |
| Vestmannasund [14] | FI-B | Minesto | Dragon 4 | 1 | 2022 | 0.50 MW | Yes | N/A | N/A |
| Vestmannasund [11] | FI-A | Minesto | DG100 | 2 | 2020 | 0.10 MW | Yes | N/A | N/A |
| **Norway** | | | | | | | | | |
| Kvalsund [2] | NO-A | Andritz Hydro Hammerfest | HS300 | 1 | 2003 | 0.30 MW | No | 1.5 GWh | $0.09^{\sqcap}$ |

**Table 9.** Summary of >0.1 MW scale tidal stream turbine installations in Asia and Australia. Capacity factors estimated based on the energy yield achieved over the following periods; $^{\wr}$Endevour: 20 months of operation [14], $^{\dagger}$Zhairuoshan Island: March - November 2018 inclusive [8], $^{\ddagger}$Uldomok Tidal Power Plant: One month of operation [14]. 'N/A' indicates fields where data has not been available.

| Project/site | ID | Developer | Turbine model(s) | Rotors | Start of operation | Installed capacity | Active | Energy yield | Capacity factor |
|---|---|---|---|---|---|---|---|---|---|
| **China** | | | | | | | | | |
| LHD Demo Project [14] | CH-P | LHD New Energy Corp. | Endevour | 1 | 2022 | 1.0 MW | Yes | 2.9 GWh | $0.20^{\wr}$ |
| Zhoushan Demo Project [10] | CH-O | China Three Gorges | N/A | 1 | 2020 | 0.3 MW | Yes | N/A | N/A |
| Zhoushan Demo Project [8] | CH-M | Hangzhou United Energy Co. | N/A | 1 | 2018 | 0.4 MW | N/A | N/A | N/A |
| Zhoushan Demo Project [8] | CH-L | Hangzhou United Energy Co. | N/A | 1 | 2018 | 0.3 MW | N/A | N/A | N/A |
| Zhairuoshan Island [8] | CH-K | Guodian United Power Technology Co. | N/A | 1 | 2018 | 0.3 MW | N/A | 0.3 GWh | $0.15^{\dagger}$ |
| Zhoushan Demo Project [8] | CH-N | Zhejiang University | ZJU 600 | 1 | 2017 | 0.6 MW | N/A | N/A | N/A |
| LHD Demon Project [6] | CH-J | Hangzhou United Energy Co. | N/A | 1 | 2016 | 0.6 MW | N/A | N/A | N/A |
| LHD Demon Project [6] | CH-I | LHD New Energy Corp. | N/A | 1 | 2016 | 0.4 MW | N/A | N/A | N/A |
| LHD Demon Project [5] | CH-H | Zhejiang Zhoushan LHD New Energy Corp. | N/A | 4 | 2016 | N/A | N/A | N/A | N/A |
| Zhoushan Demo Project [8] | CH-E | Zhejiang University | ZJU 120 | 1 | 2015 | 0.1 MW | N/A | N/A | N/A |
| Daishan [4] | CH-C | Harbin Engineering University | Haineng III | 2 | 2014 | 0.6 MW | No | N/A | N/A |
| Zhaitang Island [3] | CH-B | Harbin Engineering University | Haineng II | 2 | 2013 | 0.2 MW | No | N/A | N/A |
| Guishan Channel [3] | CH-A | Harbin Engineering University | Haineng I | 2 | 2012 | 0.3 MW | No | N/A | N/A |
| **Japan** | | | | | | | | | |
| Naru Strait [13] | JA-A | Kyuden Mirai Energy | AR500 | 1 | 2021 | 0.50 MW | Yes | N/A | N/A |
| **South Korea** | | | | | | | | | |
| Uldolmok Strait (Korea Tidal Energy Center) [14] | SK-D | KIOST | N/A | 1 | 2024 | 1.00 MW | Yes | N/A | N/A |
| Uldomok Tidal Power Plant [14] | SK-C | N/A | N/A | 1 | 2023 | 0.1 MW | Yes | 11.7 MWh | $0.16^{\ddagger}$ |
| Jindo [1] | SK-B | Voith Hydro | HyTide110-5.3 | 1 | 2011 | 0.1 MW | No | N/A | N/A |
| Uldomok Tidal Power Plant [3] | SK-A | N/A | N/A | 2 | 2009 | 1.0 MW | Yes | N/A | N/A |
| **Australia** | | | | | | | | | |
| Corio Bay [12] | AU-A | Atlantis Resources | Solon | 1 | 2008 | 0.16 MW | No | N/A | N/A |
| San Remo [12] | AU-B | Atlantis Resources | Aquanator | 1 | 2006 | 0.10 MW | No | N/A | N/A |

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