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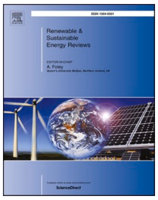

# A global cross-resource assessment of offshore renewable energy

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ABSTRACT

Current global climate mitigation efforts are considered insufficient to meet international carbon emission targets. Modeled scenarios showing how these targets can be reached are underpinned by further renewable energy development. Offshore renewable energy has been shown to have energy potentials that are more than double the global electricity demand. Previous assessments investigating Offshore renewable energy potentials typically focused on a single resource type and use a wide range of units. However, these assessments have not been compared on a global scale and therefore it is largely unknown which resource types have the largest energy potentials at any given location. This study undertakes a global cross-resource assessment of marine renewable energy potentials, collecting previous marine renewable energy resource assessments in a single database with standardized energy potentials. The assessments collected are compared to the theoretical energy potential of other resource types at each location. Tidal and ocean currents and offshore solar are found to have consistently higher energy potentials than the other resource types. An expanded feasible global energy potential for tidal currents and offshore solar is found. Results show if only 2 % of this potential is harnessed from future turbine development, $CO^2$ emissions could be significantly reduced helping meet international emission targets and United Nations Sustainable Development Goals.

## 1. Introduction

Efforts to meet the targets set by the International Panel on Climate Change to limit climate warming to 1.5 °C have been shown to be insufficient and enhanced and widespread development of renewable energy is needed to consequences of climate change such as more frequent extreme weather [1–3]. Achieving net-neutral carbon emissions is critical to meeting the International Panel on Climate Change targets and a key part of the United Nations Sustainable Development Goals [4]. In order to meet these goals, decarbonizing the electric industry is essential. Projections indicate that the energy sector must reach a minimum of 60 % of global energy generated by renewables by 2030 and 80 % by 2050 for net-neutral $CO_2$ emissions to be achieved [5,6]. Likewise, access to clean energy core part of these goals. In 2019 the global energy supply was made up of only 23 % renewable energy, with less than 1 % coming from offshore renewable energy (ORE) sources [7,8]. More than half of this ocean energy capacity came from projects located in Europe and was produced by offshore wind, tidal current, and wave energy converters.

Despite the smaller contribution to global supply, ORE could considerably contribute to future energy mixes given ORE energy potentials are estimated be up to twice the global electricity demand [9–11]. ORE has also been shown to improve access to clean energy for many nations with smaller gross-domestic products and who are dependent on fossil fuel import for electricity supply [12,13]. This help progress the United Nations Sustainable Development Goal Thirteen – Climate Action. This is especially true for island and coastal nations, which are some of the target regions identified by the United Nations Sustainable Development Goal Seven [13,14].

Determining the amount of energy is the first step towards developing these ORE energy systems, and is broadly referred to as resource assessments [15]. As a field of research, there is a robust amount resource assessment done for ORE. These assessments largely fall into two general categories: (1) global resource assessments, which provide knowledge of the total quantity and variability of the energy potential for one or more resources for the global oceans, and (2) site specific or regional resource assessments that determine total quantity and variability of the energy potential for one or more resources for a particular area or specific region [16–18]. Overall, there are far more ORE resource assessments that consider a single resource type for a specific location or region. Limited examples do exist that assess the energy potentials of

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| ORE – | Offshore renewable energy |
| OTEC – | Ocean thermal energy conversion |

*Symbols*

| | |
|---|---|
| $E$ | Theoretical energy potential |
| $\rho$ | Density (Kilogram per cubic meter) |
| $V$ | Velocity (meters per second) |
| $H_s$ | Significant wave height (meters) |
| $T_{wv}$ | Wave period (seconds) |
| $g$ | Gravitational acceleration (meters per second squared) |
| $\pi$ | Pi constant |
| $m_x$ | Minimum along-shore spacing for wave energy converters (meters) |
| $m_y$ | Minimum across-shore spacing for wave energy converters (meters) |
| $Wc$ | Capture width of a wave energy converter (meters) |
| $n$ | Number of data points |
| wd | Subscript denoting data/results for wind |
| wv | Subscript denoting data/results for wave |
| sl | Subscript denoting data/results for solar |
| tc | Subscript denoting data/results for tidal currents |
| ot | Subscript denoting data/results for OTEC |
| tr | Subscript denoting data/results for tidal range |
| $kW/m^2$ | Energy potential units in kilowatts per meter squared |
| $^{\circ}C$ | Degrees Celsius |

two or more resource types in the same region or specific coastal location [16,19,20]. However, to the best of the authors knowledge, no study exists that compares the energy potential of all ORE resource types, on any scale. This leaves a gap in current knowledge of understanding how the energy potential compares for the different ORE resources.

The research in this study aims to fill this gap by conducting interdisciplinary assessment of standardized energy potentials of the offshore wind, wave, ocean currents (tidal and other), tidal range, ocean thermal energy conversion (OTEC), and solar resources. Specifically, this cross-resource assessment 1) presents a review of studies assessing the energy potential of multiple ORE resources, 2) a develops a new comprehensive database of ORE resource assessments base on a systematic literature review, 3) demonstrates a novel energy unit conversion to explore how the energy potentials results in existing ORE resource assessments compare the energy potential of the different ORE resources, and 4) identifies what ORE resources that, to date, may be underutilized in terms of amount of research existing research and total global energy potential.

Finally, a discussion of the broader context of these results and implications for both the ORE sector and related energy fields are provided. Results from this work underscore there is a substantial amount of energy potential from ORE resources and demonstrates how a commensurate and interdisciplinary approach towards future research and development in ORE can advance access to both reliable and affordable clean energy. This type of research would make meaningful strides towards the United Nations Sustainable Development Goals Seven (Energy), Eleven (Sustainable Cities and Communities), Twelve (Responsible Consumption and Production), and Thirteen (Climate Action) by accelerating the transition to carbon neutral electricity generation which will combat climate change, improve air quality, and promote economic growth.

## 2. Review of cross-resource ORE analysis

This section provides a review of existing literature that assess the energy potential of two or more ORE resources in the same study. Studies included met the following criteria.

i) Provided quantitative energy results in terms of either energy production or energy density
ii) Assessed two or more ORE resources
iii) Novel analysis (not a review study) published in the last 10 years

The review resulted in 45 studies that assess the energy potential of at least two ORE resources. These studies are available in Table A-1 of the Appendix. Of these studies, 84 % considered two resources and 16 % considered three resources. Only two studies considered four ORE resources and no studies were found that assessed the energy of five or more ORE resources.

The most common ORE resources included in these studies were wind and wave, being considered in 82 % and 76 % of the reviewed studies. Wind and wave were also the most common pair of resources considered together, being included together in 62 % of the reviewed studies. The least common resource included was OTEC, considered in only 11 % of the studies.

These studies provide commensurate comparisons of how much energy is available for the ORE resources included in each individual study. These results can be used to gain insight can be gained on how to optimize those specific resources. However, these studies are focused on a specific location or region. Because the majority of these studies do not consider more than three ORE resources and are regional, these studies alone do not provide a comprehensive view on how the energy potential different ORE resources compare.

For a holistic view, a brief review was also conducted on literature review studies that considered multiple ORE resources. Criteria i and ii were still applied to this review. Tables 2–1 presents these studies, the ORE resources included in each review, and how energy results are presented (listed verbatim).

This body of literature reviews provides details on the progress of the ORE development, and insight into the future direction of MRE research. However, the variability in the number of ORE resources considered and the different ways results are reported make it challenging to meaningfully compare the energy potentials of the different MRE resources, both on a global and regional scale. This gap is likely due to large variability in nomenclature, variables considered, associated methods, and reporting styles used in the resource assessments these studies reviewed [31–33]. These variations are likely a product of multiple disciplines of research conducting resource assessments that have different aims and objectives. For example, a common approach used in wind resource assessments is to categorize the energy potential into optimal turbine locations by consideration of wind energy factors, environment risk factor and cost factors [34]. Likewise, some wave resource assessments use a similar, but different, classification of energy potential that consider wave specific variables such as wave swell periods [35].

## 3. Methods and data

The methodology used in this study was developed to enable a commensurate cross-resource investigation of ORE and to identify underutilized ORE resources. To achieve this, the first step was to develop a database of published ORE resource assessments using a systematic search of literature. The second step was to convert the energy estimates extracted into the database to a single set of standardized units (kW/m$^2$) representing the theoretical energy potential, or the maximum amount of energy the given resource has at that location. While it is common to use other measures of energy, such as kilowatt-hours, these energy measures are dependent on factors that are unrelated to the actual energy inherent to the resource itself, such as turbine efficiency, which are likely to change over time as turbine technologies improves.

To overcome incommensurate units, this study converts all energy results to theoretical values to allow for a level and direct comparison of the energy alone. In this research, the International Electrotechnical Commission Technical Committee definition of theoretical energy potential was used, which classify resource assessments into three levels of energy quantification [36]. Fig. 1 depicts the classifications and is an adaptation from the National Renewable Energy Laboratory [36].

The third step, reanalysis data was used to quantify energy potential of the various ORE resources in the standardized units globally and compared to the resulting energy potentials in the database. Finally, resources with high energy potential and fewer existing resource assessments were identified and an analogous global energy potential was calculated. A research framework showing each of these steps provided in Fig. 2. The remainder of this methods section provides specific methodology used for each step. To aid in interpreting the results, the data was grouped into six regions, shown in Fig. 3.

### 3.1. Database of resource assessments

The database of ORE resource assessments included six ORE resource types: offshore wind, wave, offshore solar, ocean currents, tidal range and OTEC. While other resource types exist, only these six were considered because they either are already technologically mature or are approaching technological maturity [37,38]. A rigorous search of literature based on keywords was completed to capture peer-reviewed publications, technical reports, articles, and other studies that assessed the energy potential for one or more of the considered resource types [39]. To ensure a maximum return from search results and diverse coverage three online database search engines were used: Web of Science – Core Collection from Clarivate, SUPrimo Library catalogue at the University of Strathclyde and Google Scholar.

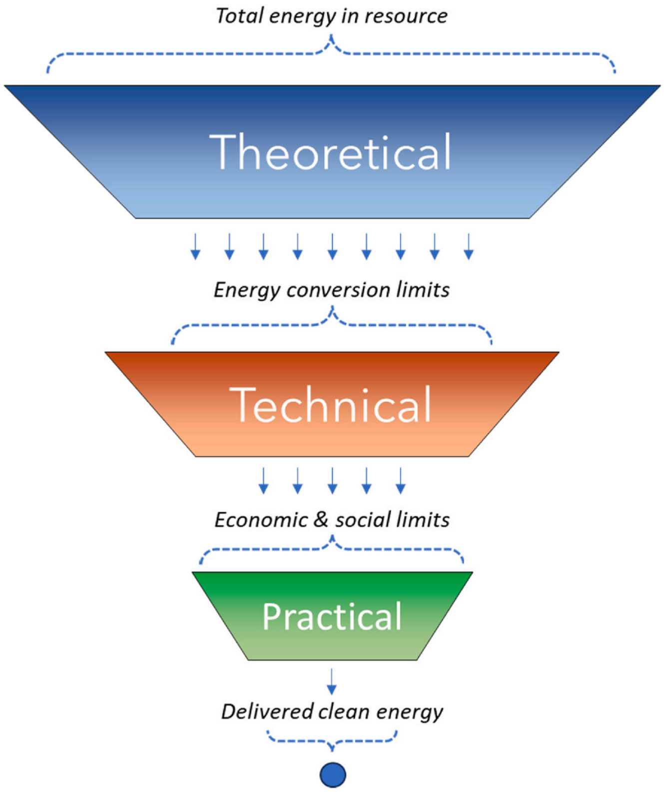

**Fig. 1.** | Nomenclature resource assessments.
The hierarchy of the three definitions of resource assessments used in this study, defined by the International Electrotechnical Commission Technical Committee. Each category applies filters to the corresponding level of energy quantification that reduces the amount resulting energy from the preceding energy classification.

The results of the search were assessed against inclusion/exclusion criterion defined by the authors. To be included, the report had to produce at least one energy estimate for a resource type at a definable location. The full criterion of the search of literature keywords and inclusion/exclusion criteria are shown in Tables 1 and 2, respectively.

From each report included, the energy estimate(s), units used, and the location of the estimate were extracted and added to the database. This approach does exclude resource assessments that consider full regions or entire bodies of water, however as the aim of this study is to cross compare energy potentials at specific locations, these reports are out of the scope for this study. The search covered reports published before 2021. Future work could use a similar approach and perform cross comparison of regional energy potentials as well as include reports published after 2021.

### 3.2. Conversion to theoretical energy potential

The extensive range of scopes, diversity of aims, goals, methodologies, and resource types considered in existing studies that make up the database required a case-by-case approach to convert the extracted energy potential units to the standardized units. The general approach was the same for all: use a dimensional analysis to account for factors specific to the turbines considered in a given report that reduce the amount of available energy from the reported maximum theoretical energy potential [40,41]. Factors that were considered in the dimensional analysis include the number of turbines, turbine sizes, turbine capacity factors, and total production time reported in each resource assessment.

In most cases the process was to take the reported energy estimate and divide it by the combined capture area of the turbines used in the study. For assessments that give energy production values (such as terawatt-hours), the energy potential value is divided by number of hours which the assessment considered. If not stated, it is assumed the values are annual energy production estimates. Lastly, turbine efficiency and losses are accounted for by dividing by turbine specific capacity factors. In some cases, the information to perform this conversion was not reported. In these cases, conservative assumptions were based on turbines frequently considered in other studies. To verify this approach the converted energy results were compared to other values in the database that were already reported in theoretical energy potential in the same regions. All converted estimates were within one order of magnitude.

For offshore wind, the Vesta V90 was used as the representative turbine and for ocean currents, the Verdant Power Rite turbine was considered [42,43]. When not supplied in the original reports, a capacity factor of 0.3 was assumed for both offshore wind and ocean currents [44,45]. This method ensures that the calculated theoretical energy potential was at least the minimum amount of energy for that resource type at the considered location. If multiple turbines styles or sizes are stated the more conservative choice (typically meaning smaller or fewer turbines) that results in a smaller theoretical energy potential was used.

To convert OTEC results to theoretical energy potentials, the cold-water intake pipe diameter multiplied by the depth of the cold-water intake was taken as the capture dimension. There is little to no prior work exploring how to convert from technical to theoretical energy quantification. While other options could have been used, this measure was chosen as these two factors directly interact with the physical resource as well as influence the rate which thermal conversion occurs [46]. Future work could explore a different capture dimension and the

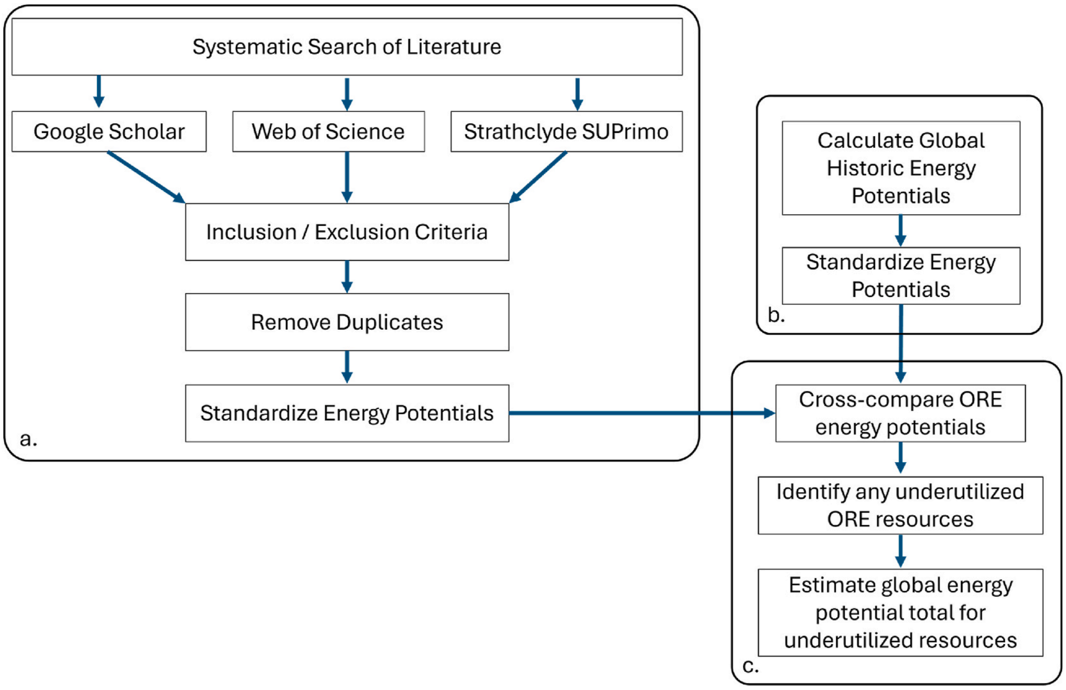

**Fig. 2.** | Research framework.
Visual representation of the steps used in this study. A) Development of the ORE resource assessment database. B) Calculating global energy potential based on ERA5 Reanalysis data. C) Cross-comparison and analysis of ORE energy potentials.

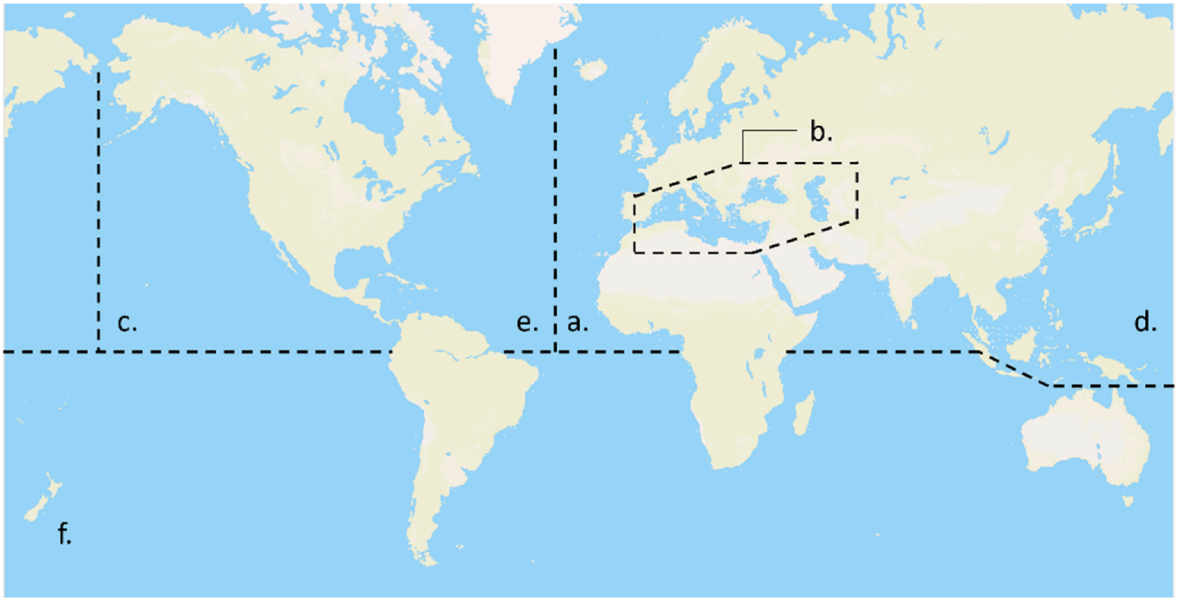

**Fig. 3.** | Study regions.
Map of the six regions used for data interpretation in this research. The regions are referred to as: (a.) eastern North Atlantic, (b.) Mediterranean, (c.) eastern North Pacific, (d.) coastal Asia, (e.) eastern North Atlantic, and (f.) southern hemisphere.

impact this would have on the conversion to a standardized set of units. There were reports used in the database that did not state the cold-water intake pipe diameter, so a value of 10 m was assumed as this was a common value stated in the reports which did [47,48]. Likewise, when not provided, a capacity factor of was 0.8 used [47,49].

Unlike the other resource types, wave energy converters have not yet converged on a single device style [10,50]. Wave theoretical resource assessments, however, frequently report energy potentials in kW/m. This is due to the nature of how wave propagate, and this approach quantifies the energy potential in the direction of the incoming waves [51]. While these units are logical when considering ocean waves alone, it does not allow for a rational comparison to other ORE resources.

To transform the wave energy estimates into the determined standardized units (kW/m$^2$), the spatial requirements of different wave energy converters devices were used. A total capture measure was found by considering the maximum number of devices that could be placed per square unit area (capture width divided by the minimum device spacing in both horizontal directions) was found, representing the maximum

**Tables 2-1**
Summary of ORE existing ORE literature reviews.

| Study | Publication Year | ORE Resources Considered | Results Reported |
|---|---|---|---|
| Analysis of hybrid offshore renewable energy sources for power generation: A literature review of hybrid solar, wind, and waves energy systems | 2024 | Wind, Wave, Solar | Growth of Hybridizing [ORE] |
| Examining the Potential of Marine Renewable Energy: A Net Energy Perspective [21] | 2023 | Tidal, Ocean Current, Wave Energy | Net Energy Available |
| Ocean energy applications for coastal communities with artificial intelligences - a state-of-the-art review | 2023 | Tidal Energy, Marine Current Power, Osmotic Power, Ocean Thermal Energy, Wave Energy | Holistic Energy Resource, Energy Characterization Methods |
| A Review of Offshore Renewable Energy in South America: Current Status and Future Perspectives | 2023 | Wind, Waves, Tides, Ocean Currents, And Thermal and Salinity Gradient | Resource Potential |
| State-of-the-art review of the flexibility and feasibility of emerging offshore and coastal ocean energy technologies in East and Southeast Asia [22] | 2022 | Wave, Tidal, Ocean Current, Offshore Floating Photovoltaic, Offshore Wind | Seasonal Power Potential, Development Status |
| What about Marine Renewable Energies in Spain? [23] | 2019 | Offshore Wind, Wave, Tidal, Marine Currents, Ocean Thermal, Osmotic (Salinity Gradient), Solar, Geothermal, Biomass | Global Potential, Global Production Potential |
| Resource Assessment of Theoretical Potential of Ocean Energy in Korea | 2019 | Wave Energy, Tidal Energy, Tidal Current Energy and Ocean Thermal Energy | Ocean Energy Utilization |
| Review and assessment of offshore renewable energy resources in morocco’ coastline | 2019 | Offshore Wind, Tidal and Wave | First Order Assessment of Their Potential |
| Attraction, Challenge and Current Status of Marine Current Energy [24] | 2018 | Ocean Thermal Energy, Osmosis Energy, Wave Energy, Tidal & Current Energy | Global Energy Potential, Environmental Impacts, Technology Challenges, Design Status, Case Studies |
| Current status and future of ocean energy sources: A global review [25] | 2018 | Tidal Energy, Wave Energy, | Technical energy potential in the United States |
| Electrical Power Supply of Remote Maritime Areas: A Review of Hybrid Systems Based on Marine Renewable Energies [26] | 2018 | Wave Energy, Tidal Energy, Wind Energy, Solar Energy | Technology Converter Classifications, Review of Hybrid Systems |
| Marine Renewable Energy in the Mediterranean Sea: Status and Perspectives [27] | 2017 | Offshore Wind, Wave, Tidal, Thermal, Salinity Gradients Energy Conversion | Development and technology status, global energy limit estimates |
| Wave and tidal current energy – A review of the current state of research beyond technology [28] | 2016 | Wave Energy, Tidal Energy | Environmental Impacts, Socio-economic impacts, Grid Integration, Development, Regulatory Affairs |
| Ocean energy development in Europe: Current status and future perspectives [29] | 2015 | Wave Energy, Tidal Energy | Development Status |
| Marine renewable energy in China: Current status and perspectives [30] | 2014 | Tidal Energy, Tidal Current Energy, Wave Energy, Ocean Thermal Energy, Salinity Gradient Energy | Potential Energy Capacity, Development Status |

amount of the theoretical resource that could be harnessed. Multiplying this value by the energy potential found in previous assessments gives a new theoretical energy potential in the standardized units. The specific dimensions for common styles of wave energy converters are given in Table 3.

There were very few assessments specifically looking at offshore solar or tidal range, and in these assessments, the reported units of energy potential were already given as theoretical energy potentials, thus no specific converter assumptions were required [52,53]. The resulting database with standardized energy potentials were visualized using Tableau. The maps included in the study are also published to Tableau Public and available online (see Data availability).

### 3.3. *Calculation of energy potentials from reanalysis data*

The energy potential for each ORE resource was calculated from reanalysis data in the standardized units and at the same locations of the database results. Due to data availability, OTEC and non-tidal currents were not calculated. Tidal range is also not considered here as future development of these systems has not been considered in previous research due to severe ecological and other impacts [11,54,55]. Of note, tidal lagoons are an emerging technology within the tidal range industry and, if realized, would justify future inclusion in similar work to this study [54].

Forty years (1979–2019) of global monthly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-5) were used to calculate energy potential for offshore wind, wave, and solar energy calculations. For tidal currents, the Oregon State University TPXO models were used to calculate energy potentials [56,57]. Note that for the rest of this study, ocean currents refer to the database results (including both tidal and ocean currents) and tidal currents refer to the newly calculated energy estimates from reanalysis data. The formulas for calculating the theoretical energy potentials of these resources are

**Table 1**
Systematic search of literature keywords.

| Term 1 | Term 2 | Term 3 | Term 4 | Term 5 | Term 6 |
|---|---|---|---|---|---|
| "Global" | "Offshore" | "Wind" | "Energy" | "Resource" | "Assessment" |
| "Regional" | "Marine" | "Wave" | "Renewable" | "Potential" | "Evaluation" |
| "Local" | "Oceanic" | "Solar" | "Power" | "Production" | "Estimate" |
| "Coastal" | "Sea" | "Tidal currents" | "Turbine" | "Source" | "Calculation" |
| "National" | "Floating" | "Ocean currents" | "Converter" | "Possibility" | "Study" |
| "International" | "Near Shore" | "Tidal Range" | "Technology" | "Reserve" | "Report" |
| "*Blank*" | | "Tidal Barrage" | "Platform" | "Supply" | "Analysis" |
| | | "Ocean Thermal Energy Conversion" | "Renewable Energy" | "*Blank*" | |
| | | "OTEC" | "Farm" | | |
| | | "Thermal" | | | |
| | | "Solar" | | | |
| | | "Physical" | | | |
| | | "*Blank*" | | | |

Keywords used in the systematic search of literature. A combination of the six different terms is used to create phrases searched for in Web of Science – Core Collection from Clarivate, SUPrimo Library catalogue search through the Andersonian Library at the University of Strathclyde, and Google Scholar.

**Table 2**
Selection criteria.

| Criteria Type | Criterium |
|---|---|
| Inclusion | • Reports an energy potential or production value with units<br>• Evaluates an offshore renewable resource (*Wind, wave, horizontal currents, tidal range, solar, ocean thermal energy conversion*)<br>• States a region or specific location of assessments |
| Exclusion | • Global assessments of entire ocean or offshore potential<br>• Turbine efficiency/performance assessments<br>• Biologic renewable energy assessments<br>• Environmental assessments<br>• Cost and financial assessments of ORE systems |

This table shows the conditions used to determine if the results from the systematic search of literature could be used in the ORE database. Search results must meet all the inclusion criteria to be included in the database. If a resulting publication met any of the exclusion criteria, that study was not used in the database regardless of if all the inclusion criteria were met.

**Table 3**
Common dimensions for wave energy converters.

| Wave Energy Converter | Capture Width (m) | Min. Spacing Along-Shore (m) | Min Spacing Across-Shore (m) |
|---|---|---|---|
| Power Buoy | 2.65 | 7.95 | 30 |
| Wave Dragon | 150 | 450 | 30 |
| Pontoon | 30 | 90 | 30 |
| Aqua Buoy | 6 | 18 | 30 |
| OceanTec | 20 | 60 | 30 |
| Pelamis | 180 | 540 | 30 |
| Oyster | 26 | 78 | 30 |
| Wavestar | 70 | 210 | 30 |
| WaveRider Buoy | 0.9 | 2.7 | 30 |

This table gives the dimensions used in some of the most commonly assessed wave energy converters in published resource assessments. These dimensions are used to convert theoretical energy potential in the units of kW/m to the standardized units in of the ORE database (kW/m2).

taken from published studies and are shown in Eqs. (1)–(4).

$$\text{Wind}: E_{wd} = \frac{1}{2}\rho_{wd}\, V_{wd}^3 \tag{Eq. 1}$$

$$\text{Wave}: E_{wv} = \frac{\rho_{oc} g^2}{64\pi} H_s^2\, T_{wv}\, \frac{Wc}{(2m_x)(2m_y)} \tag{Eq. 2}$$

$$\text{Tidal Current}: E_{tc} = \frac{1}{2}\rho_{tc}\, V_{tc}^3 \tag{Eq. 3}$$

$$\text{Offshore Solar}: E_{sl} = E_{sl} \tag{Eq. 4}$$

Where $E_{wd}$, $E_{wv}$, $E_{tc}$ and $E_{sl}$ are the calculated values for the new theoretical energy potential of wind, waves, and tidal currents, respectively. Further $\rho_{wd}$, and $\rho_{tc}$ are the densities of the air (1.225 kg/m$^3$) and ocean water (1025 kg/m$^3$), $g$ is the acceleration of gravity (9.81 m/s$^2$), $H_s$ and $T_{wv}$ are the significant wave height and wave period, $Wc$ is the capture width of the wave turbine and $m_x$ and $m_y$ are the minimum wave turbine device spacing in each direction, respectively.

For wave energy calculations the methods described in section 2.2 are used here to convert the energy potential to the standardized units. The PowerBuoy was used as the reference turbine, show in Table 3 as this has seen commercial deployment and gives more conservative results compared to other wave turbines. The data retrieved for solar was already formatted as a theoretical energy variable and no further calculation was needed.

### 3.4. Calculation of tidal current and offshore solar energy potential

Results of this studies research identified that tidal current and offshore solar consistently have larger energy potentials than other ORE resource types, but they have been studied much less than the other resource types. To explore a feasible upper limit of the global energy potential, the spatial variability of each was considered to inform an approach to calculate the total energy potential that is analogous with limitations of each resource.

Tidal currents are shown to have high spatial variability; therefore, the feasible upper limit is based on locations that have an energy potential at least as large as other ORE resources. The basis for this approach is that if the energy potentials were large enough to justify studying other ORE resources, it is fair to consider locations with tidal current energy potentials just as large. These locations are determined by defining a minimum energy potential threshold. If the energy potential calculated for tidal current at any given location is less than this threshold it is discarded and not included towards the feasible upper limit.

The threshold was calculated by taking the average of all the energy potentials in the database (excluding previous studies for ocean currents, which would have skewed the threshold upwards), shown in equation (5).

$$E_{threshold} = \frac{\sum Er_{wd} + \sum Er_{wv} + \sum Er_{tr} + \sum Er_{sl} + \sum Er_{ot}}{nr_{wd} + nr_{wv} + nr_{tr} + nr_{sl} + nr_{ot}} \tag{Eq. 5}$$

Where $E_{threshold}$ is the resulting threshold value, $Er_{wd}$, $Er_{wv}$, $Er_{tr}$, $Er_{sl}$ and $Er_{ot}$ are the energy potentials of offshore of wind, wave, tidal range, and offshore solar, from the database, and $nr_x$ is the number energy estimates in the database for each resource.

### 3.5. Determining the feasible upper limit of offshore solar

Offshore solar is found to have low spatial variability with regard to potential energy. Because of this a different approach than what was used for tidal current was needed to determine what locations could be included in the feasible upper limit. As solar is found to have far fewer reports than the other ORE resources in the database, new locations are based on making the number of locations for solar equal to those of the other ORE resources in the database. This logic is based on a trend toward hybrid turbine systems which capture multiple ORE resources in the same locations [58,59]. Further it is reasonable to assume offshore solar can have an increase in locations studied proportional to other ORE resources.

The first step for this approach was to identify the number of new locations to be included. The resource with the most locations (studies represented) in the database was wave energy. The number of locations in the database from each of the other ORE resources (not wave) was then subtracted from the total number of wave energy studies to get the number of new locations for offshore solar that are included in the feasible upper limit. This calculation is shown in Equation (6).

$$n_{slX} = n_{wave} - n_X \qquad \text{(Eq. 6)}$$

Where $n_{slX}$ is the number of new locations to be included with respect to an ORE resource from the database, $n_{wave}$ is the number of wave locations studied in the database, and $n_X$ is the number of locations studied in the database from a different respective ORE resource. The average offshore solar energy potential at the matching locations of each ORE resource in the database was found and multiplied by new number of locations for each associated ORE resource type. These additional locations are hypothetical but given the spatial consistency of the solar resource, it is likely that locations exist nearby to these locations with equivalent energy potentials. Equation (7) shows this step where $n_{slX}$ is the number of new solar datapoints used, $n_X$ is the number of existing datapoints from the other respective ORE resource types, $E_{slX}$ is the energy potential of offshore solar at the matching locations of other ORE resources in the database, and $E_{slnew}$ energy potential of offshore solar for the feasible upper limit,

$$E_{slnew} = n_{slX} {}^{*} \left( \frac{\sum E_{slX}}{\sum n_x} \right) \qquad \text{(Eq. 7)}$$

Quantifying the impact of the various limitations to ORE development has financial, environmental, political, and other restraints is outside the scope of this study. To address this, a conservative and reasonable assumption was made of only 10 % of the energy totals from the feasible upper limits of tidal currents and offshore solar being available for development.

## 4. Results

### 4.1. Database composition

A total of 661 resource assessment reports were included in the database. These reports resulted in 3019 individual energy potentials across the globe. These energy potentials were originally reported in twenty-four different sets of units. Of these results, wave and wind made up the most of the energy estimates, being studied at 1466 and 816 locations, respectively. Collectively wind and wave account for 76 % of all locations studied. Ocean currents make up 19 % of the locations previously assessed, with the remaining 5 % coming from tidal range and OTEC. Offshore solar energy estimates are less than 0.5 % of locations studied. To understand if this imbalance in assessments by resource type is reflective of energy potentials, the global average energy potential for each resource type is determined. The reports were published between 1978 and 2020. Fig. 4 shows the number of studies published per year be resource.

### 4.2. ORE average energy potentials

The resource type with the largest average energy potential is ocean currents with a value of 1.53 kW/m$^2$. This is over 4.7 times larger than offshore wind, which has the second highest average energy potential of 0.327 kW/m$^2$. The other resource types have average energy potentials an order of magnitude smaller: offshore solar has an average energy potential of 0.081 kW/m$^2$, tidal range of 0.069 kW/m$^2$, wave of 0.05 kW/m$^2$, and OTEC of 0.039 kW/m$^2$. Fig. 5 shows the global distribution and the magnitude of these energy potentials. These results suggest the

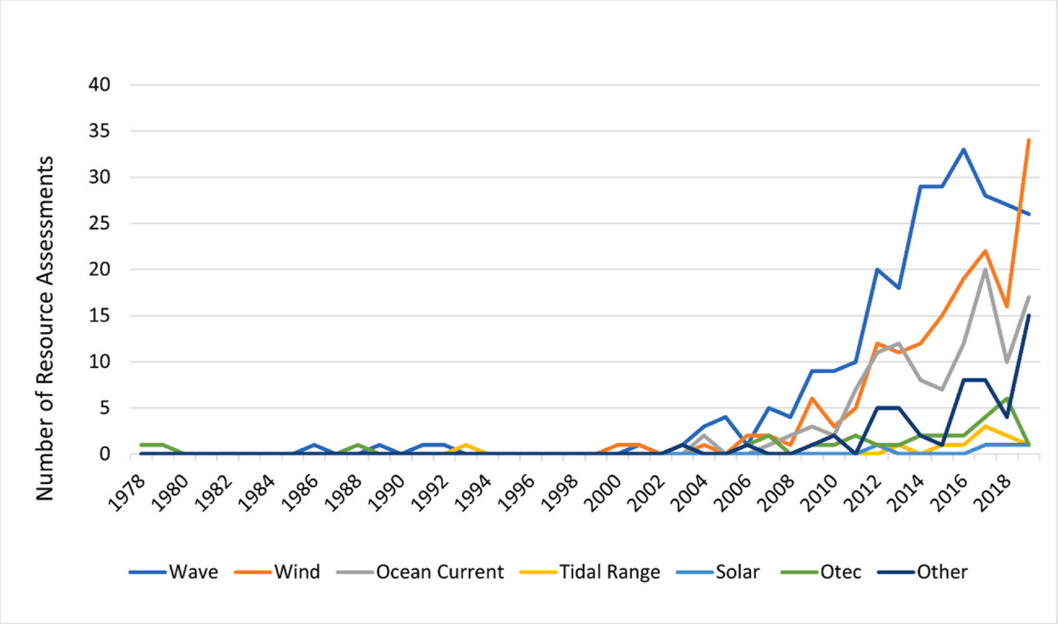

**Fig. 4.** | Number of resource assessments per year.
The number of resource assessments included in the ORE database by resource type and publication year.

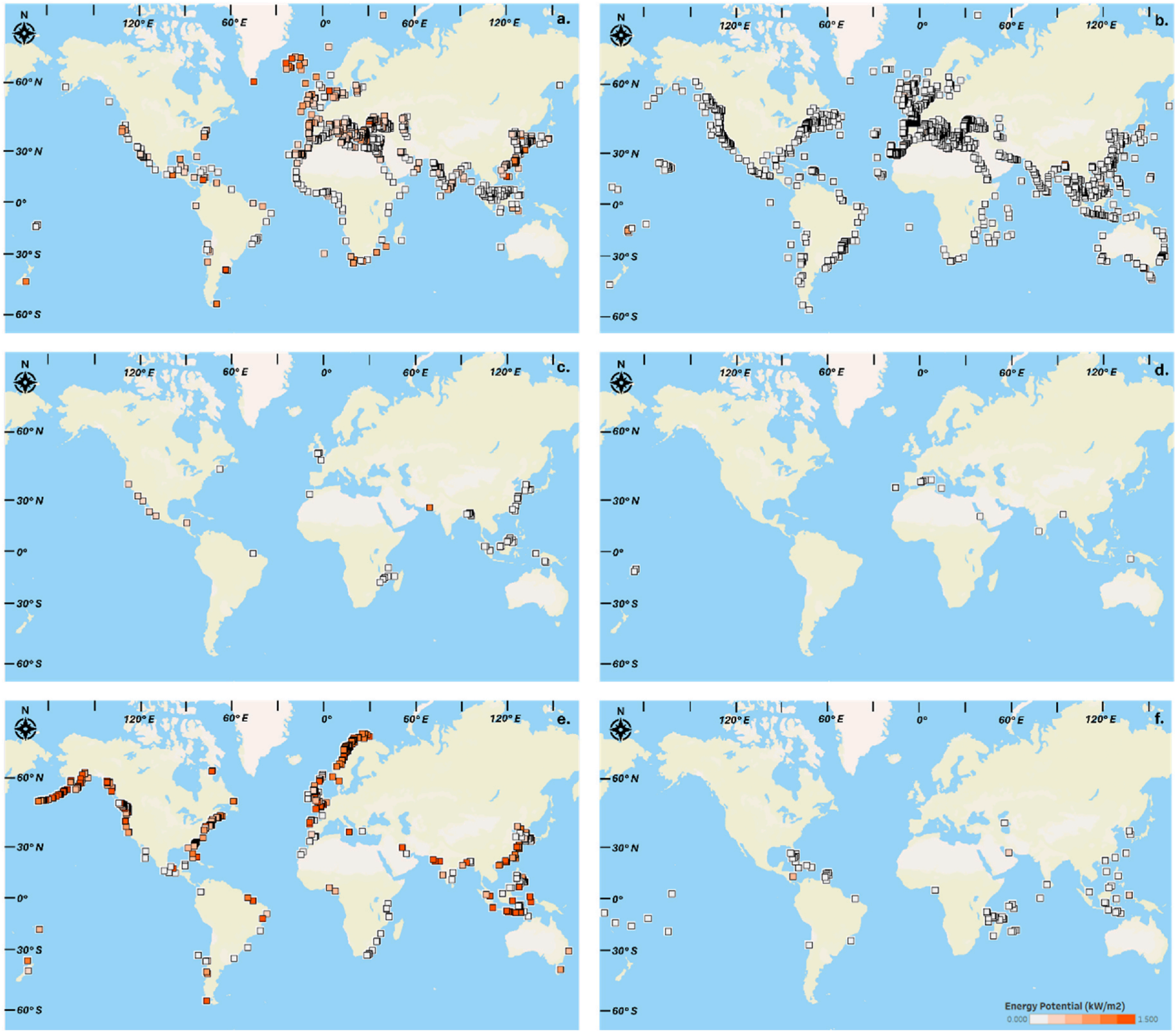

**Fig. 5.** | Global map of resource assessment energy potentials.
Global map of energy potentials reported in offshore renewable energy resource assessments in standardized units (kW/m$^2$). The maps are organized by resource type: (a.) wind, (b) wave, (c) tidal range, (d) solar, (e) ocean currents, and (f) OTEC. An interactive version of these maps is available online.

motivations behind ORE research and development have not been focused on maximizing the energy potential available.

### 4.3. *Cross-comparison of energy potentials*

As indicated in Fig. 5, there are large spatial gaps between ORE assessments. To overcome this, at each location, the energy potentials from the database are compared to the energy potentials of the other ORE resources calculated from reanalysis data. Additionally, the distribution of the sum of all these newly calculated ORE energy potentials is found. As shown by Fig. 6, the distribution by resource type highlights regional variability the total available energy potential. For example, offshore wind accounts for 9 % of the total relative energy in the coastal Asian waters compared to 23 % in the eastern North Atlantic.

In all regions, wave energy has the smallest contribution to the relative energy total, which is never greater than 2 %. Tidal currents and offshore solar are shown to be the largest contributors, together contributing a minimum of 75 % of the relative energy total in all regions. While the actual energy potential may vary at the localized level, these results imply that either horizontal currents or offshore solar will most often have the largest energy potential for any given location.

Also shown in Fig. 6 are box plots of the distribution of the difference between the energy potential in the database and calculated energy potentials from reanalysis data at the same locations. These results vary in magnitude by region and resource type considered. For example, in the southern hemisphere region, locations with previous wave energy assessments have a difference in energy potential to offshore wind with an interquartile range of 0.5 kW/m$^2$ centered over −0.1 kW/m$^2$. Conversely, in the western North Atlantic region, the maximum difference between the energy potential between these resource types is 0.01 kW/m$^2$ with an interquartile range of −0.25 kW/m$^2$. This implies waves may have higher energy potentials than offshore wind in some locations in southern hemispheric waters, but in the western North Atlantic the wave energy potential is smaller than offshore wind at most locations.

### 4.4. *Identification of possible underutilized resources*

Specific results from the cross-comparison of ORE energy potentials indicate that ocean currents and solar resource may be currently underutilized in research and development. The first finding is the large magnitude of energy potential in ocean currents, compared to other resource types, coupled with high spatial variability. At locations from the database where ocean currents have been assessed, the energy potentials are, on average, 1.8 kW/m$^2$ larger than the energy potentials of the other ORE resource types at the same locations. For perspective, the average differences in energy potentials between the other resource types is ±0.1 to ±0.5 kW/m$^2$. In some locations, such as the eastern North Pacific, horizontal currents have energy potentials that are 4.5

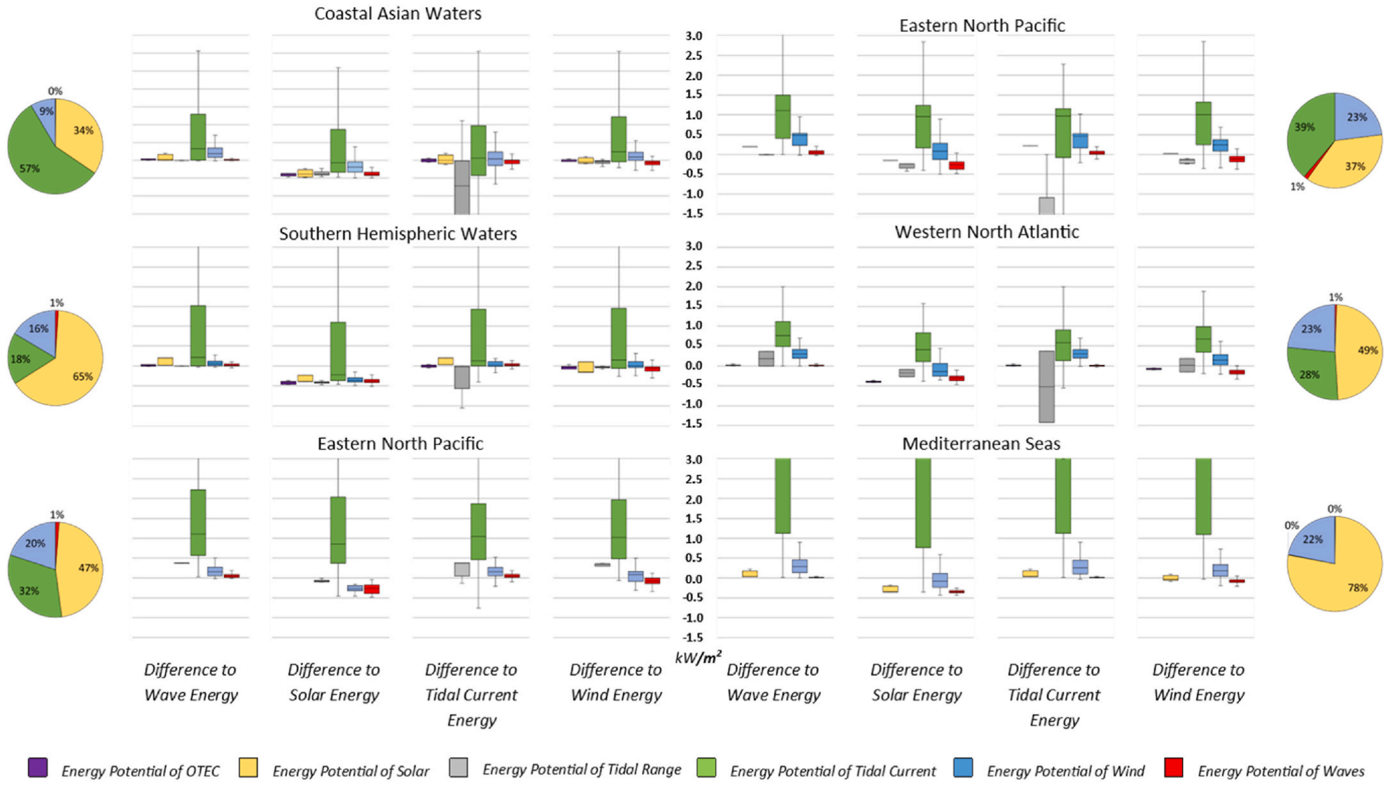

**Fig. 6.** | Regional analysis of energy potentials between ORE resource types.
Pie charts showing the percent contribution to a regional total energy potential calculated using ERA5 hindcast data. Boxplots show the distribution of the difference between the energy potentials from the database and the calculated energy potential of other ORE resources. Results are shown by resource type and by regions.

kW/m$^2$ larger than the energy potentials of the other ORE resource types calculated at the same locations. In contrast, tidal current energy potentials found to be smaller at 78 % of locations in the database considering a different ORE resource type. This implies that if a favorable location is considered, horizontal currents have energy potentials that can be up to ten times larger than other resource types.

The second finding is the consistent nature of the energy potential for offshore solar. A comparison of the energy potentials of locations from the database that assessed solar and the energy potentials of the other ORE resource types is shown in Table 4. On average, other ORE resources have smaller energy potential than solar, with differences between 0.08 and 0.38 kW/m$^2$. Wind energy in the eastern North Atlantic is the only ORE resource with average energy potentials larger than the solar energy potentials from the database.

For the other ORE resources in the database, the difference to solar energy potential ranges between 0.14 and 0.35 kW/m$^2$. While the energy potential of offshore solar is only slightly larger than other resource types, it has exceptionally low spatial variability. Of all the locations in the database, 76 % of these locations had energy potentials smaller than offshore solar. If ocean current results in the databased are not considered, 86 % of the remaining locations would have energy potentials smaller than offshore solar. Together, these results suggest solar energy potentials will have the least spatial variability and frequently have energy potentials larger than the other resource types.

These findings, combined with fact that ocean current and solar resources have less existing research compared to the other ORE resources (in particular offshore solar, which accounts for less than 1 % the results in the database) indicate that these two resources may be underutilized in current research and development of ORE.

### *4.5. Estimation of upper limits for underutilized resources*

To better understand globally how ocean currents and solar resources could compare to the other ORE resources a feasible upper limit of the global energy potential for tidal currents and offshore solar is calculated. The energy potentials of tidal currents and offshore solar are found at locations that are not in the database. Selection of the locations is based on the spatial variability of each resource (see methods).

**Table 4**
Average Difference in energy potential compared to Solar.

| Region | Wave | Wind | Horizontal Currents | Tidal Range | OTEC | Average by Region |
|---|---|---|---|---|---|---|
| **Coastal Asia** | −0.36 ± 0.12 | −0.12 ± 0.29 | 0.99 ± 2.5 | −0.33 ± 0.17 | −0.39 ± 0.06 | −0.30 ± 0.16 |
| **Eastern North Atlantic** | −0.27 ± 0.13 | 0.13 ± 0.42 | 1.28 ± 1.9 | −0.28 ± 0.07 | – | −0.14 ± 0.20 |
| **Eastern North Pacific** | −0.28 ± 0.12 | −0.21 ± 0.24 | 1.83 ± 3.2 | −0.08 ± 0.03 | – | −0.19 ± 0.13 |
| **Mediterranean Sea** | −0.35 ± 0.05 | −0.05 ± 0.24 | 2.66 ± 1.9 | – | – | −0.19 ± 0.14 |
| **Southern Hemispheric Waters** | −0.35 ± 0.12 | −0.20 ± 0.69 | 1.06 ± 2.8 | −0.42 ± 0.02 | −0.42 ± 0.04 | −0.35 ± 0.22 |
| **Western North Atlantic** | −0.30 ± 0.08 | −0.01 ± 0.38 | 0.76 ± 1.9 | −0.18 ± 0.09 | −0.34 ± 0.19 | −0.21 ± 0.19 |
| **Global Average by Resource Type** | −0.32 ± 0.10 | −0.08 ± 0.38 | 1.43 ± 2.3 | −0.26 ± 0.08 | −0.38 ± 0.10 | |

The average difference in energy potential between previous the database results and the calculated energy potential of solar at the same locations. Results are shown by resource type and region all reported in the standardized units (kW/m$^2$). Empty cells indicate there are no existing energy estimates for the corresponding resource type and region.

Recognizing that other limitations (such as technological and financial variables) exist and will lower what that the feasible energy potential, only 10 % of the calculated total is considered. These calculations provide an analogous estimation of how the energy potentials of ocean current and solar resources would compare to the other ORE resources if they had similar volumes of previous research and development.

### 4.6. *Upper limit of tidal current theoretical energy potential*

For ocean currents, the energy potential from tidal currents is used to determine the upper limit for total theoretical energy potential. Fig. 7 shows heat map of the new locations considered highlights the spatial variability globally. Coastlines with favorable physical conditions are shown to have energy potentials in excess of 1.25 kW/m$^2$, which is in line with research showing the necessary bathymetric conditions for tidal currents to have such high energy potentials [60,61]. Many of these new locations identified are near previous tidal current assessments, such as the United Kingdom coastal waters, Philippine Sea, and the Aleutian Islands. However, as shown in Fig. 5, there are numerous locations with considerable tidal energy potential that have not yet been assessed in existing studies. Of note, the east coast region of Argentina, the Sea of Okhotsk, much of northern Australia have no previous energy assessments for tidal currents but are shown to have energy potentials that can be greater than 3 kW/m$^2$.

Globally, there are over 1000 new locations considered for tidal currents, with an average energy potential of 0.88 kW/m$^2$. To put this in perspective, including all resource types, 3012 locations have been assessed with an average energy potential of 0.41 kW/m$^2$. The sum of the energy potential from these new locations included for tidal currents is 1091 kW/m$^2$. This is almost equivalent to the sum of the ocean current energy potentials from the database, which gives 1230 kW/m$^2$. This implies that the upper limit in energy potential for tidal currents is nearly double what has been previously studied, a 188 % increase in potential energy.

### 4.7. *Upper limit of offshore solar potential energy*

The offshore solar resource is found to have low small spatial variability, therefore the feasible upper limit of energy potential for solar is based on research towards hybrid ORE systems using solar [62,63]. Solar is assumed to be co-located with the locations captured in the database. Fig. 8 shows how inclusion of col-located solar can increase the total available energy potential for a given location. For offshore solar co-located with previously assessed wave locations, the energy potential of offshore solar gives an additional 935 kW/m$^2$. For offshore wind, an additional 202 kW/m$^2$, for horizontal currents 54.4 kW/m$^2$, for OTEC 36.2 kW/m$^2$, and for tidal range 24.6 kW/m$^2$. These results imply that at locations where wave energy has been studied, offshore solar would produce the largest additional amount of energy potential.

Because the number of studies be resource in the database is not even, additional locations for solar are included based on normalizing the number of locations by resource type in the database. This resulted in 209 new locations to be co-located with wind, increasing the energy potential from offshore solar by 81 kW/m$^2$. For horizontal currents, there are 246 new locations and an additional 89 kW/m$^2$ in energy potential from offshore solar. For OTEC, these values are 252 and 110 kW/m$^2$, respectively. For tidal range, these values are 254 and 96 kW/m$^2$. Collectively, the feasible upper limit of potential energy from offshore solar is 1628 kW/m$^2$. This is over a 232 % increase from the combined energy potential of all locations previously studied. For both tidal currents and offshore solar, these results there is justification for increasing the amount of future research and development towards these resources.

## 5. Discussion

The results of this study highlight that previous research into ORE has not been equal across the different resources. Wave and wind combined make up 76 % of all locations previously studied. Despite this,

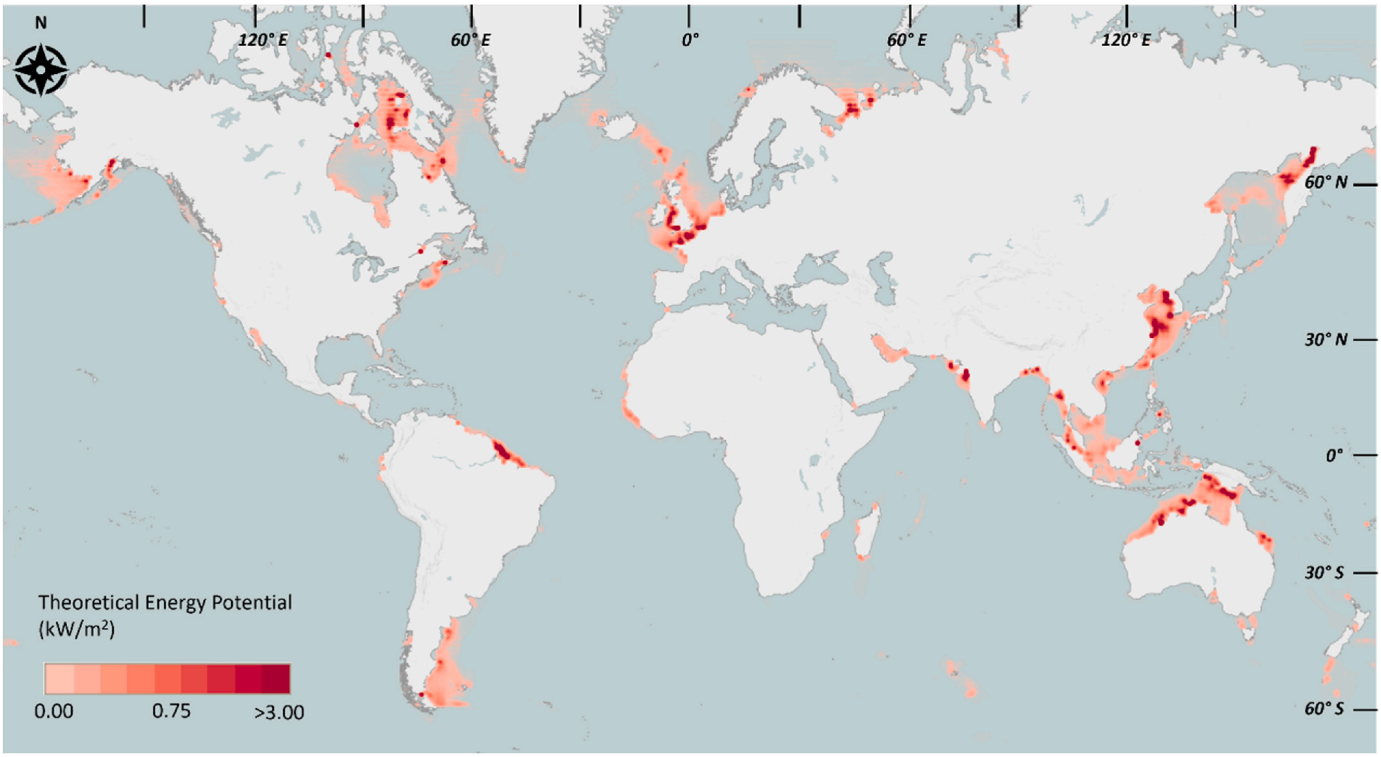

**Fig. 7.** | Map quantifying an upper limit for the global energy potential of tidal currents.
Global heat map of the theoretical potential energy for tidal currents in standardized units of kW/m2. Locations with potential energy less than a threshold value of 0.1 kW/m$^2$ are removed. Previous studies of tidal currents energy potential are overlayed. An interactive version of this Figure is available online.

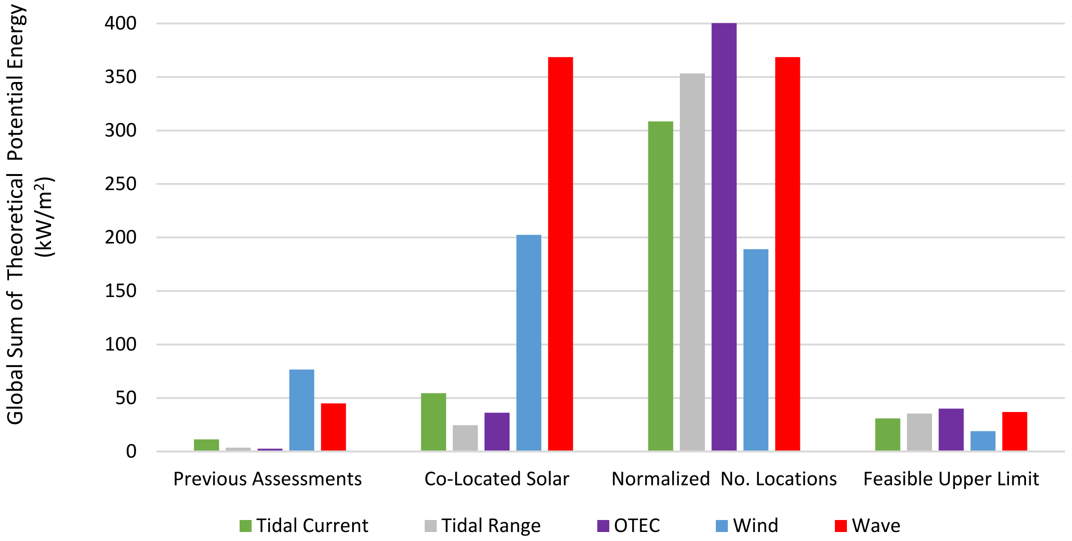

**Fig. 8.** | Feasible upper limit to total offshore solar energy potential.
The change in total energy potential (kW/m$^2$) by considering the feasible upper limit of solar. The total energy potential by resource type is shown for just the database results, co-locating the database results with solar, co-located solar with the database normalized by number of studies, and the feasible upper-limit (10 %) of the normalized co-located results.

this study shows other different ORE resource types can have larger energy potentials, such as ocean currents, which are found to have the highest average energy potential, over 4.7 times larger than any other resource type. This implies motivation behind ORE research and development was not focused maximizing the total available energy.

Motivations from an energy planning perspective may include meeting internation targets as rapidly as possible, such as the Paris Agreement or Unite Nations Sustainable Development Goal 7 – Affordable and Clean Energy [1,4]. From a developer's standpoint, another key motivator is could be to strengthen the economic position of renewable energy projects [64,65]. In both these cases, focusing on resources that are the most technologically mature has conventionally been the primary approach, and could explain the disparity in the nascent field of ORE.

However, this lower risk and conservative approach may actually hinder the transition to a net neutral energy system [66,67]. Results from this work show that the ORE resources that are the most technologically mature do not guarantee the available clean energy is optimized. While technologically mature resources can be built in a shorter time span, these systems can like lifespans up to 30 years, longer if they are repowered [68–70]. If these systems are built in locations where another ORE resource has higher energy potentials, it is possible the amount of clean energy that could be produced will be less than what other ORE resources could produce, even if built later.

This does not suggest, however, delaying development of any ORE project. There is a growing field of research exploring how to develop hybrid ORE energy systems that have turbines co-located [9,62]. As shown by the study, the co-located solar could increase the energy potential available from ORE resources by more than 200 %. Given these high energy potentials, a compelling case can be made for increased research and development into offshore solar resources.

Similarly, if the motivation is to accelerate the clean energy transition as rapidly as possible, then further research and development into resources not being considered for co-location may still be warranted. For examples tidal currents have a limited number of locations globally energy potentials sufficient for turbine development, and these locations typically are not suitable for other ORE resources [71]. Despite this, results of this study show that because of the high energy potential of the tidal current resource including these locations increase the global total energy potential by more than 185 %.

The implications of these results are relevant for government, policy makers, and energy planners or any stakeholder that works towards international clean energy targets. Taking the combined feasible upper limit of tidal currents and solar, the additional available energy potential is approximately equivalent to the electricity demand of 178 million residential homes [72,73]. If 2 % of this energy potential was converted to energy per year starting, global $CO_2$ emissions could be reduced to net neutral 68 years (1 % increase in renewable energy corresponds to a 0.39 % reduction) [73].

This study is underpinned by previously published research. Because of this, the results from this work are limited by the accuracy of these works. Likewise, any newly calculated energy potentials were based on hindcast data which can have region bias depending on the resource and variables considered [74,75]. These factors make it possible for the actual energy potentials to differ from the values reported in this work. Despite these limitations, the conservative approach used in this study and the assumption that the previous peer-reviewed studies are accurate, minimize the error in the interpretation of this studies results. Additionally, changes to energy potential ORE resources are expected as the climate continues to warm [76,77]. Future work can downscale this cross-resource approach and consider the influence of future climate change to assist in determining an optimal mix of ORE resources that could be developed to maximize the total ORE energy potential available.

## 6. Conclusions

This study complied database of energy potentials from published ORE resource assessments to compare the energy potentials of offshore wind, wave, solar, ocean currents, OTEC and tidal range in a standardized unit system. The resulting database included over 660 reports resulting in more than 3000 individual energy potentials estimates across the globe. Comparing these energy potentials show that offshore solar, wind, and ocean currents have the largest regional energy potential totals. Further, of those three, ocean current or offshore solar have the largest total energy potential total in any region. Despite these higher energy potentials, less than 20 % of the energy potentials 20 % in the database are for ocean current, and less than 1 % are for solar. Together, these results indicate that tidal current and offshore solar may be underutilized resource types.

The impact of considering additional tidal current and solar is determined. Results show that a conservative upper limit to the global total energy potential increases the total energy potential from the database by more than 185 % and 200 % respectively the combined total from these two underutilized resources in equivalent to the annual electricity demand of over 175 million residential homes. These results make a compelling case for governments, policy makers, developers, and any clean energy stakeholder to increase the amount of research and development towards ORE resources, particularly ocean currents and offshore solar.

The global cross-resource approach used in this research demonstrates how considering renewable energy development from an energy first perspective can lead to the identification of the resources with the largest energy potentials. Future work taking a similar approach considering a regional scale and future changes to the climate can use the results to develop an optimal mix of ORE resource to be developed that can maximize clean energy production. This approach can accelerate the clean energy transition and help meet internation energy targets like the Paris Agreement and United Nations Sustainable Development Goals Seven. Accelerated development of optimized offshore energy will also contribute to meeting other sustainability targets such as United Nations Sustainable Development Goals eleven through thirteen (sustainable cities and communities, responsible consumption and production, climate action, respectively). While development of renewable energy is not a direct target for these goals, the benefits of renewable energy play a fundamental role in reaching these goals through the reduction of greenhouse gas emissions, which can result in improved air quality, economic growth, and equitable access to electricity.

## CRediT authorship contribution statement

**Spalding James:** Conceptualization, Methodology, Data curation, Writing – original draft, Visualization. **White Christopher:** Supervision, Writing – review & editing. **Ross Lauren:** Writing – review & editing.

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## Declaration of competing interest

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

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## Appendix

**Table A1**
Review of studies assessing 2 or more ORE Resources

| Study Title | Year Published | Authors | ORE Resources |
|---|---|---|---|
| Hybrid offshore wind–solar energy farms: A novel approach through retrofitting | 2024 | Jin Huang, Gregorio Iglesias | Wind, Solar |
| Optimal Sizing of On-site Renewable Resources for Offshore Microgrids | 2023 | Ann Mary Toms, Xingpeng Li, Kaushik Rajashekara | Offshore Wind, Wave, Tidal energy, Solar |
| An Evaluation of Marine Renewable Energy Resources Complementarity in the Portuguese Nearshore | 2022 | Florin Onea, Eugen Rusu | Wind, Wave, Solar |
| Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the western Iberian Peninsula | 2022 | X. Costoya, M. deCastro, D. Carvalho, B. Arguilé-Pérez, M. Gómez-Gesteira | Wind, Solar |
| Offshore wind and solar complementarity in Brazil: A theoretical and technical potential assessment | 2022 | Marcolino Matheus de Souza Nascimento, Milad Shadman, Corbiniano Silva, Luiz Paulo de Freitas Assad, Segen F. Estefen, Luiz Landau | Wind, Solar |
| Exploiting offshore wind and solar resources in the Mediterranean using ERA5 reanalysis data | 2021 | Takvor H. Soukissian, Flora E. Karathanasi, Dimitrios K. Zaragkas | Offshore Wind, Solar |
| Modelling and analysis of offshore energy hubs | 2021 | Hongyu Zhang, Asgeir Tomasgard, Brage Rugstad Knudsen, Harald G. Svendsen, Steffen J. Bakker, Ignacio E. Grossmann | Offshore Wind, Solar |
| Pooling the cable: A techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park | 2021 | S.Z.M. Golroodbari, D.F. Vaartjes, J.B.L. Meit, A.P. van Hoeken, M. Eberveld, H. Jonker, W.G.J.H.M. van Sark | Wind, Solar |
| A study on the feasibility of using solar radiation energy and ocean thermal energy conversion to supply electricity for offshore oil and gas fields in the Caspian Sea | 2021 | Sajjad Zereshkian, Dariush Mansoury | Solar, OTEC |
| An assessment of the potential for Co-located offshore wind and wave farms in Ireland | 2020 | Eilis Gaughan, Breiffni Fitzgerald | Wind, Wave |
| Survey and Assessment of the Ocean Renewable Energy Resources in the Gulf of Mexico | 2020 | | Offshore Wind, Wave, OTEC |
| Assessment of the potential of combining wave and solar energy resources to power supply worldwide offshore oil and gas platforms | 2020 | Sara Oliveira-Pinto, Paulo Rosa-Santos, Francisco Taveira-Pinto | Wave, Solar |
| Combined Floating Offshore Wind and Solar PV | 2020 | Mario López, Noel Rodríguez, Gregorio Iglesias | Wind, Solar |
| A parallel evaluation of the wind and wave energy resources along the Latin American and European coastal environments | 2019 | Eugen Rusu, Florin Onea | Wind, Wave |
| A renewable energy mix to supply small islands. A comparative study applied to Balearic Islands and Fiji | 2019 | Domenico Curto, Vincenzo Franzitta, Alessia Viola, Maurizio Cirrincione, Ali Mohammadi, Ajal Kumar | Wind, Wave, Solar |
| 10-Year Wind and Wave Energy Assessment in the North Indian Ocean | 2019 | Shaobo Yang, Shanhua Duan, Linlin Fan, Chongwei Zheng, Xingfei Li, Hongyu Li, Jianjun Xu, QiangWang, Ming Feng | Wind, Wave |

(*continued on next page*)

**Table A1** (*continued*)

| Study Title | Year Published | Authors | ORE Resources |
|---|---|---|---|
| On the Marine Energy Resources of Mexico | 2019 | Jassiel V. Hernández-Fontes, Angélica Felix, Edgar Mendoza, Yandy Rodríguez Cueto, Rodolfo Silva | Wave, Ocean Currents, OTEC, Salinity |
| Co-located deployment of offshore wind turbines with tidal stream turbine arrays for improved cost of electricity generation | 2019 | D. Lande-Sudall, T. Stallardb, P. Stansby | Wind, Ocean Current |
| Wind and Wave energy resource assessment along shallow water region of Indian coast | 2019 | R. P. Patel, G. Nagababu, H. K. Jani, S. S. Kachhwaha | Wind, Wave |
| Review and assessment of offshore renewable energy resources in morocco' coastline | 2019 | Chakib Alaoui | Wind, Wave, Ocean Current |
| An assessment of the wind and wave power potential in the island environment | 2019 | Eugen Rusu, Florin Onea | Wind, Wave |
| The wave and wind power potential in the western Black Sea | 2019 | Liliana Rusu | Wind, Wave |
| Ocean Renewable Energy Potential, Technology, and Deployments: A Case Study of Brazil | 2019 | Milad Shadman, Corbiniano Silva, Daiane Faller, Zhijia Wu, Luiz Paulo de Freitas Assad, Luiz Landau, Carlos Levi, Segen F. Estefen | Wave, Ocean Current, OTEC |
| Optimized wind and wave energy resource assessment and offshore exploitability in the Mediterranean Sea | 2019 | Francesco Ferrari, Giovanni Besio, Federico Cassola, Andrea Mazzino | Wind, Wave |
| Wind and wave energy resources assessment around the Yangtze River Delta | 2019 | Sheng Dong, Yijie Gong, Zhifeng Wang, Atilla Incecik | Wind, Wave |
| Assessment of Offshore Wave Energy Potential in the Croatian Part of the Adriatic Sea and Comparison with Wind Energy Potential | 2019 | Andrea Farkas, Nastia Degiuli, Ivana Martic | Wind, Wave |
| Long-term wind and wave energy resource assessment in the South China sea based on 30-year hindcast data | 2018 | Zhifeng Wang, Chenglin Duana, Sheng Dong | Wind, Wave |
| Analysis of the potential of wind and ocean energy in the State of Maranhão | 2018 | Jonas Vicente Pinto Junior, Nadia Velez Parente, Clóvis Bôsco Mendonça Oliveira, Osvaldo Ronald Saavedra Mendez | Wind, Ocean Current |
| Assessment of the Potential of Energy Extracted from Waves and Wind to Supply Offshore Oil Platforms Operating in the Gulf of Mexico | 2018 | Francisco Haces-Fernandez, Hua Li and David Ramirez | Wind, Wave |
| Assessment of the Joint Development Potential of Wave and Wind Energy in the South China Sea | 2018 | Yong Wan, Chenqing Fan, Yongshou Dai, Ligang Li, Weifeng Sun, Peng Zhou and Xiaojun Qu | Wind, Wave |
| Integrated Sea Wave and Off-shore Photovoltaic Energy Assessment along the Sardinian Coasts | 2017 | Zang Wu, Zang Wu | Wave, Solar |
| Assessment of the potential for developing combined wind-wave projects in the European nearshore | 2017 | Florin Onea, Sorin Ciortan and Eugen Rusu | Wind, Wave |
| Offshore Wind and Wave Energy Assessment around Male and Magoodhoo Island (Maldives) | 2017 | Pasquale Contestabile, Enrico Di Lauro, Paolo Galli, Cesare Corselli, and Diego Vicinanza | Wind, Wave |
| An assessment of wind and wave climate as potential sources of renewable energy in the nearshore Shenzhen coastal zone of the South China Sea | 2017 | Xinping Chen, Kaimin Wang, Zenghai Zhang, Yindong Zeng, Yao<br>Zhang, Kieran O'Driscoll | Wind, Wave |
| Feasibility Study of Hybrid Floating Power Plant Concept at the Bay of Bengal | 2017 | Rakibul Islam Chowdhury, Parnab Saha, Mahmudur Rahman, Mohammeed Abdul Hannan | Solar, Ocean Current |
| A joint evaluation of wave and wind energy resources in the Black Sea based on 20-year hindcast information | 2017 | Liliana Rusu, Daniel Ganea, Elena Mereuta | Wind, Wave |
| A Joint Evaluation of the Wind and Wave Energy Resources Close to the Greek Islands | 2017 | Daniel Ganea, Valentin Amortila, Elena Mereuta, Eugen Rusu | Wind, Wave |
| Wave and tidal energy resource assessment in Uruguayan shelf seas | 2017 | Rodrigo Alonso, Michelle Jackson, Pablo Santoro, M onica Fossati, Sebasti an Solari, Luis Teixeira | Wave, Ocean Current |
| Wind and wave energy potential in southern Caspian Sea using uncertainty analysis | 2016 | Gholamreza Amirinia, Bahareh Kamranzad, Somayeh Mafi | Wind, Wave |
| Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-Location Feasibility index | 2016 | S Astariz, G. Iglesias | Wind, Wave |
| The Nearshore Wind and Wave Energy Potential of Ireland: A High Resolution Assessment of Availability and Accessibility | 2016 | Gallagher, S., R. Tiron, E. Whelan, E. Gleeson, F. Dias, and R. McGrath | Wind, Wave |
| Assessing the European offshore wind and wave energy resource for combined exploitation | 2016 | Christina Kalogeri, George Galanis, Christos Spyrou, Dimitris Diamantis, Foteini Baladima, Marika Koukoula, George Kallos | Wind, Wave |
| The expected efficiency and coastal impact of a hybrid energy farm operating in the Portuguese nearshore | 2016 | Florin Onea, Eugen Rusu | Wind, Wave |
| Assessment of wind energy and wave energy resources in Weifang sea area | 2016 | Zhifeng Wang, Sheng Dong, Xiangke Dong, Xin Zhang | Wind, Wave |
| A high-resolution assessment of wind and wave energy potentials in the Red Sea | 2016 | Sabique Langodan, Yesubabu Viswanadhapalli, Hari Prasad Dasari, Omar Knio, Ibrahim Hoteit | Wind, Wave |
| Assessment of the marine power potential in Colombia | 2015 | A.F. Osorio, Santiago Ortega, Santiago Arango-Aramburo | Wave, Ocean Currents, Salinity, OTEC |

## Data availability

External data is used from the ECMFW ERA5 hindcast product, OSU TPXO, EIA, and IRENA and is available from their respective websites. The ORE Resource Assessment database is available from the University of Strathclyde KnowledgeBase (DOI: 10.15129/10ff203b-a19a-4fc8-b0da-e806c038e5a7).

Interactive versions of the maps in Figs. 5 and 7 are available online at:

https://public.tableau.com/app/profile/james.spalding/viz/MapofORERespourceAssessmentData/DashboardAllORE?publish=yes

and https://public.tableau.com/app/profile/james.spalding/viz/TheoreticalEnergyPotenitalofTidalCurrents/Dashboard1.

These maps and underlying data are the original work of the authors.

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