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Ocean renewable energy for equitable energy access in a Blue Economy

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Offshore and coastal renewable energy could be a key contributor to energy sovereignty, decarbonization efforts, and co-benefits to other sectors of a Blue Economy. However, current development is predominantly focused on large-scale sites to offset emissions to meet national climate action targets, not on providing energy access where it can deliver more direct community benefits and support equity goals. We undertake a global analysis to identify where offshore renewable energy could contribute to an equity-focused goal of providing energy access to coastlines unconnected to existing electric grids, i.e., "last-mile" electrification. Results show that these energy resources are widely distributed throughout the world, and could particularly benefit coastal areas in Oceania, South America, southern and eastern Africa, western Australia, and the Arctic. In contrast, most current investment in offshore and coastal renewable energy—to date, mainly offshore wind sites—is in highly developed regions. Redirecting support to areas in need of electricity requires national and international financial institutions to shift from profit-driven renewable energy developments in highly-developed and energy-rich nations and towards equity-focused development. Making sure that economically marginalized and remote communities with unmet energy needs can both control and benefit from economic and technological developments such as renewable energy is one way to align development processes with energy equity and energy transformation goals, often stated within Blue Economy plans. This requires a conceptual and financial reorientation that emphasizes community energy needs and agency throughout development processes.

Keywords Blue Economy, Last-mile electrification, Ocean equity, Energy justice, Coastal development, Marine renewable energy

Implementing a socially-equitable Blue Economy—in alignment with international and national plans around the world—requires specific changes to the way existing and emerging marine industries are developed, starting with their goals. The 'Blue Economy' refers to the establishment of ocean-based sectors that are socially equitable in addition to environmentally sustainable and economically profitable; a focus on social equity thus differentiates the Blue Economy from related concepts like 'Blue Growth' or 'Ocean Economy'[1,2,3]. This approach emerged amidst growing qualitative and quantitative evidence that social inequity, which affects fundamental issues of human rights, has hindered all aspects of sustainable development and must therefore be centered in local and global development planning[4].

As one of the prominent new sectors of a Blue Economy, offshore renewable energy (ORE)—including offshore wind, and power generated from waves, tides, and other sources—has the potential to serve remote coastal and island communities. With some 40% of the world's population living close to the coast, many of these communities form part of the ~670 million people around the world that lack or have only partial access to electricity, which impacts daily well-being, health and livelihoods, and limits development of other industries[5].

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Alternative energy sources, such as ORE, could support energy resilience, energy diversification and energy access for vulnerable populations, particularly because connecting these often rural communities to main grids—called 'last-mile' electrification—is often deemed too expensive or impractical by those looking for investment opportunities[6]. Remote and island communities are particularly well suited for positive impacts from marine energy technologies that provide predictable power generation, the ability to complement other renewable energy sources, and decreasing reliance on imported diesel or other fuels[7]. Furthermore, locally harvestable energy sources like ORE can help populations lacking electricity establish and sustain their energy sovereignty. Energy sovereignty is defined as the right of communities to control access and decision-making regarding energy, including sources, scale, and ownership, beyond proximity to grids[8, 9, 10]. For example, some communities may be near grids but unconnected or unable to afford electricity; in other places (such as small islands or in the Arctic), energy may be available as imported diesel and other fuels, with risks of price shocks or trade disruptions[5]. Approaches such as the Multi-Tier Framework for Electricity Access (henceforth, MTF) further clarify our standards for adequate and equitable energy access. The MTF considers attributes including capacity (the main focus in this study), availability, reliability, quality, affordability, formality (i.e., legal access to energy), and the potential health and safety risks of energy sources[11]. Communities should ideally be able to consider and prioritize across these multi-dimensional aspects of energy access, beyond being connected or not to a grid[12].

Embedding the principles above in ORE development can directly support the economic autonomy and political security of un- and under-electrified communities (Sovacool and Dworkin, 13). Up to now, however, almost all ORE investments are associated with large operations to decarbonize energy generation for otherwise well-resourced urban areas[1, 2]. This may fit with other development approaches such as Blue Growth (increasing marine-related economic activity) or Sustainable Ocean Economy (using ocean sectors to help meet sustainability goals), but not a Blue Economy that emphasizes local and equitable benefits from ocean sectors, in addition to economic and sustainability goals[1, 2]. Following from this, the current study highlights alternative opportunities to identify ORE potential in ways that prioritize communities in need and thus helps operationalize stated equity goals in Blue Economy plans.

Discourses around the Blue Economy matter. Projects that employ Blue Economy narratives that disregard or contradict equity principles can cause distrust from local communities and equity-focused organizations toward Blue Economy approaches[14]. These principles commonly comprise concepts of recognition of affected parties, their inclusion in governance processes, and a subsequent say in the distribution of benefits and costs from development. While these may seem relatively simple principles to meet, equity research has highlighted that transformations and transitions to equitable ocean sectors will require significant and coordinated efforts[15, 16]. This is particularly true given the history of inequity and governance in ocean and coastal development, observable in widespread and well-established sectors such as fisheries, offshore oil and gas, or tourism[17].

While emerging renewable industries may be comparatively easier to implement in equitable and sustainable ways, for this to happen there must be an explicit focus on such equitable development during all stages of planning and implementation and, importantly, the conceptualization of the goals driving development[18, 19]. Otherwise, evidence from historical development shows that benefits end up consolidated by developers and industrial actors, while the public and local communities bear most costs[4, 20]. Thus, while the term "Blue Economy" has become a boundary object[21] that has allowed for communication across fields, it is also in danger of being used in ways that ignore sustainability and equity in ocean development[22] Voyer et al. [23]. This is especially true when it comes to social equity goals, and because of these diverse and sometimes competing meanings of the blue economy, it is important to contextualize its use[18].

By assuming a Blue Economy approach that focuses on social equity and prioritizes the needs of coastal communities, this study seeks to understand the potential for ocean and coastal renewable energy to contribute to local energy needs. Our approach builds on research that assesses "enabling conditions" for an equitable and sustainable Blue Economy, which comprise social equity criteria (e.g., human rights), sustainability (e.g., biodiversity), and economic viability (e.g., infrastructure)[24]. In this study, we directly address "gaps" in enabling conditions by assessing coastal location's renewable energy potential and potential for improvements to energy access. In doing so, we build on a growing understanding of the Blue Economy as narrative, boundary object, and collection of sectors with nuanced and globally-inclusive influences on equity and sustainability.

Our method uses a fuzzy-logic mapping methodology that explicitly incorporates uncertainty in renewable energy potential. This highlights coastlines that may lack electrification (e.g., "last-mile" communities) and are proximal to renewable energy resources with appropriate data for evaluation. This methodology allows us to visualize—at a relatively coarse yet global level—the contrasts, disparities and opportunities in coastal energy development, sovereignty, and access. As noted above, the main focus of this paper is on capacity and current grid connectivity, though we touch on other aspects of energy access in the discussion. We considered two ORE technologies at different stages of development, commercialization, and implementation: offshore wind and wave energy conversion. In the case of offshore wind energy, the most developed form of ORE to date, justifications for implementation have generally focused on economic growth and emissions reductions in the Global North, which have been achieved through public–private partnerships involving large, often multi-national, corporations aiming to develop power generation offshore of high-density urban centers[1, 2]. There is indeed enormous potential for ORE to contribute to energy production. Current estimates suggest that ORE could generate 60% of energy needs in Europe[25] and over 50% in the USA[26].

While the wave and marine energy sectors have historically focused on "grid-scale" technologies, discussion and technological innovation has widened to include smaller generation capacities suitable for uses where power at sea is needed, such as ocean observation Dillon et al. [27], or on isolated grids or off-grid remote communities. Following this, there has been a recent shift to developing smaller-scale and micro-grid wave and tidal systems[28]. As these marine energy technologies improve in readiness and become more widely available, they could become valuable alternatives or complements to other sources of power for coastal communities that do not have reliable or community-controlled grid access, but do have access to local energy sources. For example, Caribbean residents have some of the highest electricity bills in the world[29] and some islands spend half of their export revenue on fossil fuels for energy[30, 31]. We consider wave energy—a globally abundant resource with relatively high energy density Gunn and Stock-Williams [32]—as a potential technology that could support the energy sovereignty and sustainability of similar communities. Although this paper focuses on ORE technology potential, terrestrial solar, which is not an ORE technology, is an established and reliable option for powering rural communities. Thus, in the interest of making our work better aligned with potential community interests, we also consider terrestrial solar potential in our model, making for three energy technologies under evaluation (offshore wind, wave and solar).

Results

Our results show global variations in coastal energy resources (called 'energy potential' for each resource, see "Methods" section) and coastal utility grid access. These variations—which we refer to as 'gaps in enabling conditions'—highlight how historical ORE development has been focused on areas with existing electricity access and prompts investigation of how ORE could be empowering and equitable in other parts of the globe.

Existing electricity grids around the world are unevenly distributed and exist around large population centers, irrespective of broader national coverage (Fig. 1A). Figure 1B shows distributions of offshore wind energy potential. Offshore wind energy potential is more broadly distributed than wave energy potential (i.e., has a higher floor in terms of the available resource across the globe; Fig. 1B,C) but has more local variations than solar energy potential (i.e., is influenced by weather patterns more granular than latitude; Fig. 1B,D). Wave energy potential is higher along coastlines exposed to open ocean swells with directional wind forcing (e.g., when Westerlies blow over open ocean), and generally lower values in more sheltered seas (though with exceptions, see "Discussion" section). Solar energy potential is the most continuously distributed resource in our coastal model, as it is not as influenced by the coast's profile, bathymetry or open ocean as wave and wind resources. Therefore, solar energy potential is driven primarily by latitude and seasonal variations (noting that we use year-long averages here). We clarify that herein we refer to solar energy deployed on land, rather than floating solar, a less developed and proven technology.

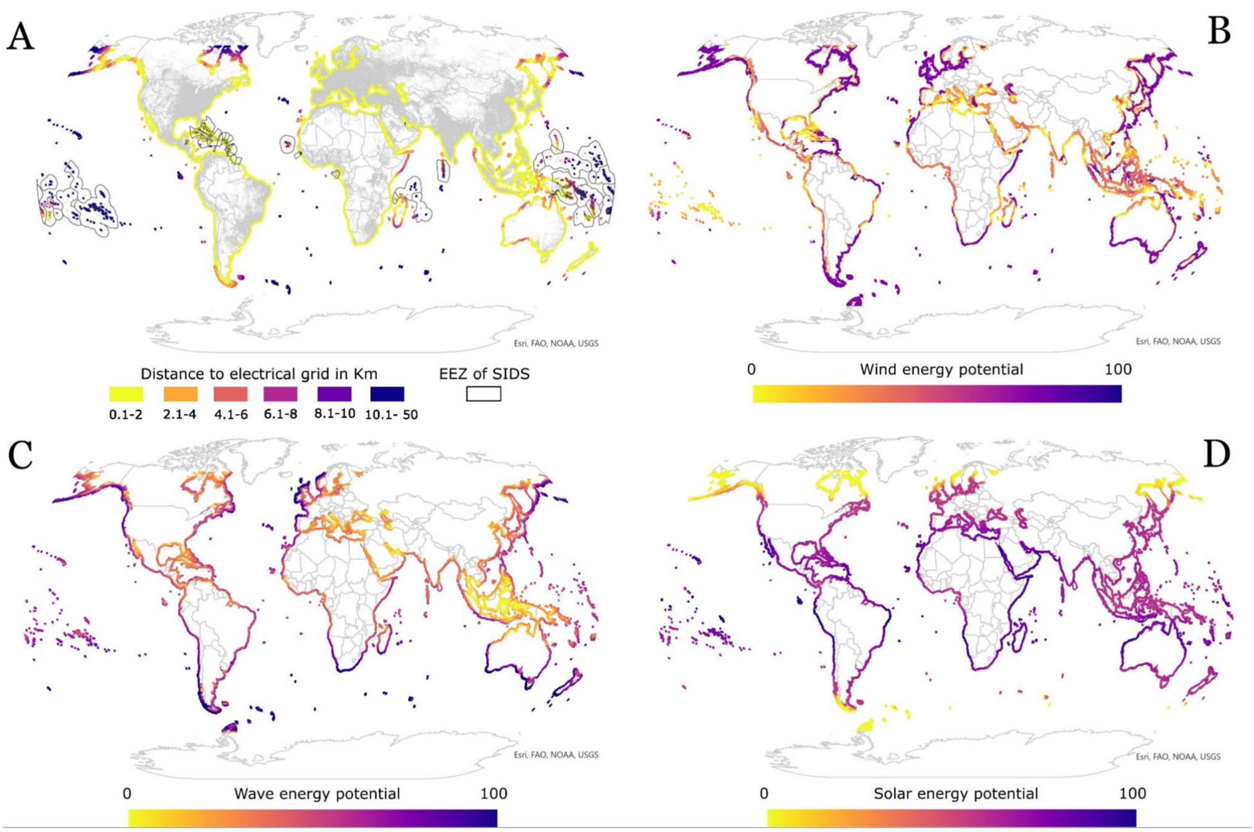

Fig. 1. (**A**) Distance of coastal cell from main medium voltage (MV) electrical grid (km); dark grey lines show main existing MV electrical grids and black outlines show the Exclusive Economic Zones (EEZs) of Small Island Developing States (SIDS). Energy potential (fuzzy logic model output) for (**B**) offshore wind, (**C**) wave, and (**D**) solar. Each of (**B**), (**C**), and (**D**) are normalized (unitless) values on a scale of 0–100, ranging from most to least energy potential across all coastal cells. Maps created using ArcGIS Pro Version 3.1.0 (Esri Inc.) using vector and raster data in the public domain in accordance with CC-BY license terms and conditions.

Figure 2 combines overall wind and wave energy potential (i.e., Fig. 1B–C) with the distance of coastal areas to existing electrical grids (Fig. 1A). This, which we call "ORE electrification potential", highlights areas without grid access that are nearby wave and offshore wind resources. Offshore wind sites, which are the most widely implemented ORE power source to date, are also shown in Fig. 2. These sites do not have significantly higher offshore wind energy potential compared to global availability, but they did show significantly higher enabling conditions scores ($p < 0.001$; Fig. S1)[24].

Figure 3 shows regional and subregional distributions energy potential and grid access. Specifically, subregional energy potential is expressed as the sum (not average) of all three resources' energy potentials (offshore wind, wave, and solar) (Fig. 3A). Thus, the possible theoretical range of subregional energy potential is 0–300. However, these values are constrained to a smaller range because no singular cell has maximum (100) or minimum (0) energy potential across all three resources. The global median energy potential scores across all coastal cells was 130 (1Q 109, 3Q 151), but there were significant differences (ANOVA, $p < 0.005$) in overall ocean and coastal renewable energy potential between subregions (Fig. 3A). The subregions with highest median energy potential were Southern Africa (190), Australia and New Zealand (167), South America (155), Polynesia (145), Micronesia (144) and Western Europe (143); the five subregions with lowest median energy potential were Southeastern Asia (108), Western Asia (111), Central Asia (112), Southern Europe (115) and Eastern Europe (117). Figure 3B also shows the distribution of distance to utility grid for all cells in each subregion (Fig. 3B).

Discussion

Renewable energy technologies can directly benefit rural and under-electrified communities. However, available data shows that development has been focused on sites that are nearby grid infrastructure (Fig. 2). This aligns with prior research on the financing of Blue Economy projects worldwide, where the majority of investment has been allocated to ORE projects in developed nations[33], prioritizing enabling conditions such as existing infrastructure, local governance, and ease of investment rather than natural resource availability[24].

Here, we examine gaps in enabling conditions that, if assessed on more granular levels, may enable a more equitable and sustainability-driven distribution of Blue Economy projects. There are many remote and rural locations along the world's coastlines that are geographically close to main grids yet not connected to them (Fig. 2). Moreover, there are extensive coastlines of the Arctic, Oceania (including large areas in southern and western Australia), eastern and northwestern Africa, and southern Asia without access to power grids (Fig. 1A). Notably, these areas disproportionately include coastal Indigenous territories and communities and/or artisanal fisheries and other marine activities[34]. Many of these communities have undertaken actions to strengthen sovereignty and self-determination at both local and global scales but still require support for high-level challenges such as climate change, pollution, and local self-sufficiency[35,36].

These efforts may be supported by new models that enable more precise and local projections of energy needs, resource potential and development capacity in locations where equitable Blue Economy projects are possible[37].

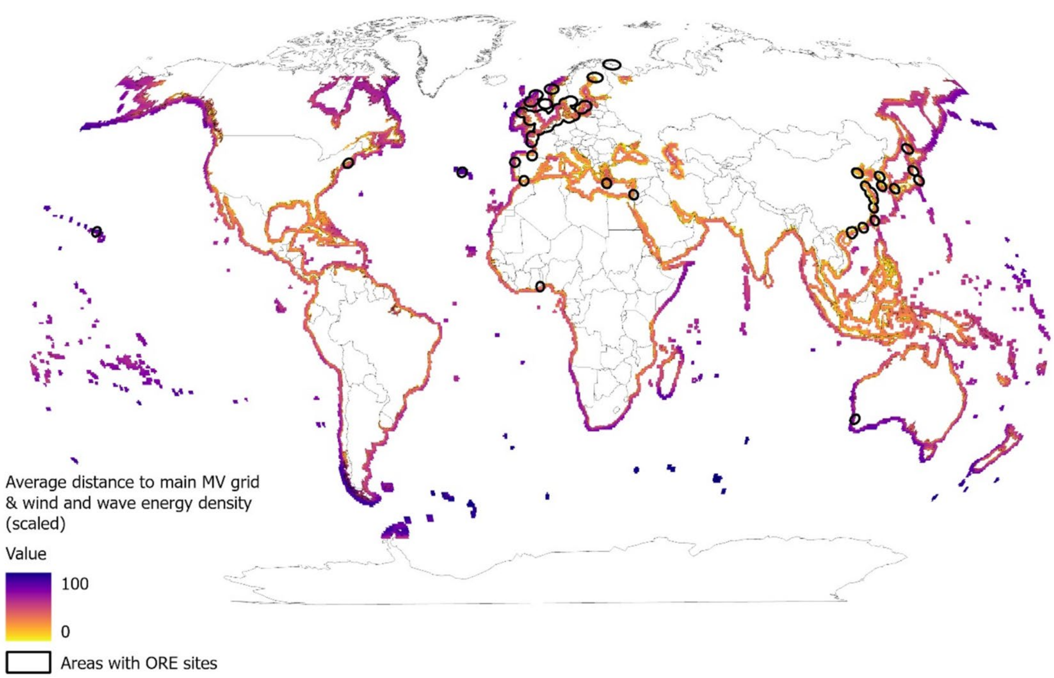

Fig. 2. ORE electrification potential, which is the average of (1) offshore wind energy potential (0–100, normalized), (2) wave energy potential (0–100, normalized) and (3) logarithmically-scaled and normalized distance from grid (0–100), re-normalized (post-average) on a scale of 0–100. Areas with developed offshore wind energy sites are outlined in red. Maps created using ArcGIS Pro Version 3.1.0 (Esri Inc.) using vector and raster data in the public domain in accordance with CC-BY license terms and conditions.

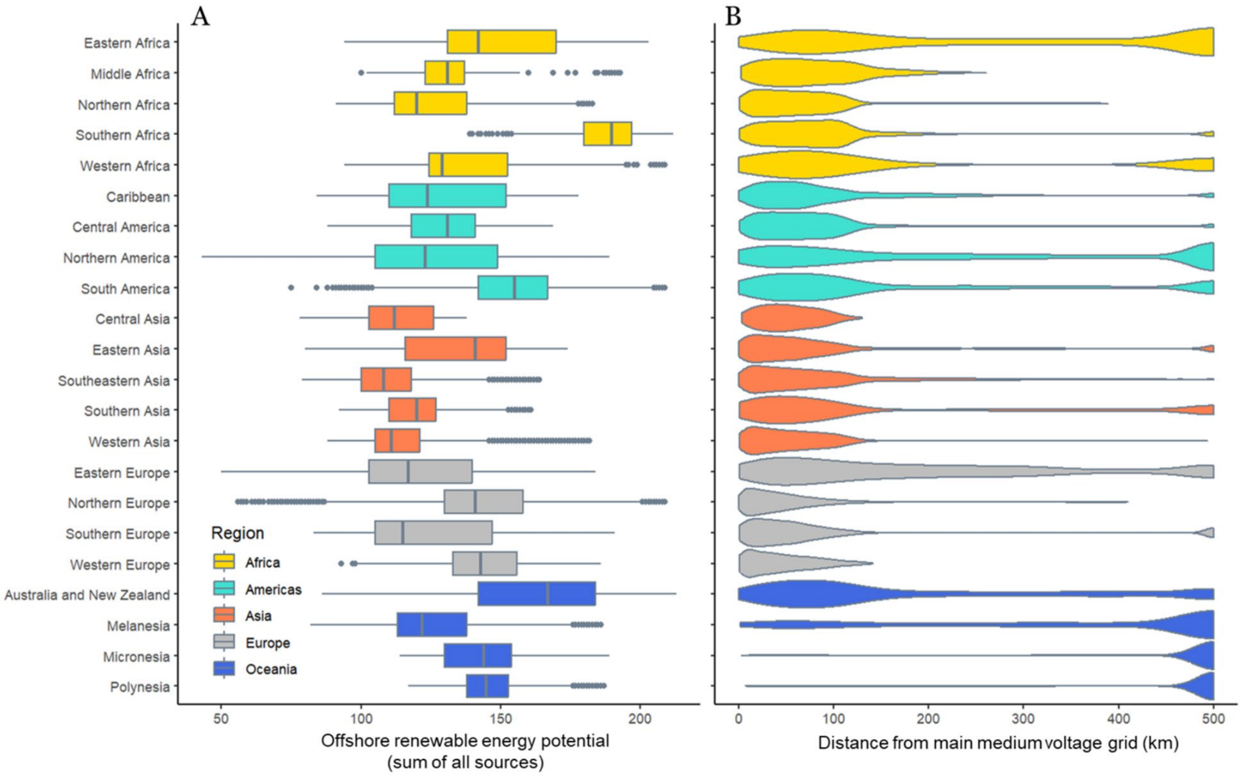

Fig. 3. (**A**) Offshore and coastal energy potential (sum of all sources) and (**B**) distance to closest existing power grid (km) by region and subregion.

Wind energy potential is broadly distributed throughout the world[38] (Fig. 1B) and because it is the most well-developed ORE, new projects in remote areas can learn from past development in well-resourced contexts. Wave energy is also widely distributed (Fig. 1C), but deployment, at present, is hindered by technological readiness, government subsidy of other technologies, and regulatory issues[39]. Solar energy, while not an ORE resource, can also provide reliable and renewable energy for underserved rural communities (Fig. 1D). Historically, solar has been used to electrify remote, coastal and riverine areas, sometimes in conjunction with other local sources. In the Amazon Basin, for example, remote communities are using solar and like run-of-river turbines to mitigate daily or seasonal variation[40, 41]. Plans that integrate solar energy potential, especially in rural equatorial communities that lack access to energy but have consistent solar resources, will improve options for coastal well-being. Thus, related national plans and granting agencies should consider coastal solar power projects within ocean and Blue Economy funding programs. It is crucial that these plans do so with awareness of the historical and present power dynamics of participating actors (e.g., governments, scientists, communities, developers), as lack of attention in this regard have resulted in similar technically-focused projects having extractive, as opposed to equitable, short- and long-term impacts (O'Neill 42).

Developing ORE depends on local infrastructure and capacity. Research into the challenges of "last-mile" electrification have found that primary barriers for grid connection include (1) regulatory mechanisms designed to support large grid development, (2) installation costs (Fig. 5), and (3) infrastructure maintenance[6, 6, 40, 41]. While there are frameworks to address these barriers and, in the context of renewable electrification, support ocean energy projects in rural areas (e.g.,[11]), this capacity must be considered and supported in a way that maintains the authority and agency of local inhabitants (Klain et al., 2014). These challenges can be conceptualized as the enabling conditions necessary for establishing ocean sectors that align with Blue Economy goals, namely, social equity, environmental sustainability, and economic viability[1, 2, 3]. It should be noted that understanding gaps and opportunities in these enabling conditions requires in situ work by local knowledge holders and/or social scientists, as local contexts can be specific and obscured in data at larger scales. This includes the different perspectives and local conditions of Indigenous Peoples compared to the broader USA, Canada, or Australia, or those of the Small Island Developing States (or 'Large Ocean States') compared to colonial metropoles.

In addition to these benefits of and considerations for equitable Blue Economy development in un- and under-electrified coastal areas, our assessment simultaneously shows that ORE projects, to date, have occurred in areas with existing access to energy infrastructure (Fig. 2). For Blue Economy developments to be sustainable and equitable, these large-scale deployments must at the very least effectively and equitably decarbonize these well-resourced and high-consuming coastlines. However, deployment of renewable energy does not necessarily result in decarbonization York and Bell [43]. Renewable deployments that decarbonize depend on and should be planned in accordance with fossil fuel decommissioning, phase out, or reduction (Mutezo and Mulopo 44), which should also consider social dimensions of decarbonization Muttitt and Kartha [45]. UN Sustainable

Development Goal (SDG) 7.2 ('increase substantially the share of renewable energy in the global energy mix') reinforces the necessity of both renewable deployment and decarbonization[46]. But we must also address the equity-focused goals that are embedded in SDG7 (as well as the other SDGs and national plans). This complexity demands intersectional and interdisciplinary approaches, capable of understanding both large- and small-scale renewable energy-related impacts at global and very local scales Calzadilla and Mauger [47].

Our focus here is on global and sub-regional patterns of energy access, but in-situ research is necessary for more detailed site characteristics that are relevant for development and can ensure community benefits. Satellite data offers valuable advantages in terms of wide-area coverage and frequent updates, but might not be sufficient for specific design and operational choices in ocean and coastal systems with high spatial and temporal variability (e.g., ocean currents, wind direction, wind speed, wave height). As noted above, local case studies highlight the importance of community goals in the selection of energy sources, as well as the potential role of co-located energy installations. For example, ongoing research has proposed developing floating solar panels in conjunction with aquaculture farms, where the shade provided can help control predation, water temperature, and evaporation; or between offshore wind turbines if navigation is already restricted and ecological processes are not affected[48, 49, 50]. Given the very rapid decreases in costs associated with solar PV in general (Fig. 5), and if floating solar installations are co-located with other developments, it is very likely that this could be an attractive option in the future.

One example worth highlighting for future efforts is energy continuity and reliability planning. This is of particular importance for wave energy, where early-stage devices are likely to be exposed to harsh ocean environments and extreme forcing, making reliability assessments necessary for individual devices, and device selection and micro-siting[51, 52]. In remote community applications throughout the Blue Economy, reliability assessments may leverage wave availability models[53], maintenance strategies[54], and community-specific operational decisions to determine location- and device-specific strategies for wave energy continuity[19].

Energy storage requirements require similar consideration for any last-mile energy source. In grid-connected deployments, grid integration batteries are used to smooth the system output for interconnection and electrical compatibility purposes[55, 56]. However, in remote community applications, where the grid may be insufficient or unavailable, larger batteries and hybrid systems (e.g., wave and PV) would be considered to promote energy continuity. To date, battery designs for off-grid and community-centered micro-grids are under-investigated, but studies may draw on literature for the energy continuity of other renewables, such as tidal micro-grids[57]. These efforts will benefit from a narrowing of scope and geography, enabling planning for energy continuity at the remote community scale.

As energy assessments refine from global to local scales, data processing, interpretation and integration of large datasets will require significant computational resources and expertise. Funding for implementation of ocean renewable energy in remote communities must make sure to support their ability to access this expertise and have input into how results are interpreted and used to inform decisions on siting, energy sources, and the implications of different technologies, preferably during the conceptualization stages of potential projects. At local scales, choosing sites for energy converters and support infrastructure is a determining factor for not only conversion efficiency and productivity, but also for social desirability and interactions with other marine industries and ecosystems (Klain et al., 2014). These multi-sectoral and social objectives follow directly from overall development goals, often at national and international levels, as well as "bottom-up" from local communities of place and practice[58, 59, 60].

There are many funding sources that could support community-driven ORE projects, but leveraging them will depend on challenging traditional notions of large-scale economic growth and development and channeling resources to "small"-scale yet high-impact initiatives that specifically prioritize the needs of frontline and marginalized communities. Possible funding resources include intergovernmental and philanthropic grants, government subsidies, preferential-rate loans, and blends of various sources[61]. For example, in Europe, from 2017 to 2021 such sources provided over US$4 billion to support the establishment of offshore wind energy[33]. Even a portion of these funds, if directed to remote development could be impactful. For example, in Canada, targeted funding programs have supported biomass energy and technological capacity to support deployment in Indigenous communities in Canada, as well as grid improvements to accommodate household-level energy generation from various sources NRCAN [62].

Specific and actionable advice already exists for multi-dimensional progress both in energy access and in social equity more broadly (e.g.,[11, 63]). For ocean renewable energy, this has followed a clear evolution from a focus on perceptions to development by external actors, to a fuller engagement, consent, and collaborative planning processes[64]. In that context, considering energy justice as a form of social justice[65, 66, 67] or just transitions[59] can offer useful guidelines. A throughline is that one must carefully consider why energy justice is an important fundamental and instrumental goal and what issues are most important in a particular place. Depending on this local context, one can then design engagement strategies that are socially appropriate and that always involve open discussion, wide inclusion, and transparency in roles and possible outcomes throughout the process[68, 69].

Through overlapping coastal energy density with the existing global energy grid at a worldwide level, we focus here primarily on the recognitional aspects of equity by contrasting places that might support ocean renewable energy for last-mile electrification but have not been (e.g., developing regions and predominantly Indigenous territories) with those that likely require less but have received much more support (mainly in the Global North[70]) (Figs. 1A and 2). These results highlight these disparities in the context of public awareness (as a first stage of public engagement) aligned with the procedural and distributional equity dimensions of energy justice[71]. As we advance towards distributive justice, these insights can inform future policies aiming to benefit coastal rural communities first—as explicitly stated in global development goals—and questioning the use of funds that do not align with these stated goals.

Our model illustrates the disparities of energy development, potential and access in the context of the Blue Economy. This view prompts discussion of how locally-targeted and locally-driven investments in ORE could benefit coastal communities, supporting their development priorities and basic human rights to energy access and energy sovereignty. This focus on electrifying "last-mile" communities can occur in parallel to current trends towards switching to renewables in energy-rich regions, directly meeting equity and well-being priorities under a Blue Economy. For this to be effective and ethical, we argue that (1) the power dynamics and history of various actors involved in coastal electrification and development projects must be responsibly considered, and (2) that large-scale ORE deployments in energy- and consumption-rich areas must decarbonize through intersectional analysis that prioritizes not renewable deployment in and of itself, but the manner and amount of resulting carbon reductions, benefits, and impacts of renewable energy deployments.

Methods

Offshore renewable energy (ORE) includes (1) power generation from the ocean itself, referred to as "marine energy," (e.g., tidal and ocean currents, wave energy, tidal range, ocean salinity or thermal gradients) and (2) power generation from ocean spaces (e.g., offshore wind, floating solar), which may be referred to as "offshore renewable" or "ocean" energy. We focus on just two ORE technologies and resources, particularly technologies that have available data required to coarsely interpret energy potential on a global scale and resource density to deliver amounts of energy needed for community impact: offshore wind energy and wave energy. Given the pragmatic focus on providing energy in places that need it and widespread availability and development of solar energy, we also consider solar energy potential in coastal areas. Here, We evaluate potential for alleviating coastal energy insufficiency along marine coastlines based on two main components: (1) estimated coastal renewable energy potential based on simplified technology assumptions and a fuzzy logic model to integrate parameters; and (2) distance of coastlines to existing electrical energy grids. These components are comprised within an overall model that highlights priority areas and potential opportunities for ORE deployments (Fig. 4). To address broader issues of development capacity in our discussion, we also contrast these results with past research on strengths and gaps in enabling conditions for Blue Economy implementation–including infrastructure, financial stability, social inequities, and ecological protection, among other key factors (Fig. 4; see "Methods" section for further description of this data).

We do not integrate potential costs of energy infrastructure and deployment in the model due to high uncertainty between regions. This is particularly true for offshore sectors that must contend with different water depths and distances from shore[72]. However, costs and availability are important aspects that we highlight in the discussion and is one of the motivations for the research. After solar (PV) and onshore wind technology, offshore wind energy is the sector with the best combination of current costs and cost decreases over the past decade (Fig. 5). This tradeoff between current costs and future expectations is important for the policy implications of this study and other research in the field.

Data for the analysis was compiled from publicly available datasets including intergovernmental data repositories and peer-reviewed research. All datasets were rescaled into a global 0.25° × 0.25° latitude/longitude grid for spatial analysis using the bilinear interpolation method. Descriptions and direct data links are provided in Table 1 and include global information on wind, wave, and solar energy, and current electrical transmission grids. Tidal energy potential is acknowledged but was not included in the analysis because the necessary global datasets are too spatially coarse to comment on suitability for a tidal energy project. Note that, due to remote sensing limitations, there was not sufficient data available to calculate energy potential at high latitudes.

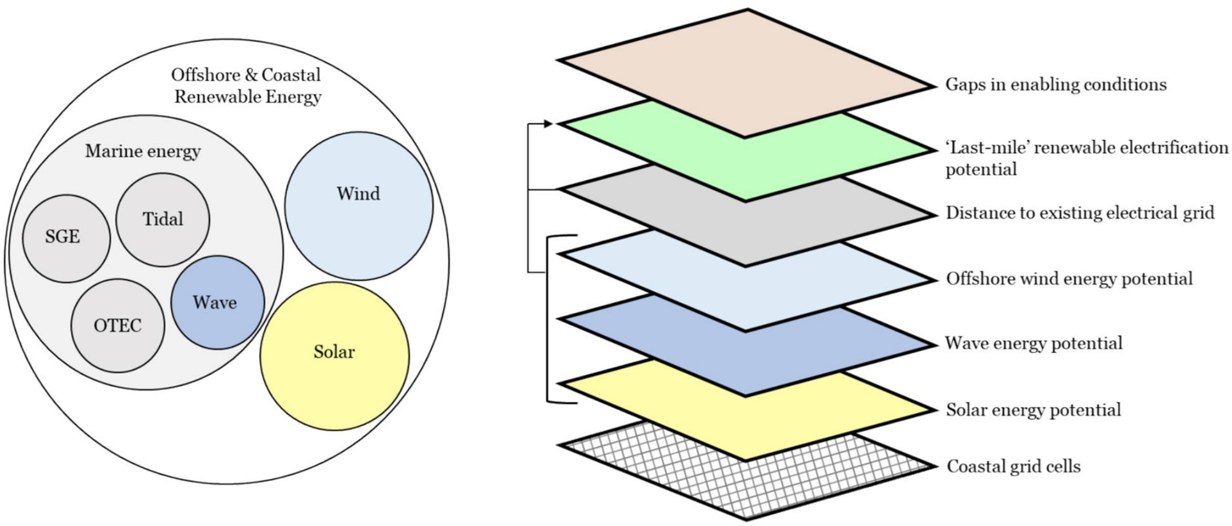

Fig. 4. Conceptual methodology and data layers. We include two components for Blue Economy electrification potential: (1) offshore wind, wave, and solar energy potential and (2) main electrical grid connectivity, identifying potential for last-mile electrification. See Table 1 for data sources and units.

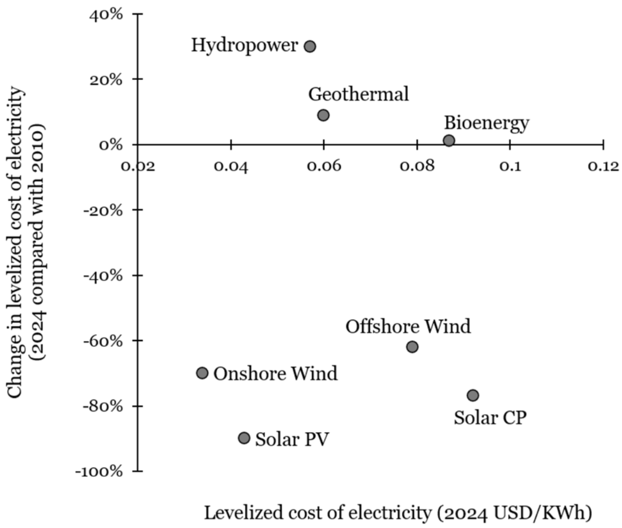

Fig. 5. Levelized cost of electricity (2024 USD/KWh) for renewable sectors, and change (%) compared with 2010 cost. Levelized costs represent the average net present cost of energy generation over the lifetime of an installation. Adapted from data in IRENA[72].

Variable	Metric	Data link
Wind speed	Wind speed mean and maximum (m/s)	https://doi.org/10.48670/moi-00181
Wave height (sea surface significant wave height; SWH)	SWH mean and range (m)	https://doi.org/10.48670/moi-00181
Solar radiation (downward shortwave radiation; DSR)	DSR mean (W/m^2)	https://doi.org/10.24381/cds.f17050d7
Global electricity transmission and distribution grid	Distance from each cell to closest cell with grid (m)	https://www.nature.com/articles/s41597-019-0347-4 https://datacatalog.worldbank.org/search/dataset/0038055
Enabling governance conditions	Score (0–100)	https://doi.org/10.1038/s41586-021-03327-3

Table 1. Environmental variables and metrics (units are in parentheses) and links to sources of input data.

Based on the key parameters in Table 1, we use a fuzzy logic method to estimate energy potential recognizing uncertainty in available technology and technology modeling, and capacity to convert availability energy resources into usable energy. Fuzzy logic methods were developed to aid in decision-making under high degrees of uncertainty, particularly when there are known relationships between independent and dependent variables but the exact strength and quantitative form cannot or has not yet been determined[73, 74]. A strength of fuzzy logic methods is that uncertainty is both expected and explicitly incorporated in the model at various stages and in ways that transparently highlight the assumptions that influence final results[75, 76]. This approach has been used in similar studies related to Blue Economy capacity and development[24].

For each of three renewable energy sources—wind, wave, solar—we establish the energy potential corresponding to low, moderate, high, or very high energy potential in each coastal cell based on subjectively defined ranges (Fig. 1A–C, respectively). Fuzzy logic explicitly incorporates uncertainty regarding the range of quantitative values comprised by each of these qualitative categories, or fuzzy sets[73]. Fuzzy sets therefore overlap, such that a particular quantitative value can correspond to one, two, or more categories. This is fundamentally different to traditional ways of categorizing variables, where any particular value has a binary (yes or no) membership in a particular category. In fuzzy logic, membership of a particular value in any of the categories can take any value between 0 and 1 (Fig. 6).

The final step in this fuzzy logic method is to calculate a resulting quantitative value for overall energy potential based on the independent variables (defuzzification). Each of the qualitative categories for independent variables corresponds to one of the four categories–low, moderate, high, very high–in total energy potential, called the 'problem set.' For each type of energy, a given value is converted into a set of four memberships [0,1]; these memberships are then matched to each of the categories in the problem set and traced back to four quantitative scores. The final score is the average of these four quantitative scores (one for each category in the problem set), weighted by each category's membership value. Finally, we normalize this value on a scale of 0–100 for each resource, shown throughout the "Results" section.

Following the analysis above, each cell in the global grid obtains an estimate of renewable energy potential (including offshore wind, wave, and solar) and its distance (km) to the closest existing electrical grid. The electrical grid dataset is publicly available through the World Bank (Table 1), and represents main medium voltage (MV) transmission lines globally at resolutions of up to 500 m. These grids were developed by the World Bank through night-time satellite images to identify light sources as indicators of electricity access, and a subsequent algorithm

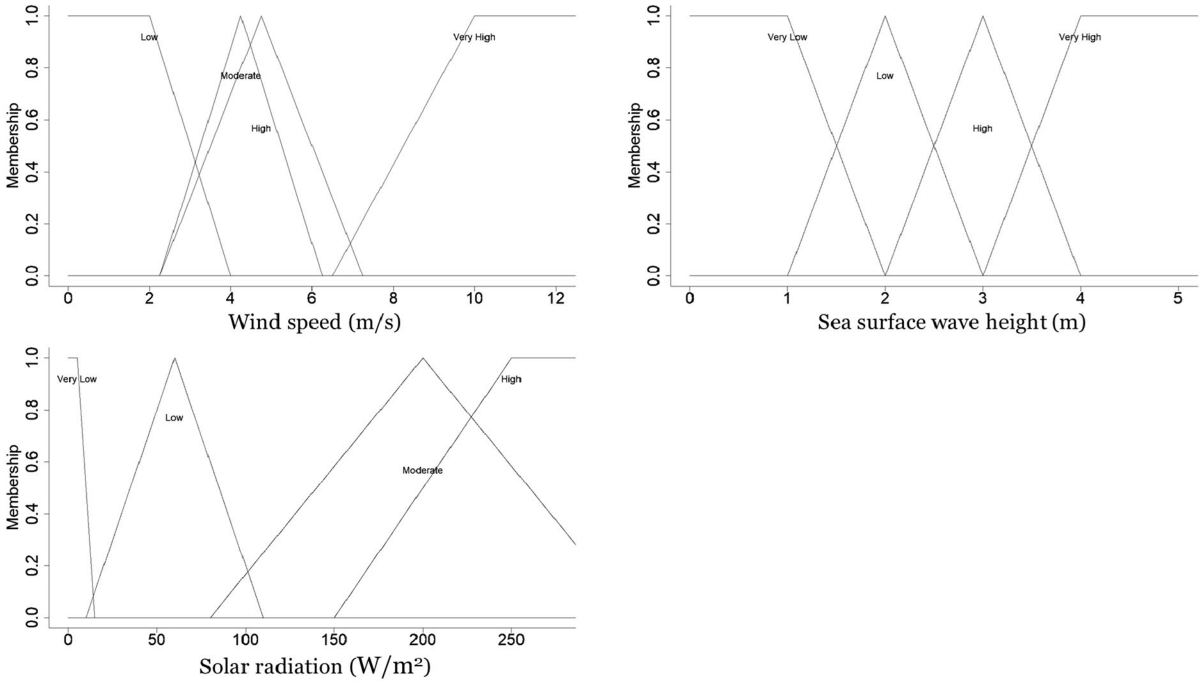

Fig. 6. Fuzzy sets showing our subjective value ranges corresponding to energy potential from wind, solar, wave resources. See Table 1 for all source data and units.

to connect these sites through the most likely pathways (e.g., road networks)[77]. The World Bank model's accuracy was validated in situ, but the dataset excluded many island areas due to difficulties with determining transmission pathways through water. The authors thus note that the resulting data represents 'main' grids and not smaller independent grids that are most often powered through imported fossil fuels[77], which aligns well with our objective to identify coastal and islanded areas that may suffer from expensive, polluting, or unreliable grid infrastructure.

Our model results are contrasted with data on enabling conditions to implement Blue Economy plans around the world, which are available at the same resolutions used in our model results[24]. The various factors considered align with scholarship and practice in equitable economic development[78,79,80] and international development goals (e.g.,[46]. They include, for example, the current ability to advance group, economic, and gender equity, existing built infrastructure and other basic services; legal and financial frameworks facilitating investment; and the implementation of marine and coastal environmental regulations[24]. All results are presented at national, subregional, and regional scales, following United Nations categories. A binomial logistic regression model was applied with wind speed and enabling conditions scores as independent variables to test for possible differences explaining the distribution of operational offshore wind energy sites (the most widely implemented ocean renewable energy to date) compared to cells without sites (glm in R statistical software[81]).

Data availability
All data are available from the sources listed in the Methods, or from the authors upon request.

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Author contributions
AMCM, SLH, and YO designed the project and research questions. AMCM, SLH, and TD designed the methodology. AMCM, PCGE, MMB, and MNT prepared and analyzed data and results. PCGE, MNT, and MMB prepared map figures. All authors wrote and reviewed the manuscript.

Declarations

Competing Interests
The authors declare no competing interests.

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