A multi-resource assessment of current and future energy potential for Marine Renewable Energy

By

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Abstract

Climate change is widely accepted as one of the most pressing challenges of modern times, with projected impacts including habitat degradation, heightened food insecurity, and an increase in the frequency and severity of extreme weather events. Reducing CO_2 emissions to either net-zero or negative emission levels by 2050 is critical to minimising the impacts of climate change. A key strategy to achieving net-zero is decarbonising the electricity sector through the development of renewable energy. Marine renewable energy is a nascent field within the renewable energy sector that has substantial power density which, if developed, could accelerate decarbonisation efforts. To assist renewable energy stakeholders such as developers, policymakers, and researchers, this research aims to provide a commensurate cross-resource comparison – covering wind, wave, marine currents, solar and ocean thermal energy conversion – of the historical, current, and future marine power density available. This research develops a standardised approach to evaluate power density, including a database of over 800 resource assessments, projections of power density changes under 'best-case' and 'worst-case' future emissions scenarios, and an evaluation of uncertainty in the data used in power density quantification. Results indicate that solar and marine current resources are underutilised based on current research and development and combined have an power density that could meet the electricity demand of 175 million residential homes, based on the 2019 average electricity demand in the United States. Further, the analysis displays non-linear future changes in power density occurring, varying in sign and magnitude depending on the emissions scenario and period considered. This thesis bridges the gap between scientific analysis and actionable intelligence, giving stakeholders a framework to compare and contrast the power density of offshore resources. By adopting this approach, stakeholders can ensure the future research and development of renewable energy can maximise clean energy generation and accelerate global decarbonisation efforts.

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Chapter 1 Introduction

1.1 Motivation

Climate change has unequivocally been linked with increased anthropogenic carbon emissions influencing increasingly frequent and extreme hazards globally (AghaKouchak et al., 2020; IPCC, 2023). To reduce future climate change impacts, 195 nations signed the 2015 Paris Agreement: an international agreement aiming to limit future climate warming to 2°C above pre-industrial levels and to further pursue a warming limit of 1.5°C above pre-industrial levels (Delbeke et al., 2019). Reaching net-zero or negative carbon emissions by 2050 is critical in achieving these goals and avoiding the compounding risks associated with continued climate change (M.-T. Huang & Zhai, 2021; IEA, 2021a). Global decarbonisation efforts, however, are not on track to meet these goals. In 2023, the total global emissions grew by 1.3%, surpassing the average emissions growth rate of 0.8% per year between 2010 and 2018 (United Nations Environment Programme, 2024). Without "deep, rapid and sustained" decarbonisation actions, climate temperatures will undoubtedly exceed the 1.5°C target (Friedlingstein et al., 2024; IPCC, 2023).

The power generation sector (i.e. electricity production) makes up the largest portion of carbon emissions, approximately 26% of global emissions in 2023 (United Nations Environment Programme, 2024). Figure 1-1 shows the emissions by sector for 2023.
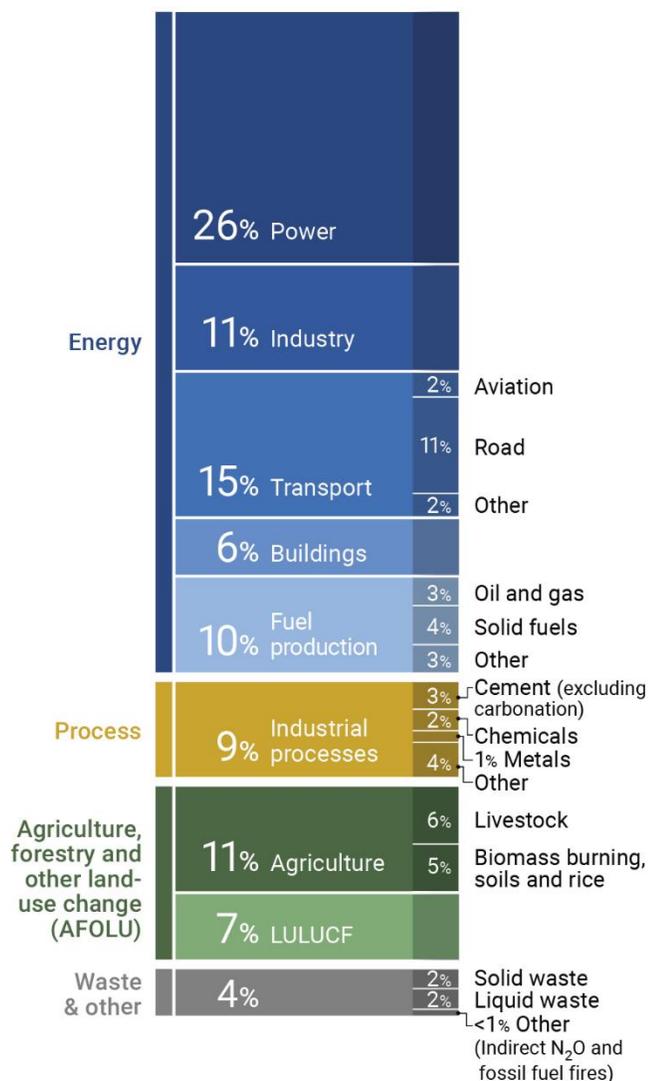
Figure 1-1 | Total global emissions in 2023 by sector. Adapted from the United Nations Emissions Gap Report 2015 (United Nations Environment Programme, 2024)

Progress has been made in decarbonising the power sector, primarily through the development of renewable energy. In 2010, 19% of the global electricity generation came from renewables, the majority from hydroelectric dams (IRENA, 2024). By 2022 the share of renewable generation had grown to 29% (IRENA, 2024). This represents an annual growth rate of 8% (IRENA, 2019). While this growth is notable, renewables still lag behind

fossil fuel electric generation, and in 2023, the growth of renewables had slowed, comprising 30% of global electric generation (IEA, 2024a).

Amplifying the need for increased renewable development is the expected acceleration of electricity demand. According to the International Energy Agency, recent electric demand growth has been small, with an average 2.7% increase per year between 2010 and 2023, and this expected to increase 3% annually by 2030 (IEA, 2024b). However, recent forecasts expect even larger increases in electric demand growth, due in part to the recent surge in data centre development. For example, (Katal et al., 2022), forecasts that by 2030, data centre power consumption will have increased from 200 TWh in 2016 to about 2967 TWh, largely because of the growth of artificial intelligence. Given renewable development is already lagging to meet international climate targets, the expected near-term increases in electricity demand exacerbate the need for accelerated adoption of renewable energy. It is estimated to meet both 1.5°C climate goal and increases of electric demand, the pace of current annual renewable development will need to triple (IRENA, 2019).

Marine renewable energy (MRE) is an emergent sector of renewable energy that could accelerate the transition to a net-zero energy sector. The theory of converting marine energy resources, such as tides, waves and wind, is not new. Mills have extracted energy from the tides since as early as the 6th Century (Murphy & Rathbone, 2006). The first wave energy device patent was filed in France in 1799 (Falcão, 2010), and the first wind turbine for generating electricity was installed in 1887 (Gipe & Möllerström, 2022b). While not for marine use, solar energy has been extracted for mechanical purposes, such as cooking or heating, since as early as 200 B.C. (Perlin, 2022). Despite this long history, the first modern MRE systems were not installed until the late 1990s and early 2000s (Mueller & Wallace, 2008). Development and research activity have increased in recent years. In 2015, the total offshore installed capacity of MRE (excluding offshore wind) was 36 MW (Lehmann et al., 2017). This capacity was made up mainly of tidal & marine

current turbines and wave energy converters By 2023, the installed combined capacity of marine current and wave energy systems had increased to 66 MW (Europe, 2023). Offshore wind has had the most growth with the global installed capacity reaching 68 GW by the end of 2023 (McCoy et al., 2024). Other MRE technologies, like OTEC, have seen increased research since the 1990s (Aresti et al., 2023; Mofor et al., 2014). Proof-of-concept facilities have been built in the United States and Japan (Kempener & Nuemann, 2014), but as of 2021 the global operating capacity is less than 0.25 MW (IRENA, 2021a).

This growth in MRE development has been motivated by the substantial power density research has shown MRE has. For example, the global power density for wave energy has been estimated to be up to 80,000 TW-hours per year, for ocean currents the power density is up to 25,880 TW-hours per year, and for OTEC the power density is estimated to be up to 90,000 TW-hours per year (Taveira-Pinto et al., 2020a). While each of these power density estimates are well above current electric demand, only a fraction of this total power density is feasible for harnessing into usable electricity.

Other assessments of MRE consider geographical areas which are feasibly for commercial development. These studies show that despite these limitations MRE still has considerable power density, for example, off the coast of the Unites States the combined power density of MRE is estimated to be 57% of the electricity use from 2019 (Kilcher, Fogarty, & Lawson, 2021a). In the United Kingdom, it was found that the total developable tidal and wave power density is equal to approximately half of the country's electricity usage from 2020 (UK Parliament, 2020). This power density has driven governments to include MRE in future energy planning. The United Kingdom awarded funding to 11 tidal stream developers in Allocation Round 5 for contracts of differences (UK Department for Energy Security and Net Zero, 2023), and California has enshrined wave energy development in legislation passed in 2023 (Senate Bill No. 605: Wave and Tidal Energy, 2023).

While the resource potential of MRE is clear, there is a gap in the practical understanding of how all the MRE resources compare, both regionally and globally. Current research most often considers a single MRE resource, recent examples include an assessment of the global wave power density (Satymov et al., 2024), a regional assessment of tidal energy in India (Satymov et al., 2024), and an evaluation of OTEC resources in Bangladesh (Rashid et al., 2024). Further, there are fewer studies available to compare given MRE is still a nascent field. For example, in northern Spain the power density for marine currents, wind, and wave power density has been studied robustly (Castro-Santos et al., 2020; Iglesias & Carballo, 2010; Mestres et al., 2019). However, for the southern and Mediterranean coasts of Spain, far fewer studies, if any, are available for these three MRE resources, or offshore solar and OTEC. While the absence of these studies may be indicative of general knowledge of lower power density, this absence makes answering questions such as 'Which MRE resource has the most power density in southern Spain?' challenging to answer. There is limited research considering multiple MRE resources at the same time to answer questions like these. Of these studies, very few consider more than three MRE resources.

Additionally, there are numerous ways to define and calculate power density, and these different approaches make comparing results from different studies challenging, if not possible at all (Cox et al., 2018). In general, power density is the amount of energy that can be harnessed for electricity production from a given resource. Assessment of power density is the first step in any renewable energy development and essential information for policy makers, researchers, developers and financiers. The core of this thesis presents results on theoretical power density, which is the calculation of the available flow of the resource through a specified area (Hennessey Jr, 1977). This quantification method was chosen as it has the least number of variables needed (a flow rate and a cross-sectional area) to calculate the power density. This reduces the number of assumptions needed to calculate standardised, commensurate comparison of MRE resources. This

methodology is atypical for some resources, especially for characterizing wave energy. Thus, to provide context, the results are also presented when the wave power density was calculated using more traditional units. The formulation of quantifying the power density for each MRE resource is presented in section 2.3.

The individual-MRE resource focused approach makes any critical or meaningful cross-comparisons of different MRE resources impractical. Further, basic questions such as which MRE resource has the largest power density at a given location, or which MRE resource is most susceptible to future climate change, remain unanswered. Questions like these are critical for planning future research and development and meeting climate change targets.

1.2 Aim and research questions

The goal of this thesis is to provide a comprehensive understanding of the power density for MRE resources, how they compare to one another regionally and globally, and to assess the impact of future climate change on MRE. For the purposes of this thesis, five MRE resources are considered: wind, wave, solar, tidal and ocean currents, and ocean thermal energy conversion (OTEC). Other MRE resources exist, including tidal range and salinity gradients, but are not considered here. While tidal range projects have notable amounts of power density, future development has received little interest because of the limited number of suitable locations globally, the significant environmental impacts, and prohibitive construction cost (Etemadi et al., 2011; Hooper & Austen, 2013). Likewise, salinity gradients have been shown to have high theoretical power density (Alvarez-Silva et al., 2016), however, the technology has not been proven to be efficient beyond the laboratory scale (Alvarez-Silva et al., 2016).

Four research questions (RQs) guided this research, which are detailed in Table 1-1. The questions and supporting results presented in this work provide a holistic picture of how much energy is available from MRE resources. By commensurately comparing the current

state of knowledge of MRE, and how this compares to the historic power density of each MRE resource (RQ.1 and RQ.2), this research will provide a comprehensive understanding of which MRE resources have the most power density and where that power density is located. Furthermore, the analysis of how much the power density of MRE could increase or decrease under future climate change (RQ.3), and the quantification of variability in MRE assessments of energy (RQ.4) allow for uncertainty in future research and development in MRE to be minimised.

Table 1-1 | Thesis research questions

RQ.1	Based on current knowledge, which MRE resources have the highest power density both for different regions and globally?
RQ.2	How does the power density of MRE as understood today compare to historic averages?
RQ.3	Will climate change increase or decrease the power density for MRE resources and which MRE resources will change the most?
RQ.4	How can uncertainty in assessing and interpreting the power density of MRE be minimised?

The overarching goal of this work is to aid stakeholders such as researchers, policy makers, investors, and developers who are considering future development of MRE on how optimise the available energy in the offshore environment.

1.3 Thesis structure

This thesis is organised into the following chapters as detailed in Table 1-2, which also shows the structure of the thesis and how each chapter relates to the research questions presented above. Chapter 2 provides relevant background on energy quantification and the theory of energy capture for each MRE resource. Chapters 3, 4 and 5 contain the core analysis of the research. Chapter 3 assesses the current state of knowledge of the power density of MRE and compares this to the historic averages. This work is supported by a

creation of a database containing over 800 resource assessments of MRE. Chapter 4 addresses how the power density of each MRE resource may change under future climate change. Chapter 5 analyses the uncertainty in the quantification of the power density for each MRE resource and what impact each has on the results. Taken together these chapters show how the cross-resource power density is comprised, the range of possible future change in the power density for MRE, and how stakeholders can minimise uncertainty when planning future MRE research and development.

Chapter 3 and Chapter 4 have been submitted to peer reviewed journals (see Statement of Co-Authorship) and as such, each has its own abstract, introduction, methods, analysis, and findings. Chapter 5 was in the process of being submitted to a peer reviewed journal at the time this thesis was submitted and has been structured in the same way. Preceding chapters 3, 4 and 5 is a preface linking together the overarching goals of this thesis to the outcomes of each chapter. Chapter 3 and Chapter 4 are unchanged other than formatting to match the rest of this thesis, including fonts, figure and table naming conventions, and citation style. Chapter 6 and Chapter 7 provide a discussion of this research, recommendations for future work, and final conclusions.

Table 1-2 | Thesis structure

Chapter 2	Background	
Chapter 3	A cross-resource assessment of marine renewable energy	*RQ. 1, RQ.2*
Chapter 4	A global assessment of the impact of climate change on the marine renewable power density	*RQ. 1, RQ.3*
Chapter 5	Minimising uncertainty in marine renewable energy assessments	*RQ.4*
Chapter 6	Discussion	
Chapter 7	Conclusions and Recommendations	

Chapter 2 Background

Preface

This chapter provides background on MRE energy mechanics, the technological status the different MRE conversion technologies, the varying definitions of power density, and power density quantification for each MRE resource. While all MRE technologies harness energy from the offshore environment, how these technologies capture this energy and convert to it to electricity is fundamentally different. Similarly, the technological maturity of the different types of systems used to harness MRE are also different. The challenge in comparing power density for MRE is also reviewed. This background provides the broader context necessary for a thorough understanding of the research presented in Chapters 3-5.

2.1 Status of MRE

2.1.1 Offshore wind

Offshore wind is the most mature MRE conversion technology. Since the mid 1980's, the most common wind turbine design has been a three-blade horizontal axis turbine (Gipe & Möllerström, 2022a). These modern turbines operate by having incoming wind spin the blades oriented perpendicular to the wind direction, and this rotation spins a mechanical generator to produce electricity (Grogg, 2005). An example of these modern turbines is shown in Figure 2-1. As technology improved, turbine sizes have increased, improving efficiency and power production while lowering total system costs (Bošnjaković et al., 2022; Shields et al., 2021).
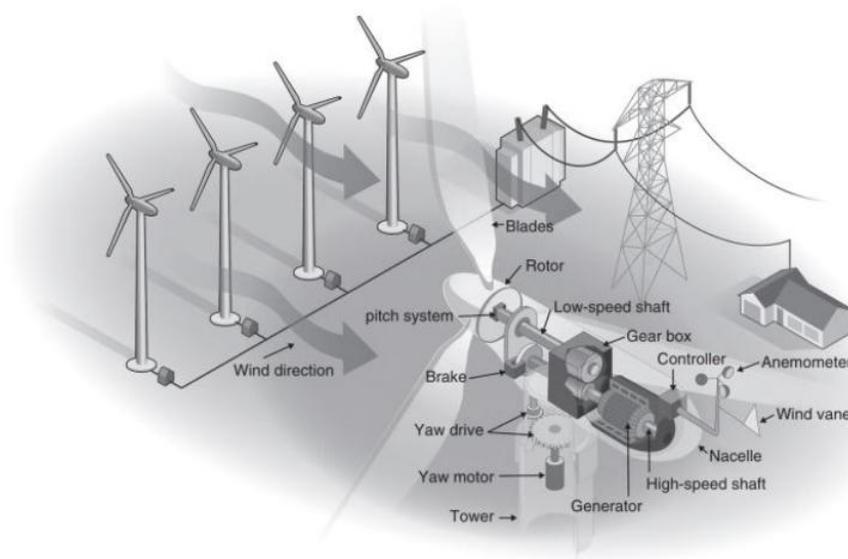
Figure 2-1| Diagram of modern wind turbines *taken* from (Schmitz, 2020)

The first offshore wind turbine was installed in 1991 and by 2023 there were 292 operating offshore wind projects giving a global capacity of 59 GW (Feddersen et al., 2023; Musial et al., 2023). Recent economic analysis shows the levelized cost of energy

for offshore wind is $0.075/kilowatt-hour, approximately 55% higher than onshore wind and 43% higher than natural gas plant costs (Al Mubarak et al., 2024; Osman et al., 2023). However, a downward trend in offshore wind costs has been observed, and forecasts expect offshore wind to be cost competitive with other renewable and fossil fuel-based energy resources by 2030 (Rubio-Domingo & Linares, 2021).

The growth area for offshore wind is currently in developing floating foundation platforms and development of higher capacity turbines of 15 MW or greater (Barooni et al., 2023; Musial et al., 2023). These advancements will enable offshore wind turbines to be installed further offshore in deep waters, where the wind speeds are typically faster and more consistent. The first commercially sized floating wind turbines were installed in the late 2010's. As of 2024 there were at least 86 floating wind projects under development (Edwards et al., 2024; Ibrion & Nejad, 2023).

2.1.2 Waves

Wave energy conversion (WEC) is a developing MRE technology with significant potential for power generation. Unlike offshore wind, WEC does not yet have a dominant design, and various device types are being tested and deployed, each capturing wave energy in different ways (Falcao, 2010; E. Rusu & Onea, 2018). The most common types of WEC designs are shown in Figure 2-2 and include floating point absorbers, submerged point absorbers (also known as pressure differential), onshore and offshore oscillating water columns, attenuators, overtopping devices, and terminators (Clément et al., 2002). These can also be broadly be grouped into three categories: oscillating water columns, overtopping devices, and oscillating bodies (Aderinto & Li, 2018; Bouhrim et al., 2024).
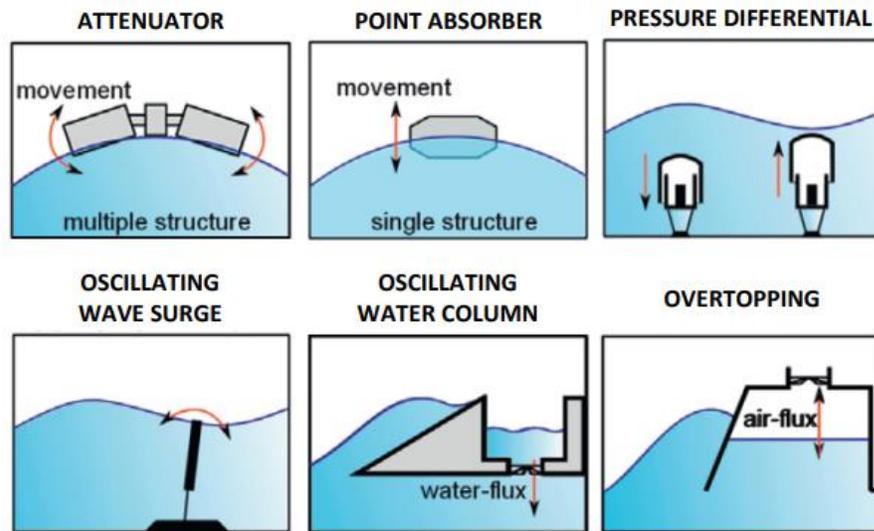
Figure 2-2 | Diagram of the different type of wave energy converters, taken from (Titah-Benbouzid & Benbouzid, 2015)

Wave energy conversion is based on the capture of the wave-induced orbital motion of a point in the water. Three primary forms of energy capture can occur: heave (vertical motion), pitch (rotational motion around a horizontal axis), and surge (horizontal motion in the direction of wave travel) (Cruz, 2007). Oscillating water columns are partially submerged hollow structures that capture air compression caused by waves entering and exiting a chamber, driving a turbine. Oscillating bodies include floating or submerged devices that move up and down with wave motion, typically using hydraulic or mechanical systems to generate electricity. Overtopping devices collect incoming wave energy by channelling water into a raised reservoir, which then flows through hydro turbines.

Research and development of wave energy is in part motivated by the higher density of sea water compared to the air, which can result in a larger theoretical power density than other renewable resources such as wind energy (Khojasteh et al., 2023). However, waves by nature can be destructive, presenting a complex design problem of how to make an efficient and cost-effective wave energy converter, that can survive the destructive

environment (Czech & Bauer, 2012). As a result, the industry has not yet converged on a single device style and actual development has been limited (Mofor et al., 2014). The first wave energy converter that delivered power to end users was installed in 1991 (WHITTAKER et al., 1997). By 2023, the global installed wave capacity had reached approximately 2.8 MW (IEA, 2024a). The levelized cost of energy for WEC is estimated to range from $0.09 to $0.14 per kilowatt-hour, but the lack of commercial-scale wave energy converters leaves notable uncertainty in what cost reductions can be achieved in the future. However, continued research and policy support are expected to drive down costs and improve commercialisation prospects in the coming decade (Hannon et al., 2017; Jin & Greaves, 2021). In addition, current research in wave energy seeks to improve device efficiency, scaling up prototype deployments, and integrating wave energy converters into hybrid offshore energy systems (Guo & Ringwood, 2021a; Ramos et al., 2022).

2.1.3 Solar

Offshore solar energy is an emerging MRE technology that uses the existing onshore photovoltaic technology which converts incoming solar irradiation and to electricity and deploys it on offshore structures (V. Kumar et al., 2015). Offshore solar offers several advantages over traditional land-based solar installations, including reduced land use competition and system cooling from the water, which can improve panel efficiency (Vo et al., 2021). However, the transition to offshore environments introduces additional challenges, including survivability in harsher ocean conditions, corrosive effects from ocean salinity, and more complex installation and maintenance processes (Oliveira-Pinto & Stokkermans, 2020).

Despite solar photovoltaic technology being a mature technology, with levelized cost of energy for onshore systems declining 88% since 2010 (reaching $0.048/kWh in 2021), offshore deployment is limited (IRENA, 2022; Martinez & Iglesias, 2024a). As of 2020, the

global capacity of floating solar systems 2.6 GW, however, most of this capacity came from inland freshwater systems (Fan et al., 2025). In additional to the design challenges, the limited development of offshore solar is in part due to higher costs for offshore solar. (Martinez & Iglesias, 2024a) found the levelized cost of energy for offshore solar in the Mediterranean Sea to be €1.5/MWh, which is approximately $0.157/kWh (based on a conversion rate between Euros and US Dollars as of February 2025).

Offshore solar is receiving recent interest and there has been notable growth in the industry in recent years. For example, in 2024, 1 GW offshore solar project was built in China, the first offshore project to reach the GW scale (Bloomberg, 2024). Other nations have also started to plan on development of offshore solar. For example, in 2024 nine European countries (Cyprus, Slovenia, Malta, Croatia Greece, Italy, France, Portugal and Spain) announced a joint agreement to streamline the development of offshore renewable energy development including solar (Hadjicostis, 2024; *Joint Statement of the Ministers of Energy of the MED9*, 2024).

Current research in offshore solar technology is focused on cost reductions. This is being approached through different sub-topics of research, such design of foundations/floating platforms and development of novel solar panels that are flexible (Bahroinudin et al., 2024; Djalab et al., 2024). There is also increasing research looking to integrate or co-located offshore solar with other MRE development (J. Huang & Iglesias, 2024; Vázquez et al., 2024).

2.1.4 Ocean currents

Ocean current energy converters (also known as tidal stream or tidal current) harnesses the horizontal kinetic energy derived from tides or other surface currents ocean circulations to generate electricity (Yuce & Muratoglu, 2015). These turbines are typically installed in locations where the ocean flows are faster, with minimum current velocities of 2 meters per second (Giorgi & Ringwood, 2013; Nicholls-Lee & Turnock, 2008).

Multiple designs have been developed to capture this energy and convert it to electricity, shown in Figure 2-3. These include horizontal-axis turbines, vertical-axis turbines, oscillating hydrofoils, ducted turbines, Archimedes' screw, and tidal kites (Nachtane et al., 2020a).
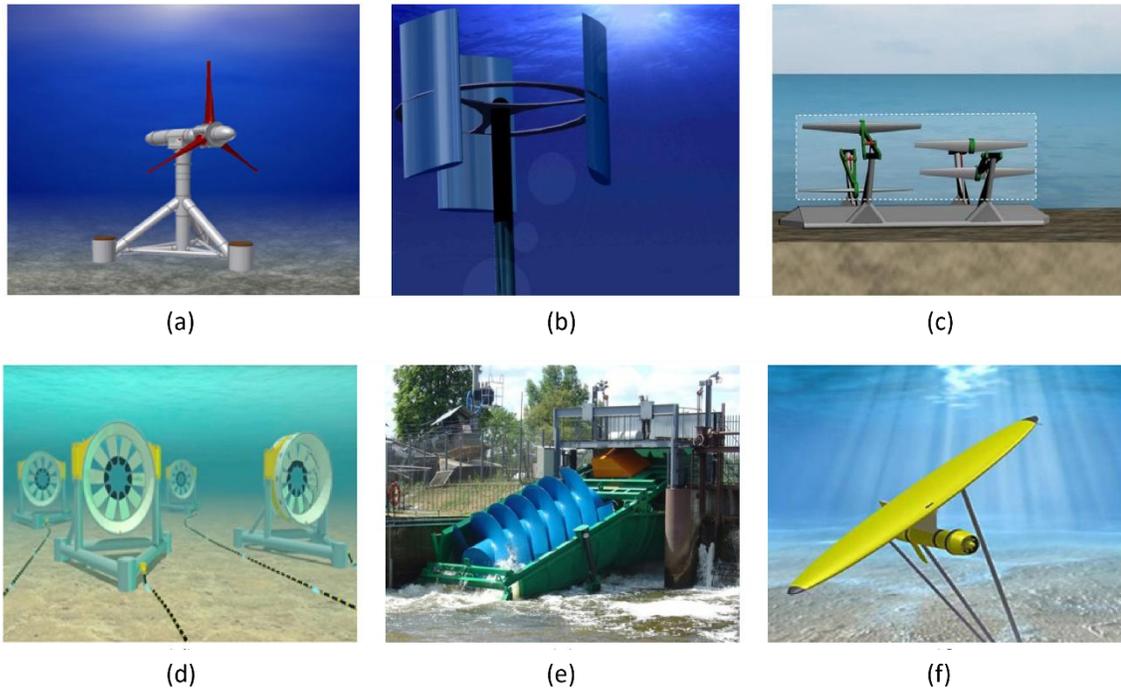
Figure 2-3 | Renderings of different type of ocean current turbines: a) horizontal axis turbine, b) vertical axis turbine, c) oscillating hydrofoil, d) ducted turbine, e) Archimedes' screw, f) kite turbine. Adapted from (Nachtane et al., 2020b)

The most common design style is a horizontal-axis turbine which use the same principle as wind turbines – using horizontal flowing water to rotate blades around a horizontal axis turbine. Vertical axis turbines also use blades to spin a turbine that is oriented in the vertical direction. Oscillating hydrofoils use a fixed wing that generates lift as ocean water flows over it, this lift results in an upwards and downwards motion of the wing which drives a hydraulic generator. Ducted turbines act on a similar principle of horizontal turbines but have an additional funnel shaped enclosure to amplify the incoming water velocities. Archimedes' screws also spin horizontal turbines that are driven by variations

of water level through a helix shaped shaft. Tidal kites use a tethered wing which flow in an orbital motion oriented with the direction of the ocean current to drive a hydraulic generator.

The first ocean current turbine was installed in 2003. By 2022, the global installed capacity had reached 13 MW (Europe, 2023; Sleiti, 2017). Most of this existing capacity comes from pre-commercial demonstration projects, however full-scale growth in ocean current development is expected, with the global capacity forecasted to reach 2.96 GW by 2030 (Mordor Intelligence, 2024).

Recent economic assessments indicate that the levelized cost of energy for marine current energy is variable. For example, (Vazquez & Iglesias, 2015b) found the LCOE ranges from £0.125 per kWh to £0.55 per kWh (approximately $0.158/kWh to $0.696/kWh based on publicly available exchange rates from February 2025) in the United Kingdom. However, recent research shows large cost reductions (up to $0.28/kWh) can be obtained from simple changes involving site selection a turbine array layouts (Ordonez Sanchez et al., 2021; Vazquez & Iglesias, 2015a). Current research is working towards full commercialization and decreasing costs of ocean current turbines, this includes work improving turbine materials and manufacturing, addressing environmental concerns and interconnection to local grids (G. Li & Zhu, 2023).

2.1.5 OTEC

OTEC exploits the temperature differential between warm surface seawater and cold deep seawater to generate electricity. This process involves circulating warm surface water through a heat exchanger to vaporize a working fluid, which then drives a turbine connected to a generator (Masutani & Takahashi, 2001). The vaporised fluid is subsequently cooled using cold deep seawater, condensing it back into a liquid to repeat the cycle. OTEC systems are typically categorized into three types: closed-cycle, open-cycle, and hybrid systems. Diagrams of closed-cycle and open-cycle OTEC systems are

shown in Figure 2-4 and Figure 2-5. Closed-cycle systems use a working fluid with a low boiling point, such as ammonia, to drive the turbine (M.-H. Yang & Yeh, 2014). Open-cycle systems directly utilise the warm seawater, creating a low-pressure environment to flash-evaporate the water, which then drives the turbine (Aresti et al., 2023). Hybrid systems combine elements of both closed and open cycles to enhance efficiency and performance.
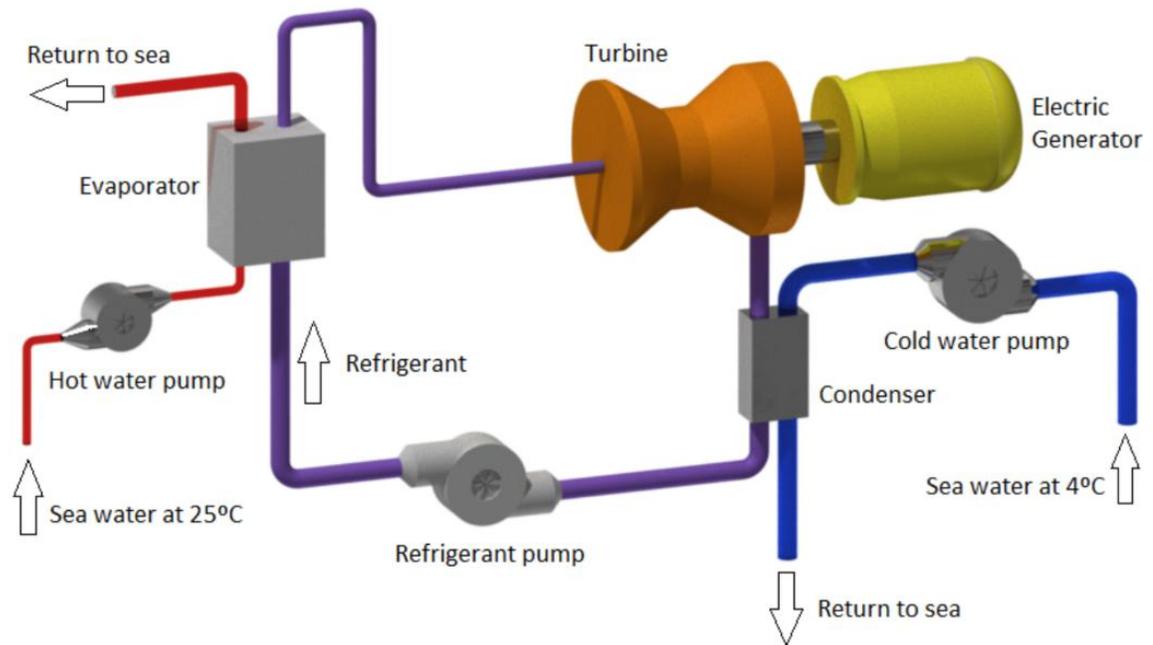
Figure 2-4 | Diagram of a closed-cycle OTEC plant, taken from (Herrera et al., 2021)
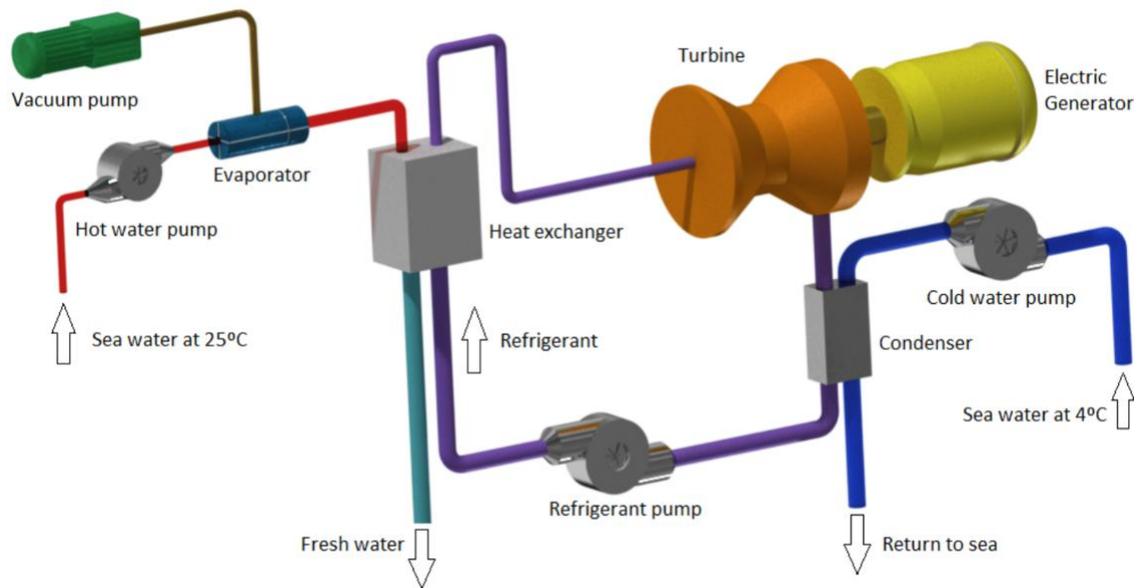
Figure 2-5 | Diagram of an open-cycle OTEC plant, taken from (Herrera et al., 2021)

The first OTEC demonstration plant built was in 1930s and full-size demonstration projects were completed in the late 1970s and early 1980s (Aresti et al., 2023). Notable projects include the 50 kW OTEC plant built in 1979 in Hawaii and the 100 kW plant built in 1981 in the Republic of Nauru (McHale, 1979; Mitsui et al., 1983). While development of OTEC has been occurring for over 90 years, the actual installed capacity remains low, reaching 1 MW in 2019 (Nakib et al., 2025).

Given OTEC is a proven concept with several success demonstration projects but has not yet reached wider adoption for commercial development, there is variation in assessments of the levelized cost of energy. In the (Nakib et al., 2025)) review of OTEC, they found the costs range from $0.13 per kWh to $0.65 per kWh. Recent research has shown that scaling up OTEC plants may not actually achieve cost reductions, noting optimisation of the current technology could result in a consistent levelized cost of $0.15 per kWh (Langer et al., 2021, 2022). Further research in OTEC aims to improve the mechanical components, provide case studies to determine the applicability of OTEC at

specific locations, and develop dual use systems such as water desalination (Nakib et al., 2025; Rashid et al., 2024; Yilmaz et al., 2024).

2.2 Defining power density

Power density – in broad terms – refers to the amount of energy that is available from a given resource. However, how energy is quantified, and its nomenclature, is highly variable. For example, (Twidell, 2022)), defined two types of power density: the *theoretical potential* which is defined as "the upper limit of what may be produced from an energy resource based on physical principles and current scientific knowledge" and the *technical potential* which is defined as "energy output obtainable by the full implementation of demonstrated technologies or practices in the specified region." Further specificity has been used to define power density. In their book, (Z. Yang et al., 2017) defined three categories of power density: theoretical potential, technical potential, and practical potential. The first two definitions closely align with the definitions provided in (Twidell, 2022) with the third classified as *practical potential* which is "how much of the technical resource is available after considering social, economic, and environmental constraints."

Conflicting nomenclature exists as well. An assessment from the U.S. National Renewable Energy Laboratory (NREL) used four categories of power density: Resource, Technical, Economic, and Market (A. Lopez et al., 2012). However, a recent report from NREL used only three categories: the theoretical resource which they define as "energy available in the resource"; the technical resource which they define as "[the] proportion of the theoretical resource that can be captured using existing technology options without consideration of external constraints"; and, the practical resource which was defined as " [the] proportion of the technical resource that is available after consideration of external constraints" (Kilcher, Fogarty, & Lawson, 2021b). Further highlighting the inconsistent naming convention, another recent assessment conducted by the U.S.

Department of Energy used four definitions: resource potential, technical potential, economic potential, and market potential (Brooks, 2022).

The differences in nomenclature are likely driven by individual study motivations and the timing of publication. Throughout this research, we use the definitions of power density shown in Table 2-1.

Table 2-1 | Classification of power density

Theoretical Potential	The maximum amount of energy from occurring naturally from resource flowing through a unit area (i.e. the calculated energy from wind speed over a square meter of land)
Technical Potential	The upper limit of the amount of energy that can be captured by a renewable energy system and converted into electricity (i.e. the calculated energy production of a tidal current turbine)

There are numerous approaches to calculating technical power density for MRE. These approaches can vary by whether or not actual turbine performance metrics are considered, the number of turbines considered, the size of the turbines considered, and turbine operational limitations. For example, some studies do not consider a specific turbine but rather rely on the Betz limit (which states no horizontal axis turbine can extract more than 59% of the energy for a resource) to estimate the upper limit of the amount of energy a wind turbine could produce (Betz, 2013; de Castro et al., 2011). Recent research, however, has asserted it is possible for both wind turbines and tidal current turbines to exceed this limit (Lecanu et al., 2023; Vennell, 2013).

The number of approaches for calculating the technical potential of MRE is unconstrained when individual turbine specifications are included. Taking offshore wind as an example, (Nagababu et al., 2017)), used forty, 5 MW offshore wind turbines with hub heights of 80 meters to assess the offshore wind technical potential of India. In, (Nie & Li, 2018a), the a varying number of 6 MW turbine was used to determine the technical potential of

offshore wind near China. Other examples use larger turbines with a wider range of operating parameters, such as (de Souza Nascimento et al., 2022a)), which used sixteen, 15 MW turbines with hub heights (the height of the centre of the turbine blades) of 150 meters.

Other assessments of technical potential do not use a specific turbine (i.e. number of turbines or size of turbine) but rather use general operating parameters of turbines to determine the amount of power produced at different wind speeds. This approach is referred to as modelling a power curve and can be as simple as just modelling wind speed (Gill et al., 2012), or more complex and include variables such as wind direction, air density, humidity, turbulence intensity, and wind shears (G. Lee et al., 2015). Two examples are shown in Figure 2-1, adapted from reviews of power curve modelling (Carrillo et al., 2013; Lydia et al., 2014).
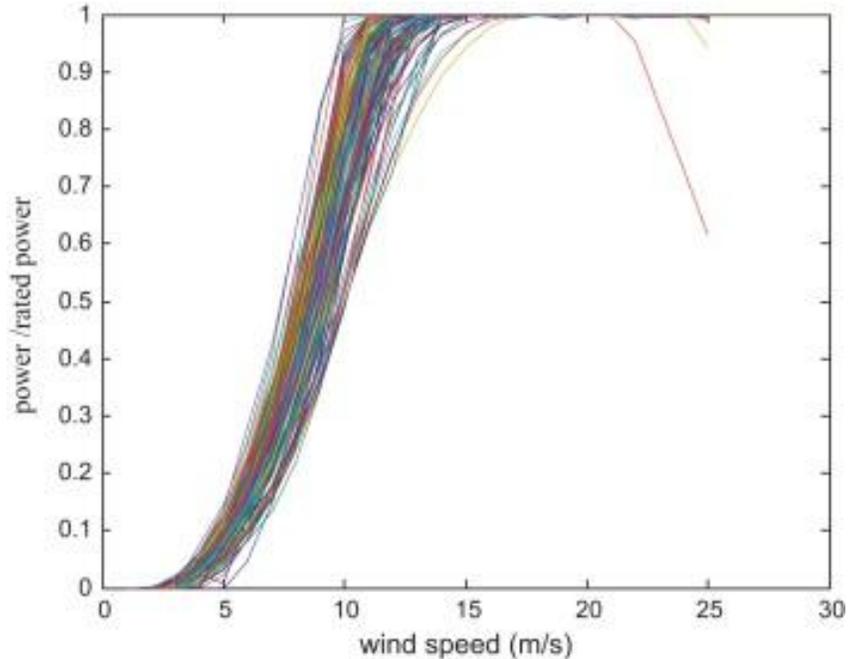
Figure 2-6 | Example power curve for wind turbines showing the power output from a wind turbine at different wind speeds. Taken from (Carrillo et al., 2013; Lydia et al., 2014)

More complexity is introduced as more MRE resources are considered, as the variables considered for each are different. In technical potential assessments of wave energy, a wider variety in operation parameters exists because of the fundamental differences in how the different styles of wave energy converters operate. For example, (Ozkop & Altas, 2017), identified how over 25 different wave energy converter control system methodologies materially influence the energy production (an overview is provided in section 2.3 of the natural mechanisms driving MRE and the different turbine types used to harness the energy). Similarly, examples of typical variables included in technical potential assessments of OTEC are pipe diameters, pumping efficiency, evaporator and condenser rates, friction losses and head losses (VanZwieten et al., 2017a).

There is a multiplying effect when determining the number of unique approaches for calculating practical potential of MRE. In addition to including any number of the

variables used for calculating theoretical and technical potential, a large number of additional variables are also introduced when considering economic, political, and other factors that influence the development of MRE. For example, in an economic assessment of offshore wind (Beiter et al., 2017), additional variables were considered to determined the levelized cost of energy and levelized avoided cost of energy in the United States. Other works have reviewed the capital and operational expenses of MRE in practical assessments (Stegman et al., 2017). A recent example forecasting the practical potential of wave and tidal energy included several variables independent of the technology or resource including: political support, spatial conflicts, Blue Economy growth, public acceptance, and availability of ocean data (Vieira et al., 2024). All of these studies can be categorized as assessments of practical potential.

2.3 Formulation of theoretical power density of MRE

2.3.1 Offshore wind

Calculation of offshore wind uses the same principles as the onshore counterpart. The resource is the air flowing across the ocean surface. The winds are driven by variations in atmospheric temperature, which arise from the uneven heating of the Earth's surface by solar radiation and the influence of local topography (Golston et al., 2019). These factors create a pressure gradient which induces forces on the atmosphere and result in wind with a certain magnitude and direction (Le Gourieres, 2014). The theoretical power density (E_{wd}), shown in Eq. 2-1, is calculated by taking the square of the wind speed (V_{wd}) multiplied by half the air density (ρ_a). The resulting values are given in kW/m^2.

$$E_{wd} = \frac{1}{2} \rho_a V_{wd}^3 \qquad \text{Eq. 2-1}$$

Another typical approach to calculating theoretical potential is using the Weibull distribution, which statistically models wind speed variations over time and provides a probability of wind speeds, and in turn the theoretical potential (Bowden et al., 1983).

This approach is used because it is computationally simple, accounts for the variations of wind speed over time, and can be extrapolated to determine wind speeds at different heights (Arslan et al., 2014). However, (Drobinski & Coulais, 2012), noted the Weibull is limited as it is "purely empirical and there is a lack of physical background justifying the use of the Weibull distribution to model wind statistics." Likewise, it is debated what the best model is for estimating Weibull parameters in wind energy applications (Azad et al., 2015; Teimourian et al., 2022).

2.3.2 Waves

Wave energy as a resource is the propagation of energy through a body of water. Conceptually, the generation of waves is initiated by friction between winds blowing on a water surface resulting in small ripples on the water surface that continually grow in size with consistent wind (Phillips, 1957). As it relates to MRE, the energy of waves travels through the body of water, causing an orbital motion with both a vertical and horizontal component which can be harnessed by wave energy converters (Drew et al., 2009; Reguero et al., 2015a). One of the most common ways to quantify the power density of waves (E_{wv}), shown in equation 2-2, is the squared significant wave height (mean wave height of the largest third of the wave heights in the sea-state) multiplied by the density of the water (ρ_w), acceleration constant due to gravity (g^2) and the wave period (T_w). This is the quantification method used to determine the traditional reference presented throughout the thesis for the novel standardized wave power density results (the methodology for the standardized wave power density is presented in Chapter 3).

$$E_{wv} = \frac{\rho_w g^2}{64\pi} H_s^2 T_w \qquad\qquad \text{Eq. 2-2}$$

2.3.3 Solar

The theoretical power density for offshore solar is the net irradiance emitted from the sun that passes through the atmosphere and reaches the earth's surface (Rosa-Clot &

Tina, 2020; Willson, 1984). This can be measured directly with specialized radiometry equipment (Pyrheliometers and Pyranometers) that either measure the thermoelectric or photoelectric properties of the incoming irradiance (Eltbaakh et al., 2011; Willson, 1984). These devices provide direct quantifications of theoretical potential for solar energy over a unit area, and for the purposes of this thesis, no additional calculations are required. In practice these means the raw data (E_i) used in the analysis is equal to the theoretical potential (E_{sl}), shown in equation 2-3.

$$E_{sl} = E_i \qquad \text{Eq. 2-3}$$

2.3.4 Ocean currents

For the purposes of this thesis, ocean currents refer to the horizontal flows of ocean waters. This includes flows from tidal forces and flows from large-scale ocean circulation driven by wind, temperature, salinity gradients, and the Earth's rotation (Niiler, 2001; Ordonez-Sanchez et al., 2021). Similar to wind energy, the theoretical potential for ocean currents is calculated by taking the square of the ocean velocity (V_{wt}) multiplied by ocean water density (ρ_{wt}), divided in half, shown in equation 2-4 (Ross et al., 2021).

$$E_{oc} = \tfrac{1}{2} \, \rho_{wt} \, V_{wt}^3 \qquad \text{Eq. 2-4}$$

2.3.5 OTEC

The power density for OTEC comes from the thermal gradient of a water column in the ocean. It is widely accepted that the necessary temperature difference between deep cold waters and warm surface waters used in OTECE plants is 20°C (Nakib et al., 2025; Vega, 2012). However, beyond this consensus, there is not a commonly agreed upon approach for calculating the theoretical potential of OTEC. For example, some studies use global circulation models to determine heat sinks and sources to determine the theoretical potential (Rajagopalan & Nihous, 2013). Other studies use the Carnot efficiency (which is the maximum efficiency of converting heat from water into

mechanical energy) as a proxy to determine the upper limit of the theoretical potential (Syamsuddin et al., 2015).

2.4 Approaches to cross-compare MRE

Multiple approaches that can be used to compare renewable energy and the selection of renewable technologies exist. One well used approach is the application of multicriteria decision-making (MCDM). MCDM is a methodology to select or rank alternative solutions to complex problems based on multiple criteria that are often in conflict or non-homogeneous (Henig & Buchanan, 1996). MCDA is used across a number of different disciplines such as management, economics, medicine, environment and energy (Azhar et al., 2021). Further, a variety of different MCDA methodologies have been developed and used. Common examples used in energy planning include the weighted sum method, weighted product method, analytical hierarchy process (AHP), preference ranking organization method for enrichment evaluation (PROMETHEE), elimination and choice translating reality (ELECTRE), technique for order preference by similarity to ideal solutions (TOPIS), multi-attribute utility theory (MAUT), and compromise programming (Pohekar & Ramachandran, 2004). Figure 2-7 shows the general process for the MCDM approach, which includes defying the problem, establishing pre-requisites and objectives, identifying alternative options, assigning a criteria and applying the decision model (Bohra & Anvari-Moghaddam, 2022).
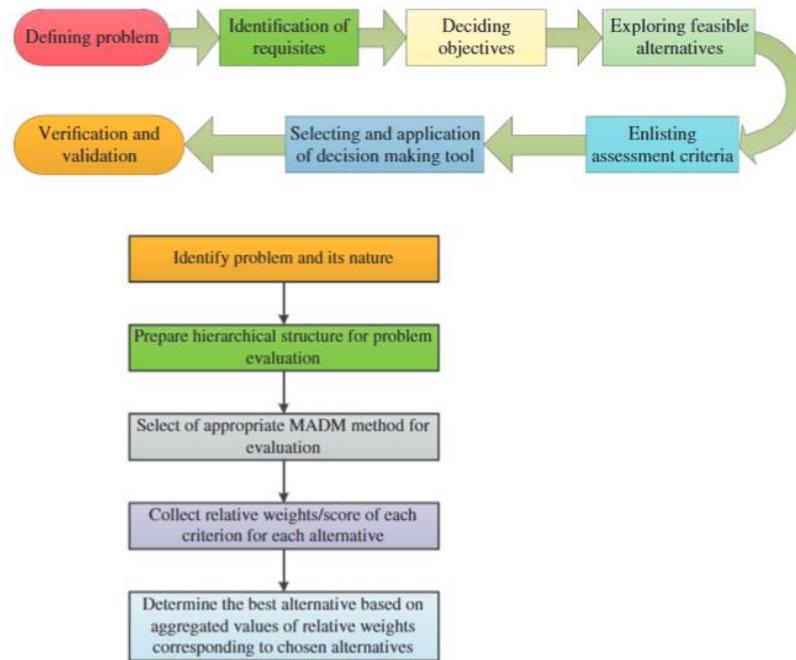
Figure 2-7 | Overview of general methodology used in multicriteria decision-making. Adapted from (Bohra & Anvari-Moghaddam, 2022)

Several studies have applied MCDM methods to MRE. For example, (Abaei et al., 2017)) used a Bayesian Network MCDM approach to assess different possible locations for wave energy converter development. Likewise, (Vasileiou et al., 2017) used a AHP MCDM approach for the site selection of a hybrid wind-wave energy system in the Mediterranean Sea. Other studies have used MCDM to support the design of MRE systems, such as a hybrid AHP-VIKOR MCDM approach to optimise the power take off equipment for MRE (Ma et al., 2025).

While existing applications of MCDM methods provide useful results for development of specific MRE, they largely do not cross-compare the power density of different MRE resources. While there are limited examples of studies using MCDM that cross-compare MRE resources, one example evaluated MRE technologies in Colombia focusing on technical, financial, and environmental aspects (Serrato et al., 2021). While this study presents a ranking of MRE technologies, it does not specify the energy output of the

alternatives or what data is used to drive the analysis, limiting the ability to cross-compare the energy available from each MRE resource. Other research has provided a review of studies that use MCDM in site selection of solar, onshore wind, offshore wind, wave and marine current resources (Shao et al., 2020). This review provides insight on how MCDM is used in MRE studies but does not directly compare the energy from the different resources.

While different MCDM approaches provide methods to overcome the inherent complexities when comparing different energy alternatives against multiple criteria, they have notable limitations (Sahoo & Goswami, 2023). This has been highlighted by (Mardani et al., 2017)), which noted that because of the wide range of MDCM options and uniqueness of problems they are applied to, choosing a MCDM method is essentially a MCDM problem itself. This is further underscored by (Baumann et al., 2019)), which found the diverging goals, scopes and heterogeneity of MCDM approaches limit their practical use as the results of different MCDM studies are challenging to compare in a meaningful way.

Specific to the cross-comparison of power density from different renewable resources, MCDM methods have several limitations including data selection and energy quantification. For example, some applications of MCDM use capacity factor as the energy input into the MCDM model (Sitorus & Brito-Parada, 2020). While this approach provides a widely accepted and straight forward way to account for power density, it is dependent on specific technology efficiencies and therefore does not give a direct comparison of the total power density. Further, research has shown comparing capacity factors between different resources is impractical due to the differences in technical maturity and spatial variations in resource availability (Bolson et al., 2022; Jung & Schindler, 2022). As a result, MCDM studies that use of capacity factor as a measure of power density tend to favour the resources with greatest technical maturity (Amer & Daim, 2011). It is also common for MCDM studies assessing renewable energy options

to not use power density data at all, rather relying on current installed capacities or assumed values of future electricity production (G. Lopez et al., 2022; Sitorus & Brito-Parada, 2020).

Additional limitations exist when comparing the result of different MCDM studies. This includes a lack of available data (Elena Arce et al., 2015), varying criteria used between studies each with inter-criteria independencies (Baumann et al., 2019; Yazdani et al., 2018), and conflicting evaluation objectives (Doukas et al., 2010; Liang et al., 2022). As a result, it is challenging to derive any meaningful conclusions about the power density of MRE from available MCDM studies.

Other disciplines of research comparing MRE resources include life cycle assessments, electricity system and sub-system assessments, environmental impact analyses, and financial evaluations. However, similar to MCDM studies, this research is generally limited in its usefulness to cross-compare the power density from MRE. For example, (Evans et al., 2009), provided a comparison of solar, wind, hydro and geothermal resources across several categories including life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts, but noted each resource is significantly geographically affected, which could change the findings presented in the study.

Specific to the evaluation of electric systems and sub-systems, there is a general lack of research which include MRE resources. In those that do, such as (Deason, 2018), current installed capacity or assumed capacity factors are commonly used to quantify the power density of the different resources. As with MCDM, this approach is impacted by differences in technology maturity and efficiency and does not give a clear understanding of how the power density compares between these resources.

When assessing the climate and future impacts, there is an overall lack of research that cross-compares the power density of MRE. This was identified by (Widén et al., 2015a),

which noted published studies typically focus on a single renewable energy resource and do not attempt compare it to the others. Existing studies that do look at the impacts of climate change on multiple renewable resources are primarily focused on onshore resources (Gernaat et al., 2021). While this gap in research is known, there remains a need for an assessment of the actual MRE cross-resource power density and how it could change from climate change to better inform policy, research and development of renewable energy.

2.5 Summary

This background chapter, summarising the latest evidence in the literature, provides the necessary information to understand the complexities that arise when comparing the power density between different MRE resources. These complexities are amplified by the differences in MRE technology maturity, driving mechanisms behind power density, and the varying definitions and methods used in energy quantification. As a result, to date, MRE research has primarily been focused on individual resources and the reported power density values are often in different, non-homogeneous units. Together these differences have made cross-comparison of MRE impractical.

While well-established approaches to assess multiple objectives and resources are available in energy planning, such as MCDM, these methods fall short in providing a direct and quantitative comparison of power density. Additionally, the impact of climate change has notably been excluded in existing MCDM studies and there is a gap in understanding of how climate change will impact the cross-resource power density of MRE. The lack of adequate methods to compare power density of MRE and gap in climate change research of MRE leaves it unknown which MRE resource has the most energy available, and how this available energy will change in the future.

In the following chapters, these questions will be addressed by determining how the standardised power density of MRE available in research compares (Chapter 3), what the

range of possible power density change is for MRE (Chapter 4), and by assessing how stakeholders can account for uncertainty in MRE studies (Chapter 5).

Chapter 3 A global cross-resource assessment of offshore renewable energy

Preface

This chapter (excluding this preface) has been published in Renewable and Sustainable Energy Reviews (Spalding et al., 2025). The published version is available online at https://doi.org/10.1016/j.rser.2025.115563. The numberings of sections, figures, tables, and some basic abbreviations and nomenclature have been adapted for consistency with the rest of this thesis. For example, in the published version of this chapter, MRE is referred to as offshore renewable energy (ORE). The references have been compiled at the end of the thesis. In addition, further wave power density results have also been added to this chapter since publication. These results quantify the power density using the commonly used units of kW/m to provide context on how using standardized units changes the interpretation of the cross-resource energy densities.

This chapter addresses the following research questions of this thesis (presented in Chapter 1.2, Table 1-1):

RQ.1   *Based on current knowledge, which MRE resources have the highest power density both for different regions and globally?*

RQ.2   *How does the power density of MRE as understood today compare to historic averages?*

The aim of this chapter is to understand how the power density of MRE compares based on current available research. To accomplish this, a systematic search of literature is used to collect published MRE resource assessments and create a global database of power density for MRE, standardized to kW/m^2.

3.1 Abstract

Current global climate mitigation efforts are considered insufficient to meet international carbon emission targets. Modelled scenarios showing how these targets can be reached are underpinned by further renewable energy development. Offshore renewable energy has been shown to have power densities that are more than double the global electricity demand. Previous assessments investigating Offshore renewable power densities 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 power densities at any given location. This study undertakes a global cross-resource assessment of marine renewable power densities, collecting previous marine renewable energy resource assessments in a single database with standardised power densities. The assessments collected are compared to the theoretical power density of other resource types at each location. Tidal and ocean currents and offshore solar are found to have consistently higher power densities than the other resource types. An expanded feasible global power density 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.

3.2 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 (Bellprat et al., 2019; Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, 2021; United Nations, 2015). Achieving net-zero carbon emissions is critical to meeting the International Panel on Climate Change targets and a key part of the United

Nations Sustainable Development Goals (Küfeoğlu, 2022). In order to meet these goals, decarbonising 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-zero CO_2 emissions to be achieved (IEA, 2021b; Teske, 2019). 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 (IEA, 2021c; IRENA, 2021b; REN21, 2020). 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 power densities are estimated be up to twice the global electricity demand (N. Khan et al., 2017; Neill et al., 2018a; E. Rusu & Venugopal, 2019a). 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 (Hernández-Fontes et al., 2020; Kabir et al., 2022b). 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 (Hernández-Fontes et al., 2020; Kabir et al., 2022a).

Determining the amount of energy is the first step towards developing these ORE energy systems, and is broadly referred to as resource assessments (Robert Springer & National Renewable Energy Laboratory (NREL), 2013). 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 power density 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 power density for one or more resources for a particular

area or specific region (Elsner, 2019; Farkas et al., 2019; Ulazia et al., 2019). 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 power densities of two or more resource types in the same region or specific coastal location (Dong et al., 2019; Farkas et al., 2019; L. Rusu, 2019). However, to the best of the authors knowledge, no study exists that compares the power density of all ORE resource types, on any scale. This leaves a gap in current knowledge of understanding how the power density compares for the different ORE resources.

The research in this study aims to fill this gap by conducting interdisciplinary assessment of standardised power densities 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 power density 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 power densities results in existing ORE resource assessments compare the power density of the different ORE resources, and 4) identifies what ORE resources that, to date, may be underutilised in terms of amount of research existing research and total global power density. For some MRE resources, particularly wave, the new standardized power density quantification provides results starkly different than traditional approaches. For reference and transparency, the results, while non-homogenous to the other resources, are also presented using a traditional quantification approach.

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 power density 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.

3.3 Review of cross-resource ORE analysis

This section provides a review of existing literature that assess the power density 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 power density 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 optimise 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 power density 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. Table 3-1 presents these studies, the ORE resources included in each review, and how energy results are presented (listed verbatim).

Table 3-1 | 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 (Samsó et al., 2023)	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 (M. Li et al., 2022)	2022	Wave, Tidal, Ocean Current, Offshore Floating Photovoltaic, Offshore Wind	Seasonal Power Potential, Development Status
What about Marine Renewable Energies in Spain? (Esteban et al., 2019)	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 (H. Chen et al., 2018)	2018	Ocean Thermal Energy, Osmosis Energy, Wave Energy, Tidal & Current Energy	Global Power density, Environmental Impacts, Technology Challenges, Design Status, Case Studies
Current status and future of ocean energy sources: A global review (Melikoglu, 2018)	2018	Tidal Energy, Wave Energy,	Technical power density in the

			United States
Electrical Power Supply of Remote Maritime Areas: A Review of Hybrid Systems Based on Marine Renewable Energies (Roy et al., 2018a)	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 (Soukissian et al., 2017)	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 (Uihlein & Magagna, 2016)	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 (Magagna & Uihlein, 2015a)	2015	Wave Energy, Tidal Energy	Development Status
Marine renewable energy in China: Current status and perspectives (Y. Zhang et al., 2014)	2014	Tidal Energy, Tidal Current Energy, Wave Energy, Ocean Thermal Energy, Salinity Gradient Energy	Potential Energy Capacity, Development Status

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 power densities 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 (Izadyar et al., 2016; Widén et al., 2015b; Yavor et al., 2021a). 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 power density into optimal turbine locations by consideration of wind energy factors, environment risk factor and cost factors (Zheng et al., 2019). Likewise, some wave

resource assessments use a similar, but different, classification of power density that consider wave specific variables such as wave swell periods (Ahn et al., 2019).

3.4 Methods and data

The methodology used in this study was developed to enable a commensurate cross-resource investigation of ORE and to identify underutilised 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 standardised units (kW/m^2) representing the theoretical power density, 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 power density was used, which classify resource assessments into three levels of energy quantification (Kilcher, Fogarty, & Lawson, 2021b). Figure 3-1 depicts the classifications and is an adaptation from the National Renewable Energy Laboratory (Kilcher, Fogarty, & Lawson, 2021b).
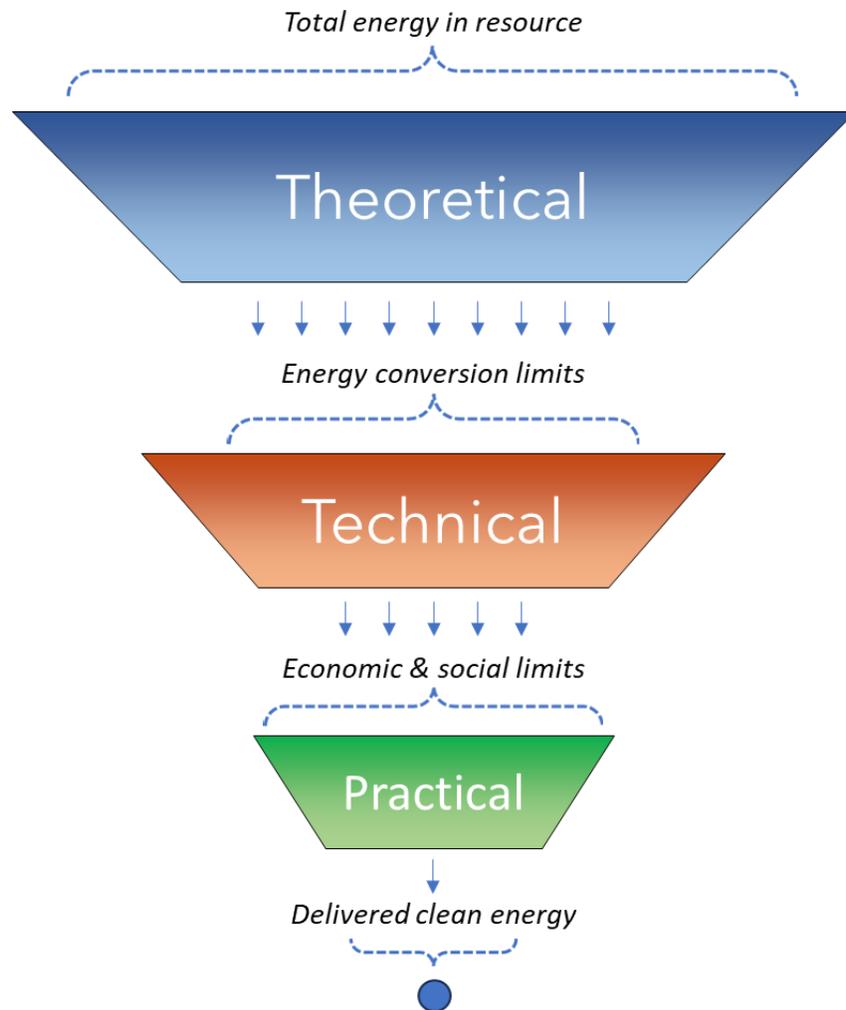
Figure 3-1 | Nomenclature resource assessments. The hierarchy of the three definitions of resource assessments used in this study, defined by the International Electrotechnical Commission Technical Committee. Each category applies filters to the corresponding level of energy quantification that reduces the amount resulting energy from the preceding energy classification.

The third step, reanalysis data was used to quantify power density of the various ORE resources in the standardised units globally and compared to the resulting power densities in the database. Finally, resources with high power density and fewer existing resource assessments were identified and an analogous global power density was calculated. A research framework showing each of these steps provided in Figure 3-2. 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 Figure 3-3.
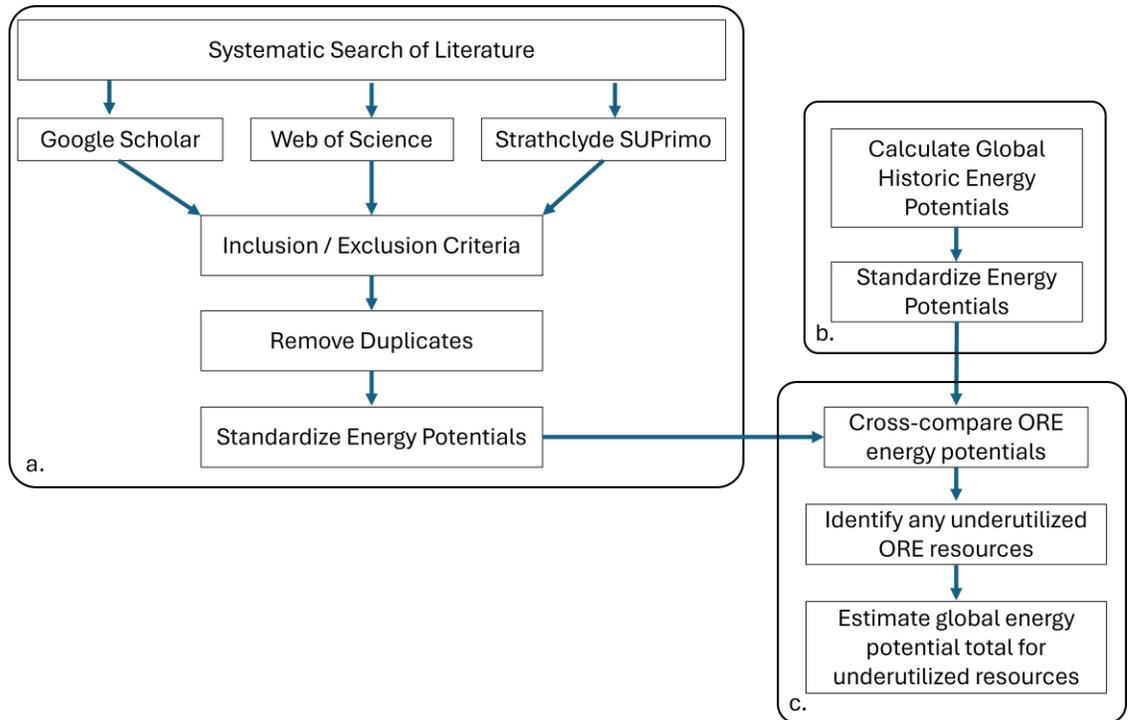
Figure 3-2 | Research Framework. Visual representation of the steps used in this study. A) Development of the ORE resource assessment database. B) Calculating global power density based on ERA5 Reanalysis data. C) Cross-comparison and analysis of ORE power densities
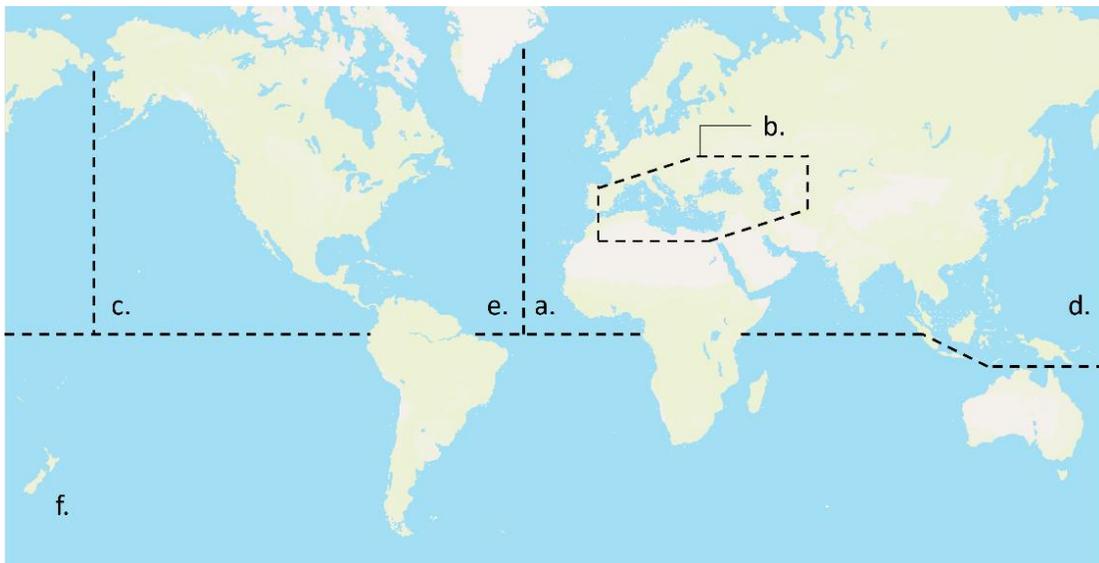
Figure 3-3 | Study Regions. Map of the six regions used for data interpretation in this research. The regions are referred to as: (a.) western North Atlantic, (b.) Mediterranean, (c.) eastern North Pacific, (d.) coastal Asia, (e.) eastern North Atlantic, and (f.) southern hemisphere

3.4.1 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(Magagna & Uihlein, 2015b; Nachtane et al., 2020c). A rigorous search of literature based on keywords was completed to capture peer-reviewed publications, technical reports, articles, and other studies that assessed the power density for one or more of the considered resource types(Harari et al., 2020). 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.

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 Table 3-2 and Table 3-3, respectively.

Table 3-2 | Systematic Search of Literature Keywords used in a 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.

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*"			

Table 3-3 | Selection Criteria. 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.

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

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 power densities 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 power densities as well as include reports published after 2021.

3.4.2 Conversion to theoretical power density

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 power density units to the standardised 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 power density (Barenblatt, 1987; Gibbings, 2011). 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 power density 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 power density 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 (Shirzadeh et al., 2013). When not supplied in the original reports, a capacity factor of 0.3 was assumed for both offshore wind and ocean currents (Ko et al., 2018; Nie & Li, 2018b). This method ensures that the calculated theoretical power density 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 power density was used.

To convert OTEC results to theoretical power densities, 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 (Giordani et al., 2015). Future work could explore a different capture dimension and the impact this would have on the conversion to a standardised 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 meters was assumed as this was a common value stated in the reports which did (Oko & Obeneme, 2018; VanZwieten et al., 2017b). Likewise, when not provided, a capacity factor of was 0.8 used (Oko & Obeneme, 2018; Sinuhaji, 2015).

Unlike the other resource types, wave energy converters have not yet converged on a single device style (Guo & Ringwood, 2021b; N. Khan et al., 2017). Wave theoretical resource assessments, however, frequently report power densities in kW/m. This is due to the nature of how wave propagate, and this approach quantifies the power density in the direction of the incoming waves (Guillou & Lavidas, 2020). 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 power density into the determined standardised 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 amount of the theoretical resource that could be harnessed. Multiplying this value by the power density found in previous assessments gives a new theoretical power density in the standardised

units. The specific dimensions for common styles of wave energy converters are given in Table 3-4.

Table 3-4 | Common Dimensions for Wave Energy Converters. 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 power density in the units of kW/m to the standardised units in of the ORE database (kW/m^2).

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

There were very few assessments specifically looking at offshore solar or tidal range, and in these assessments, the reported units of power density were already given as theoretical power densities, thus no specific converter assumptions were required (Ahmad et al., 2018; Trapani & Millar, 2013). The resulting database with standardised power densities were visualized using Tableau. The maps included in the study are also published to Tableau Public and available online (see Data availability).

3.4.3 Calculation of power densities from reanalysis data

The power density for each ORE resource was calculated from reanalysis data in the standardised 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 (Baker et al., 2020; Neill et al., 2018b; Waters & Aggidis, 2016). 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 (Waters & Aggidis, 2016).

Forty years (1979-2019) of global monthly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-5) were used to calculate power density for offshore wind, wave, and solar energy calculations. For tidal currents, the Oregon State University TPXO models were used to calculate power densities (Copernicus Climate Change Service, 2021; Egbert & Erofeeva, 2002). 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 power densities of these resources are taken the from published studies (except for wave, which is modified as described in chapter 3.4.2) in the units of kW/m², and are shown in Eq. 1-4.

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

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

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

$$\text{Offshore Solar:} \qquad E_{sl} = E_{sl} \qquad\qquad \text{(Eq. 4)}$$

Where E_{wd}, E_{wv}, E_{tc} and E_{sl} are the calculated values for the new theoretical power density of wind, waves, and tidal currents, respectively. Further ρ_{wd}, and ρ_{tc} are the densities of the air (1.225 kg/m³) and ocean water (1025 kg/m³), g is the acceleration of gravity (9.81 m/s²), 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 power density calculations the methods described in section 2.2 are used here to convert the power density to the standardised 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.

3.4.4 Traditional quantification of wave power density

To present a reference to the standardised wave power density results, a traditional quantification method was also used to determine the wave power denisty. This approach, shown in Eq. 5, provides the results in units of kW/m. This equation is the commonly used approach to calculate wave power density and is take from literature. The constants for gravity and density remain unchanged from how they are used in Eq. 2.

$$E_{wv} = \frac{\rho_{oc}g^2}{64\pi} \, H_s^2 \, T_{wv} \qquad\qquad\qquad\qquad \text{(Eq. 5)}$$

3.4.5 Calculation of tidal current and offshore solar power density

Results of this studies research identified that tidal current and offshore solar consistently have larger power densities 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

power density, the spatial variability of each was considered to inform an approach to calculate the total power density 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 power density at least as large as other ORE resources. The basis for this approach is that if the power densities were large enough to justify studying other ORE resources, it is fair to consider locations with tidal current power densities just as large. These locations are determined by defining a minimum power density threshold. If the power density 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 power densities in the database (excluding previous studies for ocean currents, which would have skewed the threshold upwards), shown in Eq. 6.

$$E_{threshold} = \frac{\sum Er_{wd} + \sum Er_{wv} + \sum Er_{tr} + \sum Er_{sl} + \sum Er_{ot}}{nr_{wd} + nr_{wv} + nr_{tr} + nr_{sl} + nr_{ot}} \qquad \text{(Eq. 6)}$$

Where $E_{threshold}$ is the resulting threshold value, Er_{wd}, Er_{wv}, Er_{tr}, Er_{sl} and Er_{ot} are the power densities 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.

3.4.6 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(Oliveira-Pinto et al., 2020; Roy et al., 2018b). 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 Eq. 7.

$$n_{slX} = n_{wave} - n_X \qquad\qquad\text{(Eq. 7)}$$

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 power density 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 power densities. Eq. 8 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 power density of offshore solar at the matching locations of other ORE resources in the database, and E_{slnew} power density of offshore solar for the feasible upper limit,

$$E_{slnew} = n_{slX} * \left(\frac{\sum E_{slX}}{\sum n_x}\right) \qquad\qquad\text{(Eq. 8)}$$

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.

3.5 Results

3.5.1 Database composition

A total of 661 resource assessment reports were included in the database. These reports resulted in 3,019 individual power densities across the globe. These power densities 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 1,466 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 power density estimates are less than 0.5% of locations studied. To understand if this imbalance in assessments by resource type is reflective of power densities, the global average power density for each resource type is determined. The reports were published between 1978 and 2020. Figure 3-4 shows the number of studies published per year be resource.
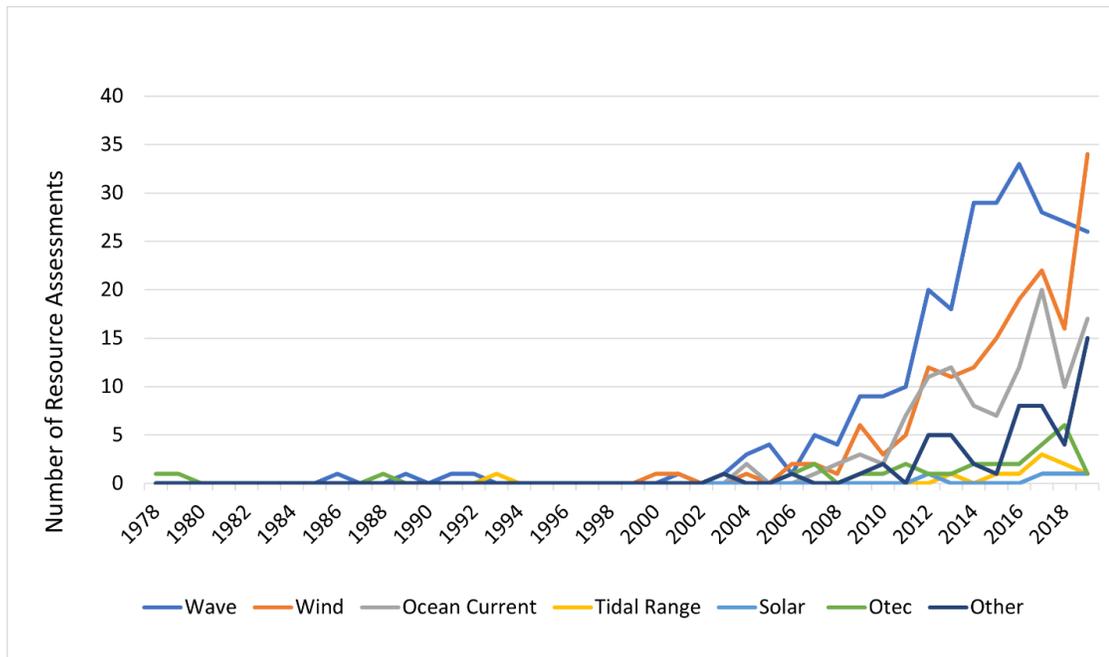
Figure 3-4 | Number of resource assessments per year included in the ORE database by resource type and publication year

3.5.2 ORE average power densities

The resource type with the largest average power density 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 power density of 0.327 kW/m^2. The other resource types have average power densities an order of magnitude smaller: offshore solar has an average power density 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. Figure 3-5 shows the global distribution and the magnitude of these power densities. These results suggest the motivations behind ORE research and development have not been focused on maximising the power density available.
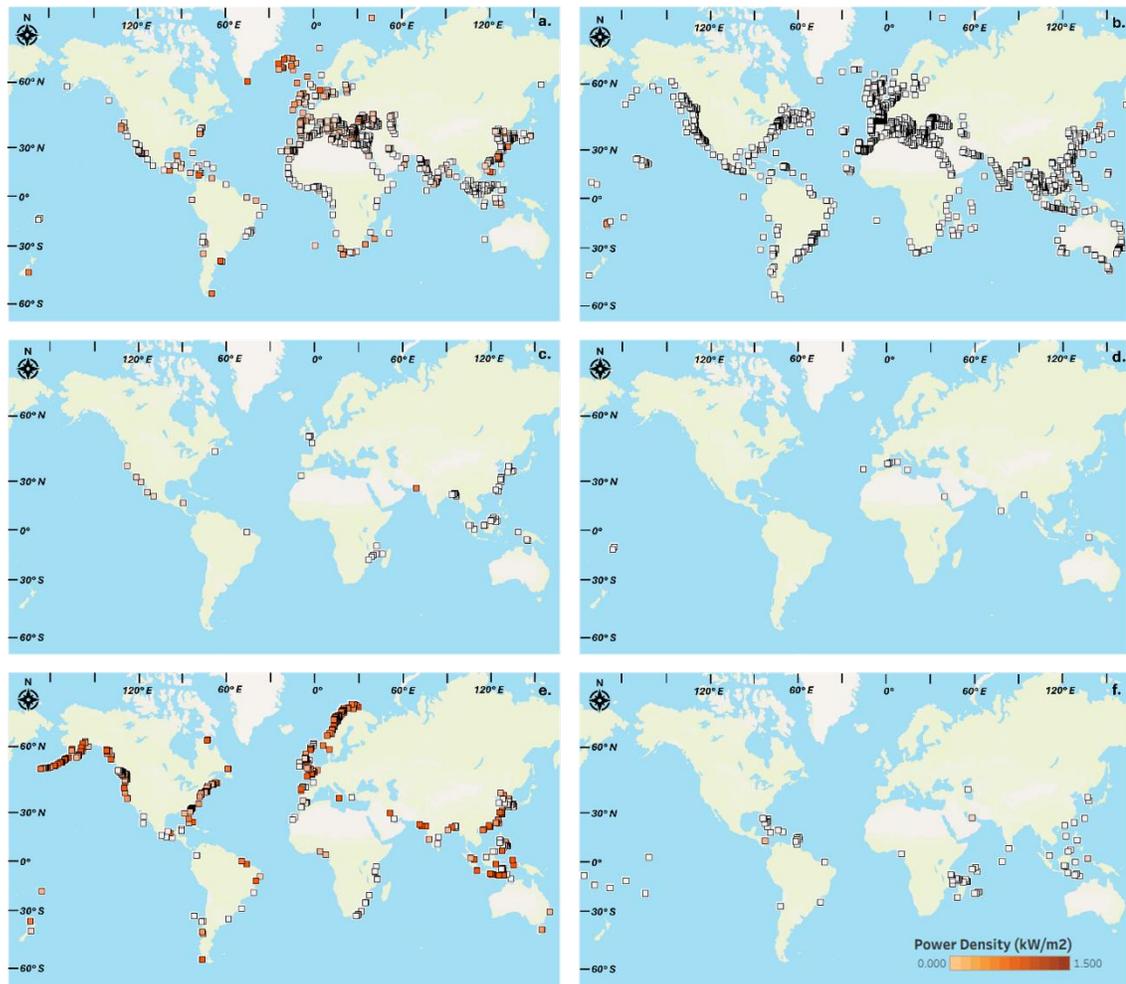
Figure 3-5 | Global map of resource assessment power densities reported in offshore renewable energy resource assessments in standardised units (kW/m^2). The maps are organized by resource type: (a.) wind, (b) wave, (c) tidal range, (d) solar, (e) ocean currents, and (f) OTEC. An interactive version of these maps is available online.

3.5.3 Cross-comparison of power densities

As indicated in Figure 5, there are large spatial gaps between ORE assessments. To overcome this, at each location, the power densities from the database are compared to the power densities of the other ORE resources calculated from reanalysis data. Additionally, the distribution of the sum of all these newly calculated ORE power densities is found. As shown by Figure 3-6, the distribution by resource type highlights

regional variability the total available power density. 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.
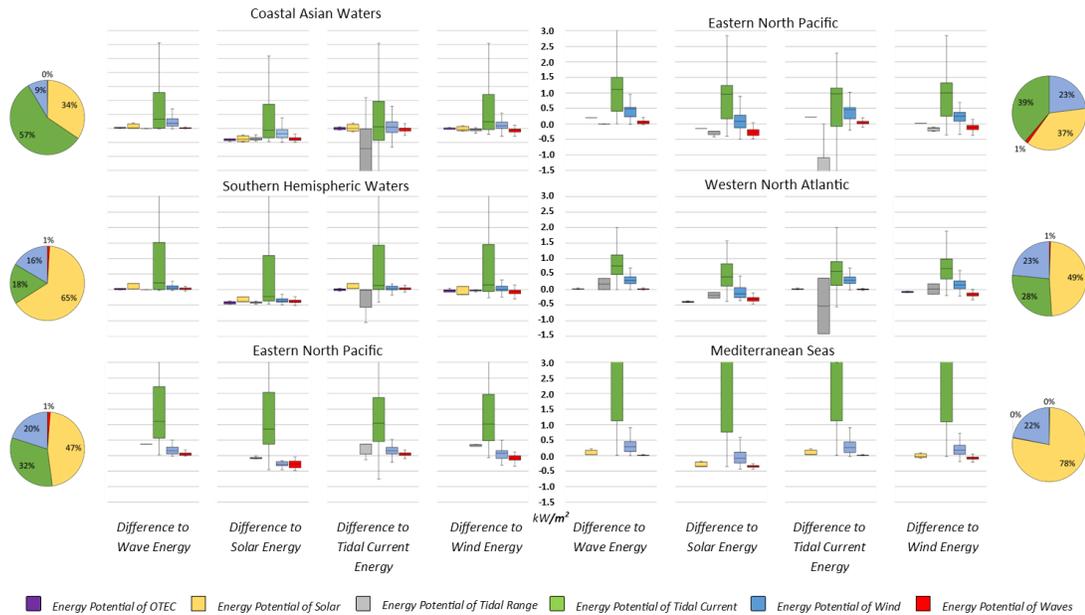
Figure 3-6 | Regional analysis of power densities between ORE resource types. Pie charts showing the percent contribution to a regional total power density calculated using ERA5 hindcast data. Boxplots show the distribution of the difference between the power densities from the database and the calculated power density of other ORE resources. Results are shown by resource type and by regions.

In all regions, wave energy has the smallest contribution to the relative power density 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 power density total in all regions. While the actual power density may vary at the localized level, these results imply that either horizontal currents or offshore solar will most often have the largest power density for any given location.

Also shown in Figure 3-6 are box plots of the distribution of the difference between the power density in the database and calculated power densities 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 power density to offshore wind with an interquartile range of 0.5 kW/m^2 centred over -0.1 kW/m^2. Conversely, in the western North Atlantic region, the maximum difference between the power density 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 power densities than offshore wind in some locations in southern hemispheric waters, but in the western North Atlantic the wave power density is smaller than offshore wind at most locations.

3.5.4 Results using traditional wave powder density as reference

When the analysis was completed using the traditional method for quantifying the wave power density, the cross-comparison between MRE resource notably changes. Looking at the global maps of MRE resources (Figure 3-7), the wave power density results ranged from 0.008 kW/m, to over 400 kW/m, with an average of 17.99 kW/m. These results taken as a one-to-one comparison are on the scale of three orders of magnitudes larger than the standardized wave results in the database. For perspective, results are shown in the same absolute scale as the standardized results (Figure 3-5). At this scale, more than 90% of the wave power density results in the database exceed the 1.5 kW/m max on the scale.
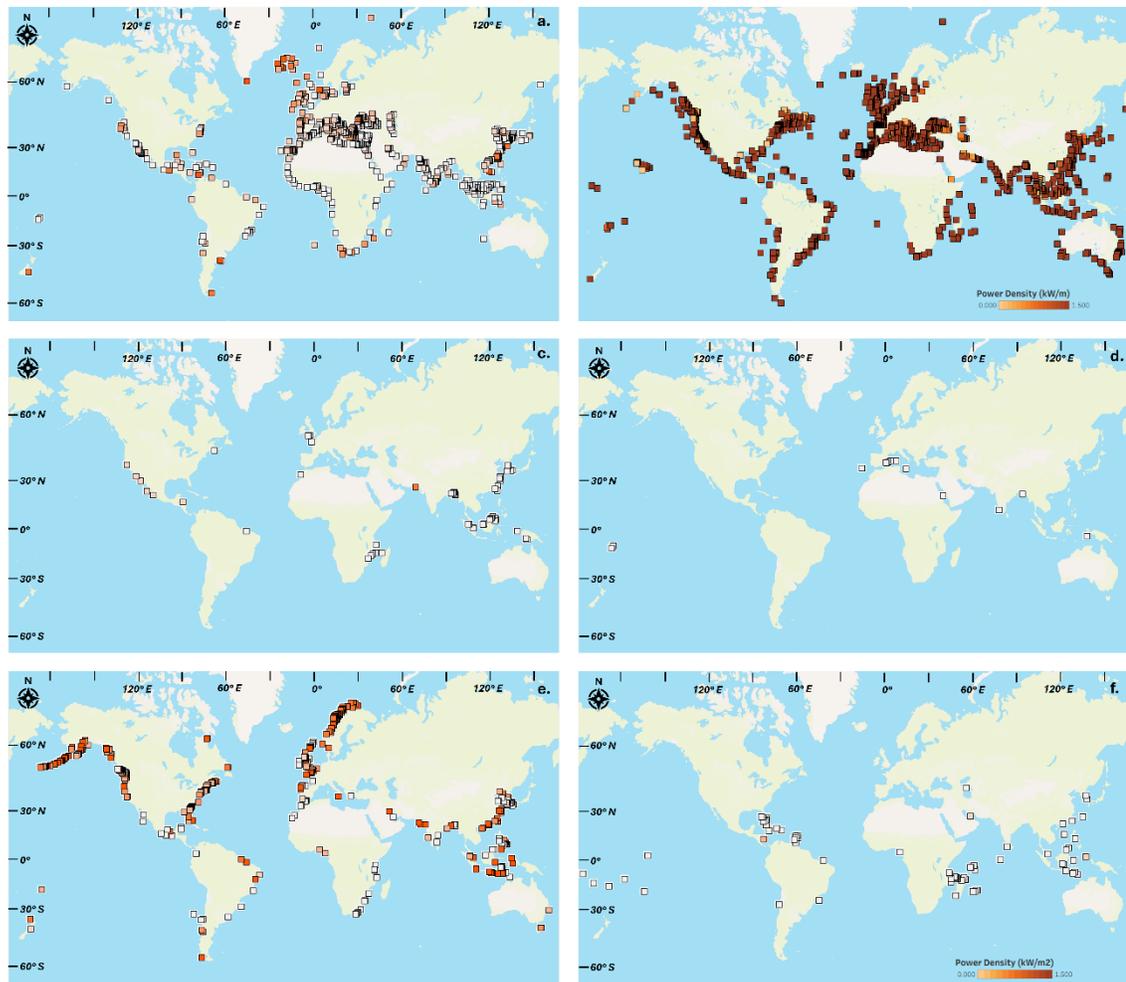
Figure 3-7 | Same as Figure 3-5, except presented with the wave power density results in kW/m.

The increase of multiple orders magnitudes in the wave power density for the traditional wave power density quantification is also highlighted by the cross-resource comparison to the other MER resources. As shown in the pie charts of Figure 3-5, in all regions the wave power density made up a minimum of 37% (Coastal Asian Waters) of the relative power density total, and up to 82% (in the Eastern North Atlantic). Likewise, when comparing the average wave power densities in the database (using the traditional quantification) to the theoretical power density of the other MRE resources calculated at the same locations, the wave power density was almost always larger by a full magnitude in every region. For example, in the Mediterranean Sea, the traditional wave power

density results in the database were 3.52 kW/m larger than the average theoretical solar power density, 3.91 kW/m larger than the average theoretical tidal current powder density, and 3.80 kW/m larger than the average theoretical wind powder density.
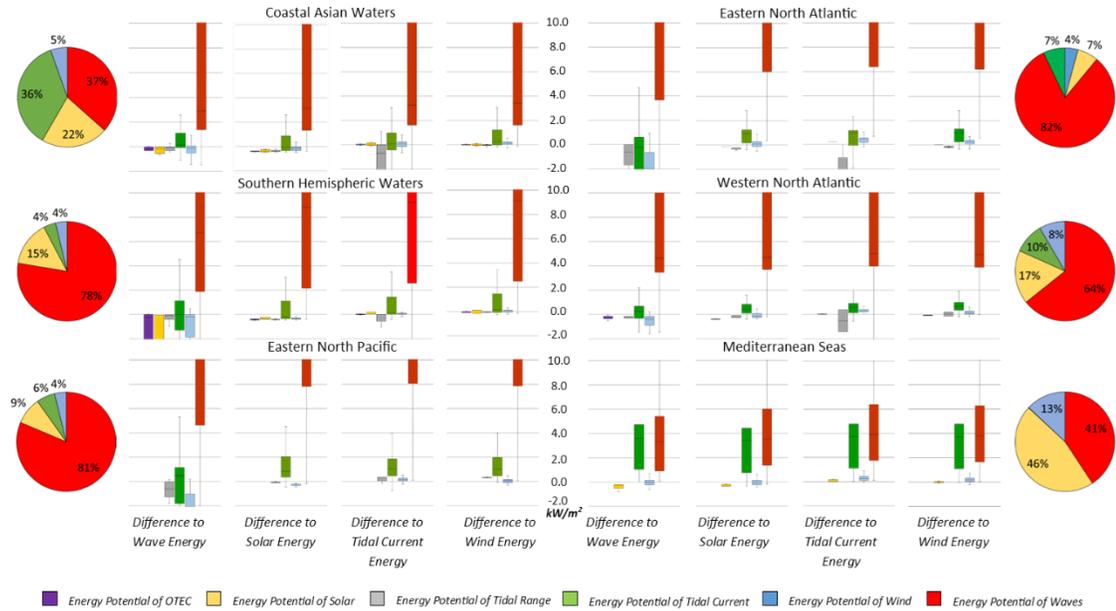
Figure 3-8 | Same as Figure 3-6, except presented with the wave power density results in kW/m.

3.5.5 Identification of possible underutilised resources

Specific results from the cross-comparison of ORE power densities indicate that ocean currents and solar resource may be currently underutilised in research and development. The first finding is the large magnitude of power density 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 power densities are, on average, 1.8 kW/m^2 larger than the power densities of the other ORE resource types at the same locations. For perspective, the average differences in power density 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 power densities that are 4.5 kW/m^2 larger than the power

densities of the other ORE resource types calculated at the same locations. In contrast, tidal current power densities found to be smaller at 78% of locations in the database considering a different ORE resource type. This implies that if a favourable location is considered, horizontal currents have power densities that can be up to ten times larger than other resource types.

The second finding is the consistent nature of the power density for offshore solar. A comparison of the power densities of locations from the database that assessed solar and the power densities of the other ORE resource types is shown in Table 3-5. On average, other ORE resources have smaller power density than solar, with differences between 0.08 to 0.38 kW/m^2. Wind energy in the eastern North Atlantic is the only ORE resource with average power densities larger than the solar power densities from the database.

For the other ORE resources in the database, the difference to solar power density ranges between 0.14 and 0.35 kW/m^2. While the power density 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 power densities smaller than offshore solar. If ocean current results in the databased are not considered, 86% of the remaining locations would have power densities smaller than offshore solar. Together, these results suggest solar power densities will have the least spatial variability and frequently have power densities larger than the other resource types. Of note, when the When the traditional method for quantifying wave power density is considered, solar power densities are smaller in every region by two orders of magnitude (shown in Table 3-6).

Table 3-5 | The average difference in power density between the database results and the calculated power density of solar at the same locations. Results are shown by resource type and region all reported in the standardised units (kW/m^2). Empty cells indicate there are no existing energy estimates for the corresponding resource type and region.

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
Average by Resource Type	-0.32 ± 0.10	-0.08 ± 0.38	1.43 ± 2.3	-0.26 ± 0.08	-0.38 ± 0.10	

Table 3-6 | Same as Table 3-5, except for the traditional quantification of wave power densities is used (kW/m).

Region	Wave	Wind	Horizontal Currents	Tidal Range	OTEC	Average by Region
Coastal Asia	13.50 $\pm$ 34.5	-0.12 $\pm$ 0.29	0.99 $\pm$ 2.5	-0.33 $\pm$ 0.17	-0.39 $\pm$ 0.06	3.16 $\pm$ 0.24
Eastern North Atlantic	25.31 $\pm$ 22.9	0.13 $\pm$ 0.42	1.28 $\pm$ 1.9	-0.28 $\pm$ 0.07	-	8.39 $\pm$ 0.31
Eastern North Pacific	22.86 $\pm$ 16.3	-0.21 $\pm$ 0.24	1.83 $\pm$ 3.2	-0.08 $\pm$ 0.03	-	7.53 $\pm$ 0.15
Mediterranean Sea	5.37 $\pm$ 11.9	-0.05 $\pm$ 0.24	2.66 $\pm$ 1.9	-	-	2.66 $\pm$ 0.22
Southern Hemispheric Waters	18.77 $\pm$ 35.84	-0.20 $\pm$ 0.69	1.06 $\pm$ 2.8	-0.42 $\pm$ 0.02	-0.42 $\pm$ 0.04	4.43 $\pm$ 0.38
Western North Atlantic	9.54 $\pm$ 10.9	-0.01 $\pm$ 0.38	0.76 $\pm$ 1.9	-0.18 $\pm$ 0.09	-0.34 $\pm$ 0.19	2.25 $\pm$ 0.20
Average by Resource Type	15.89 $\pm$ 0.11	-0.08 $\pm$ 0.38	1.43 $\pm$ 2.3	-0.26 $\pm$ 0.08	-0.38 $\pm$ 0.10	

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 underutilised in current research and development of ORE.

3.5.6 Estimation of upper limits for underutilised 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 power density for tidal currents and offshore solar is calculated. The power densities 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). Recognizing

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

3.5.7 Upper limit of tidal current theoretical power density

For ocean currents, the power density from tidal currents is used to determine the upper limit for total theoretical power density. Figure 3-7 shows heat map of the new locations considered highlights the spatial variability globally. Coastlines with favourable physical conditions are shown to have power densities 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 power densities (Charlier, 2003; O'Rourke et al., 2010). 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, Figure 3-5 shows there are numerous locations with considerable tidal power density 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   that can be greater than 3 kW/m^2.
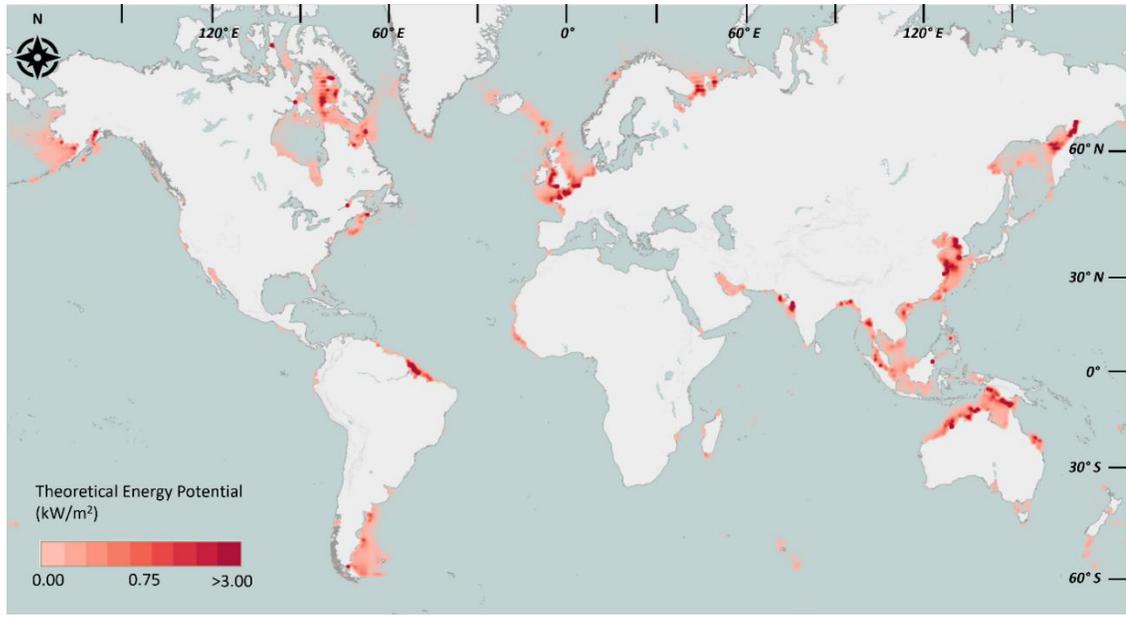
Figure 3-9 | Map quantifying an upper limit for the global power density of tidal currents. Global heat map of the theoretical potential energy for tidal currents in standardised units of kW/m2. Locations with potential energy less than a threshold value of 0.1 kW/m^2 are removed. Previous studies of tidal currents power density are overlayed. An interactive version of this Figure is available online.

Globally, there are over 1,000 new locations considered for tidal currents, with an average power density of 0.88 kW/m^2. To put this in perspective, including all resource types, 3,012 locations have been assessed with an average power density of 0.41 kW/m^2. The sum of the power density from these new locations included for tidal currents is 1,091 kW/m^2. This is almost equivalent to the sum of the ocean current power densities from the database, which gives 1,230 kW/m^2. This implies that the upper limit in power density for tidal currents is nearly double what has been previously studied, a 188% increase in potential energy.

3.5.8 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 power density for solar is based on research towards hybrid ORE systems using solar (N. Lee et al., 2020; López et al., 2020a). Solar is assumed to be co-

located with the locations captured in the database. Figure 3-8 shows how inclusion of co-located solar can increase the total available power density for a given location. For offshore solar co-located with previously assessed wave locations, the power density 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 power density.
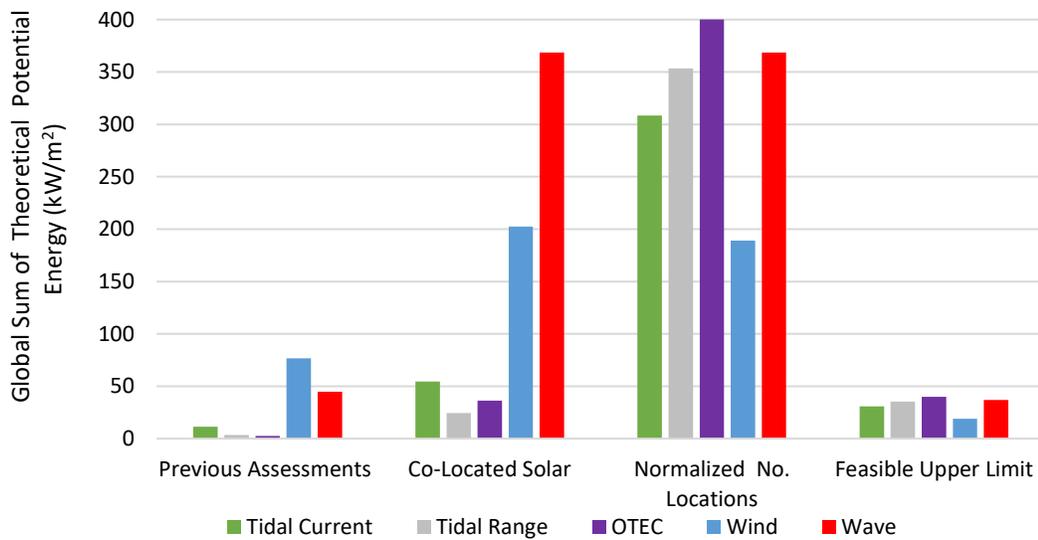
Figure 3-10 | Feasible upper limit to total offshore solar power density. The change in total power density (kW/m^2) by considering the feasible upper limit of solar. The total power density by resource type is shown for just the database results, co-locating the database results with solar, co-located solar with the database normalized by number of studies, and the feasible upper-limit (10%) of the normalized co-located results.

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 power density from offshore solar by 81 kW/m^2. For horizontal currents, there are 246 new locations and an additional 89 kW/m^2 in power density 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 1,628 kW/m^2. This is over a 232% increase from the combined power density 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.

3.6 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, this study shows other different ORE resource types can have larger power densities, such as ocean currents, which are found to have the highest average power density, over 4.7 times larger than any other resource type. This implies motivation behind ORE research and development was not focused maximising 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 (Küfeoğlu, 2022; *UNFCCC Paris Agreement 1–25 (UNFCCC, Paris, 2015).*, n.d.). From a developer's standpoint, another key motivator is could be to strengthen the economic position of renewable energy projects(Balakrishnan et al., 2020; Soeiro & Ferreira Dias, 2020). 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 (Al-Shetwi, 2022; Ogungbemi et al., 2018). Results from this work show that the ORE resources that are the most technologically mature do not

guarantee the available clean energy is optimised. 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 (Kolios et al., 2018; Lacal-Arántegui et al., 2020; Weinzettel et al., 2009). If these systems are built in locations where another ORE resource has higher power densities, 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 (López et al., 2020a; E. Rusu & Venugopal, 2019b). As shown by the study, the co-located solar could increase the power density available from ORE resources by more than 200%. Given these high power densities, 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 power densities sufficient for turbine development, and these locations typically are not suitable for other ORE resources (Tao et al., 2021). Despite this, results of this study show that because of the high power density of the tidal current resource including these locations increase the global total power density 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 power density is approximately equivalent to the electricity demand of 178 million residential homes (*U.S. EPA, Avoided Emissions and GeneRation Tool (AVERT 2019), Accessed June 19, 2021, Http://Www.Epa.Gov/Avert/*, n.d.; R. Wang et al., 2020). If 2% of this power density 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) (R. Wang et al., 2020).

In addition, when considering the results using a traditional wave quantification method, the result showed almost a complete reversal of how the wave resource compares to other MRE resources. This highlights an underlying gap in the field of MRE research and development were comparing the power densities of different MRE resource using non-homogeneous gives inconsistent findings. This gap will become critical as further offshore development occurs, and the available areas for future MRE development becomes scarcer (Pettersen et al., 2023; Pryor & Barthelmie, 2024). Decision makers will need to make strategic choices about which MRE resource are deployed, and by using a standardized set of units to compare power densities, decision makers can confidently assess how to best optimize and accelerate offshore renewables development.

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 power densities were based on hindcast data which can have region bias depending on the resource and variables considered (Hersbach et al., 2020; Wilczak et al., 2024). These factors make it possible for the actual power densities 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, minimise the error in the interpretation of this studies results. Additionally, changes to power density ORE resources are expected as the climate continues to warm (Carvalho et al., 2021; Ibarra-Berastegui et al., 2023).

This work also presented a novel method to standardize the power density of wave resources and OTEC resources. While this approach is internally consistent with the database, it is not the only possible approach which could be used. Future work could use different methodologies to get standardized theoretical power densities for all MER

resources and compare those results to this study. Additionally, future work can also 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 maximise the total ORE power density available.

3.7 Conclusions

This study complied database of power densities from published ORE resource assessments to compare the power densities of offshore wind, wave, solar, ocean currents, OTEC and tidal range in a standardised unit system. The resulting database included over 660 reports resulting in more than 3,000 individual power densities estimates across the globe. Comparing these power densities show that offshore solar, wind, and ocean currents have the largest regional power density totals. Further, of those three, ocean current or offshore solar have the largest total power density total in any region. Despite these higher power densities, less than 20% of the power densities 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 underutilised resource types.

The impact of considering additional tidal current and solar is determined. Results show that a conservative upper limit to the global total power density increases the total power density from the database by more than 185% and 200% respectively the combined total from these two underutilised 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 power densities. 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 maximise clean energy production. Notably, the novel approach used to standardize the wave results gave an overall reduction of the wave power density of one or more orders magnitudes was compared to the traditional quantification approach. The authors do not believe these implies the wave power densities have been overstated, but rather, the current quantification standard is non-commensurate with the power densities of MRE resources. Future work could explore other novel quantification methods to standardize wave power density and compare those results to the MRE database presented in this work.

Overall, a standardized approach to quantifying MRE power density 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 optimised 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.

3.8 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: https://doi.org/10.15129/10ff203b-a19a-4fc8-b0da-e806c038e5a7).

Interactive versions of the maps in Figure 3-5 and Figure 3-7 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.

Chapter 4 A global assessment of the impact of climate change on the marine renewable power density

Preface

This chapter (excluding this preface) has been submitted for review to Energy Policy. The numberings of chapters, figures tables, and some basic abbreviations have been adapted for consistency with the rest of this thesis. In addition, further wave power density results have been added to this chapter since submission for publication. To provide greater context on the magnitude, these results use the common units of kW/m for wave power density.

This chapter addresses the following research questions (presented in Chapter 1.2, Table 1-1):

RQ. 1   *Based on current knowledge, which MRE resources have the highest power density both for different regions and globally?*

RQ.3   *Will climate change increase or decrease the power density for MRE resources and which MRE resources will change the most?*

This chapter builds on the findings from Chapter 2 and uses the standardised, cross-resource, approach to determine how the power density of each MRE resource could change in the future due to climate change. The aim to determine how much the current power density of MRE will change due to climate. Data is used from the climate projections included in the Coupled Model Intercomparison Project (CMIP6) to calculate the range of possible change in power density under a low emissions, 'best-case', scenario and a high emissions 'worst-case' scenario.

4.1 Abstract

The marine renewable energy (MRE) sector has experienced rapid growth in the last decade, driven by the need for clean energy generation to further efforts toward reaching net-zero emissions. New marine technologies harnessing abiotic ocean resources have recently been successfully deployed are poised to be used commercially. The advent of these new MRE technologies presents an opportunity to add additional clean energy into the electricity generation mix and accelerate the transition to net neutral emissions. It is, however, largely unknown how the power density from MRE resources will change in the future due to continued climate change. This study uses data from the Coupled Model Intercomparison Project to determine how much the cross-resource global power density of offshore wind, wave, marine current, marine solar, and ocean thermal energy conversion may change under two future emissions scenarios. Results show that some MRE resources, including offshore wind and OTEC, could have energy increases of up to 0.50 kW/m2. However, the project change in power density is highly sensitive to the emission scenario considered. This study demonstrates how a cross-resource approach that considers both the near-term and long-term power density can inform future clean energy policy and accelerate the clean energy transition.

4.2 Introduction

The 2015 Paris Agreement set an international limit on future climate warming to 2°C above pre-industrial levels, requiring anthropogenic emissions to reach net-zero (United Nations, 2015). Transitioning the energy sector to clean energy resources is fundamental to cutting emissions and meeting the Paris Agreement target. Progress since the signing of the Paris Agreement has been made, with renewable energy making up over 12% of the global energy supply in 2023 (IEA, 2023). Despite this progress, research has shown that accelerating renewable energy development will be required in the next half-decade. For example, the International Energy Agency Net Zero Roadmap 2023 update

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found that the installed capacity of renewable energy will need to triple by 2030 to remain on track to meet emission reduction targets (IEA, 2023).

Marine renewable energy (MRE) is a nascent field with high power density which, if developed, could accelerate the clean energy transition (Taveira-Pinto et al., 2020b). In the United States for example, the total power density of MRE is estimated to be 57% of the electricity use in 2019 (Kilcher, Fogarty, Lawson, et al., 2021). In the United Kingdom, it was found that the total developable tidal and wave power density is equal to approximately half of the country's electricity usage from 2020 (UK Parliament, 2020). Aside from power density, MRE has other benefits over traditional renewable energy resources, such as the ability for load balancing, higher rates of availability, and being more predictable (Bhattacharya et al., 2021a; Taveira-Pinto et al., 2020c). These benefits have driven a recent surge of research and development in MRE. As a result, the installed capacity has doubled in the past decade (Hu et al., 2022; Kabir et al., 2022b). Similarly, nations worldwide have planned MRE developments to contribute to clean energy production by 2030 and 2050.

If the international target of a net-zero energy sector is realised, understanding how renewable energy resources may change due to climate change is essential for effective energy planning and maintaining a reliable electricity supply (Donk et al., 2023). For MRE there is a growing field of research that is assessing the future power density of MRE. This work typically focuses on a single renewable energy resource in a specific region (Badriana & Lee, 2021; De Dominicis et al., 2018). For example, in the United Kingdom and the United States the offshore wind power density is expected to decrease with continued climate change (Carvalho et al., 2021; Martinez & Iglesias, 2022). In the South China Sea, however, the offshore wind power density is expected to increase (S. Zhang & Li, 2021a). In a few cases, the change in power density for multiple MRE resources has been investigated; however, these are predominantly limited to assessing two MRE resources (Costoya et al., 2023; Lira-Loarca et al., 2021). One example found that 10-15%

of locations suitable for offshore wind and wave would see a notable change in future power density (Ibarra-Berastegui et al., 2023).

These studies provide insights into how a single resource may change due to climate change for a given location. However, a comprehensive, global assessment of possible change in power density for MRE due to climate change is lacking in current research. Without this understanding, future research, funding, and development could be directed toward resources that may be sub-optimal for the future power density (Fuss et al., 2012). The possibility of sub-optimal MRE development is not insignificant. For example, offshore solar and marine currents have received the least amount of research in MRE, but the combined upper-limit power density could more than double the combined power density found in existing offshore wind and wave studies (Spalding et al., 2025).

To allow for optimal planning of research and development of MRE, this study aims to assess the range of plausible future changes in global power density across the MRE resources. Here, a cross-resource approach is used considering offshore wind (referred to as wind hereafter), wave, marine currents (including tidal and other near-surface ocean currents), solar, and ocean thermal energy conversion (OTEC). Understanding these results will enable policymakers, researchers, developers and other stakeholders of MRE to confidently invest in the future development of MRE systems and, in turn, accelerate the clean energy transition. This study provides a standardised calculation of the change in power density under 'best-case' and 'worst-case' emissions scenarios for each MRE resource, followed by a cross-resource assessment of climate change sensitivity, a case study demonstrating the applicability of a cross-resource comparison, and a discussion of the impact on near-tern MRE research and development.

4.3 Methods

4.3.1 Study approach

The power density of a renewable resource can be quantified in different ways. The nomenclature for the quantification of these methods has changed over time (Musial et al., 2016a; National Research Council, 2013a; Yavor et al., 2021b). To account for differences in technology readiness and to provide a comprehensive of how the total amount of energy available from MRE may change in the future, this study quantifies energy using the *theoretical* power density (referred to as power density hereafter) (Musial et al., 2016b; National Research Council, 2013b). This measure of energy represents the maximum amount of energy inherent to the renewable resource. Further, to allow for a direct and commensurate comparison across the different MRE resources, the power density is calculated in standardised units of kW/m^2. The formulation of the power density for each MRE resource in these units is discussed below.

4.3.2 Data selection and preparation

To calculate future changes in MRE power density, data was retrieved from The Coupled Model Intercomparison Project (CMIP6). CMIP6 is a state-of-the-art program comprising over fifty global climate models (GCMs) that have supported over 1400 peer-reviewed papers investigating the potential impact of future emissions on the climate (*Publication Hub*, n.d.; *The CMIP6 Landscape*, 2022). Specifically, data from the EC-Earth3 model was used (EC-Earth-Consortium, 2019). EC-Earth3 was chosen as was the only model that provided the required variables to calculate the power density for all the MRE resources (except wave) considered in this work. These variables are shown in Table 4-1. Despite the limitations of using a single model, for this study, a single model approach was deemed appropriate for this study as the aim is to provide the range of possible change, as opposed to specific power densities. Further, it has been shown that multi-model ensembles do not always overcome the known regional biases associated with GCMs (Eyring et al., 2019; Hausfather et al., n.d.; Sippel et al., 2019; Tokarska et al., 2020).

The data used to calculate the theoretical power density of waves (Sea Surface Wave Significant Height and Sea Surface Wave Period) were taken from the Commonwealth Scientific and Industrial Research Organization's (CSIRO) 2024 global wind-wave 21st Century climate projection dataset. This model was chosen as it was also run with data from the EC-Earth3 GCM – the same model providing the rest of the data for this study – thereby minimising additional uncertainty (Meucci et al., 2021).

Table 4-1 shows the variables taken from the EC-Earth 3 GCM: Near-Surface Wind Speed, Sea Surface Wave Significant Height, Sea Surface Wave Period, Sea Water X Velocity, Sea Water Y Velocity, Sea Water Potential Temperature, and Net Downward Shortwave Radiation at Sea Water Surface. For each variable, monthly averages from 2015 to 2100 on a global 100 km x 100 km spatial grid were calculated. The Sea Water Velocity was taken at 5m depth (Iglesias et al., 2012; Pacheco et al., 2014).

Table 4-1 | Variables taken from EC-Earth3. Used to calculate the range of possible change in future power density from MRE resources. Data denoted with an Asterix (*) was taken from the CSIRO global wind-wave 21st century climate projection, run with EC-Earth data

Variable Name	Variable Long Name	MRE Resource	Starting Units	Standardised Energy Units
sfcWind	Near-Surface Wind Speed	Offshore Wind	m/s (meters per second)	kW/m^2
hs_mean*	Sea Surface Wave Significant Height	Wave	m (meters)	kW/m^2
t02*	Sea Surface Wave Period	Wave	s (seconds)	kW/m^2
uo	Sea Water X Velocity	Marine Current	m/s (meters per second)	kW/m^2
vo	Sea Water Y Velocity	Marine Current	m/s (meters per second)	kW/m^2
thetao	Sea Water Potential Temperature	OTEC	m (meters)	kW/m^2
rsntds	Net Downward Shortwave Radiation at Sea Water Surface	Marine Solar	kW/m^2 (kilowatt per square meter)	kW/m^2

The climate projections datasets used include two shared socioeconomic pathways (SSPs): SSP1.2-6 and SSP5.8-5. These future climate scenarios represent different narratives for future socioeconomic, demographic, technological, lifestyle, policy, and

institutional trends and lay out an associated framework used by GCMs for each scenario (O'Neill et al., 2020; Riahi et al., 2017). These two SSPs were chosen to represent the maximum and minimum range (lower and upper bounds) of likely possible futures with SSP1.2-6 the 'best-case scenario' in slowing or stopping future climate change and SSP5.8-5 the 'worst-case scenario' where climate change not only continues but accelerates.

4.3.3 Standardised cross-resource energy calculations

Standardised units of kW/m² were used to compare the power density across each MRE resource. This unit was selected as it is frequently used in wind, solar, and tidal and marine current resource assessments (Artal et al., 2019; de Souza Nascimento et al., 2022b; Oh et al., 2012). However, kW/m² is not regularly used studies which quantify the power density from wave and OTEC resource for MRE development (Barbariol et al., 2013a; VanZwieten et al., 2017c). For wind, tidal and marine currents, and solar the typical and routinely used formula were used to calculate the power density; for wave and OTEC the typical formulas were modified to get results in the standardised units (discussed in subsequent sections) (Barbariol et al., 2013b; de Souza Nascimento et al., 2022c; Neill et al., 2021; VanZwieten et al., 2017d). These equations are shown below in Eq. 4-1 through Eq. 4-5:

Wind: $\quad\quad\quad\quad\quad\quad E_{wd} = \frac{1}{2}\rho_{air}V_{wd}^3 \quad\quad\quad\quad\quad$ (Eq. 4-1)

Wave: $\quad\quad\quad\quad\quad\quad E_{wv} = \frac{\rho_{oc}g^2}{64\pi}H_s^2 T_{wv} \quad\quad\quad\quad$ (Eq. 4-2)

Ocean current: $\quad\quad\quad E_{tmc} = \frac{1}{2}\rho_{oc}V_{tc}^3 \quad\quad\quad\quad\quad$ (Eq. 4-3)

Solar: $\quad\quad\quad\quad\quad\quad E_{sl} = E_{sl} \quad\quad\quad\quad\quad\quad\quad$ (Eq. 4-4)

OTEC: $\quad\quad\quad\quad\quad\quad E_{ot} = 13.89 * \Delta T - 149.71 \quad\quad$ (Eq. 4-5)

Where E is the power density of the respective MRE resource in kW/m². In, Eq. 1 and 3, ρ_{air} and ρ_{oc} are the densities of the air and seawater (1.225 kg/m³ & 1025 kg/m³, respectively). The velocities of the wind and seawater are V_{wd} and V_{tc} (in m/s). In Eq. 4-2, H_s is the significant wave height (in m), T_{wv} is the wave period (in seconds) and g is gravitational acceleration. In Eq. 4-4, E_{sl} is the net downward shortwave radiation at sea water surface. In Eq. 4-5 ΔT is the depth in a water column where a 20°C difference occurs from the sea surface temperature.

4.3.4 Modified wave power density calculation

Recent research quantifying the power density available from a renewable energy perspective of waves is frequently calculated in a single dimension, in units of kW/m (Amiruddin et al., 2019; Portilla et al., 2013a). To convert results to represent an energy flux over a square unit of area, the minimum device spacing of a typical wave energy converter was used as a proxy to transform the typical theoretical power density quantified in one dimension (Spalding et al., 2025). The two dimensions were taken as the ratio between the capture width and the minimum spacing requirement of a reference wave energy converter, representing the usable area of a farm of the reference wave energy converter (Varin, 2023). Because this study aimed to obtain a theoretical power density independent of any technical limitations from specific turbines, the newly two-dimension theoretical power density was divided by the reference turbine's stated capacity factor to account for the technical efficiency of the particular device.

Equation 4-6 shows how this two-dimension theoretical power density was calculated. The standard theoretical power density (Eq. 4-6) was divided by the ratio of capture width to device spacing and the representative wave energy converters capacity factor (Cf).

$$E_{wv} = \left(\frac{\rho_{oc}g^2}{64\pi}H_s^2 T_{wv}\right)\left(\frac{Wc}{(2m_x)(2m_y)}\right)\left(\frac{1}{Cf}\right) \qquad \text{(Eq. 4-6)}$$

Where the capture width and the minimum spacing requirements of the reference wave energy converter in the x and y-axes are Wc, m_x and m_y respectively. The reference wave energy converter used was PowerBouy as it is a commercially proven device and has a smaller footprint compared to other wave energy converters, thus providing a smaller ratio and more conservative power density results (Sarokhan & Stewart, 2017).

4.3.5 Reference wave power density quantification

Given that calculating power density using modified formula (Eq. 4-6) acts as a reduction to the typical results for wave resources, throughout a second set of wave results are presented as a reference which use an approximation of the typical wave power density in units of kW/m. These results are provided to aid the understanding of the magnitude of the change in the power density for wave resources. The reference results were calculated by applying a scalar multiplier to the standardized wave power density results. The scalar value was calculated by taking the ratio of the average standardized power densities from to the average traditional power densities from the database presented in Chapter 3. This scalar value simplified to 342.

4.3.6 Modified OTEC energy calculation

OTEC does not have a single set of units that are commonly used to quantify the power density (Nihous, 2005a; NOAA, 2014; VanZwieten et al., 2017d). To calculate the power density in standardised units, the power available to the OTEC system (Eq. 4-5) in kW was divided by the cross-area of where the water flows through the system, giving an estimate of energy per square area (kW/m^2). For this study, the cross-sectional area of the intake pipe was used as it is the first segment of the entire OTEC system, affecting the production of every subsequent part of the OTEC plant. Based on existing literature on existing and proposed OTEC plants, a diameter of 8 metres was used as the intake pipe size for this study (Chiles, 2009; Cunningham et al., 2010; Nihous, 2005b; NOAA, 2014). The simplified equation for OTEC power density is shown in Equation 4-7:

$$E_{ot} = 0.087 * \Delta T - 0.936 \qquad\qquad \text{(Eq. 4-7)}$$

4.3.7 Calculating future changes in theoretical power density

The change in power density for each MRE resource was quantified by finding the average power density of 10-year periods and determining the anomaly relative to a 10-year reference period. The 10-year period was used to account for the accelerating impacts of climate change, which have recently been shown to be occurring on a decadal time scale (Forster et al., 2024; World Meteorological Organization, 2023). Additionally, by using a 10-year time period, more extreme climate data is preserved, which otherwise may be lost when taking the average over a longer period (Abraham et al., 2011; Y. Wang et al., 2025). This is appropriate as more frequent extreme climate events are expected with continuing climate change (S. Zhou et al., 2023). A 10-year span of 2016-2025 was used for the reference period to provide a useful measure of how the energy available current may change. The approach of using shorter time periods to account for more extreme climate change results is not unprecedented. For example, (Maharjan et al., 2021), assessed the project change in stream flows over decadal periods out to 2100. Likewise, (McCrystall et al., 2021) assess the average increase in Arctic precipitation for 2090 to 2100.

This study considers three representative 10-year averaged future time periods: a near-term period (2026-2035), a mid-century time period (2055-2065), and an end-of-century time period (2090-2099). The periods were chosen as they cover approximately three full lifespans of MRE devices with no overlap (García-Segura et al., 2016; Kolios et al., 2018; Weinzettel et al., 2009). The power density anomaly for each time period (E_{xx_a1}, E_{xx_a2}, E_{xx_a3},) was calculated using Eq. 4-8 as the difference between the power density for the considered time period (E_{Ft}) and the reference period (E_{Rt}).

$$E_{xx\_an} = E_{Ft} - E_{Rt} \qquad\qquad \text{(Eq. 4-8)}$$

4.4 Results

4.4.1 Wind

Under SSP1.2-6 the average near-term power density of offshore wind (E_{wd_a1}) is projected to increase by 0.002 kW/m². In the middle of the century the average wind potential (E_{wd_a2}) is shown to decrease by -0.002 kW/m². At the end of the century, however, average power density (E_{wd_a2}) reverts back to increasing by 0.003 kW/m². Under SSP5.8-5 the sign of the change in offshore wind power density is the same as SSP1.2-6, but the magnitude increases over time. For the near-term, the global average of E_{wd_a1} is 0.001 kW/m², in the middle of the century E_{wd_a2} is -0.003 kW/m², and by the end of the century $E_{wd_{a3}}$ is 0.040 kW/m². This increase of magnitude is likely a result of more frequent extreme wind events which are expected to occur more often with continued climate change (Gastineau & Soden, 2009; Ridder et al., 2022).

While the global average is indicative of how wind energy will change in general, regional variation exists. For example, Figure 4-1 (i) and (ii) show the sign and magnitude of the change in power density in the Mediterranean Sea and the Sea of Japan (East Sea) is different for each time period and SPP considered. However, other regions have constant change, such as central portions of the Gulf Sea, where the power density is found to predominately increase under all three time periods and for both SSP1.2-6 and SSP5.8-5. This global spatial variability is shown by the standard deviation as well. For SSP1.2-6, the standard deviation of E_{wd_a1}, E_{wd_a2}, and E_{wd_a3} is 0.014 kW/m², 0.015 kW/m², and 0.020 kW/m², respectively. For SSP5.8-5, these values become 0.014 kW/m², 0.020 kW/m², and 0.040 kW/m², respectively.

Figure 4-1 | Anomaly in future wind power density (in kW/m^2) compared to the average power density between the years 2016-2025. This figure shows two emissions scenarios (SSP1.2-6 and SSP5.8-5) are considered for three different time periods: The near-term (2026-2035 subplots a. and d.), middle of the century (2056-2065 subplots b. and e.), and end of the century (2090-2099 subplots c. and f.). Blue data points represent a decrease in power density and red datapoint represent an increase. Noted results are labelled and boxed as: i) Mediterranean ii) Sea of Japan, iii) Gulf Sea

Noteworthy differences are also present in wider oceanic regions. For example, the

Pacific Ocean under SSP1.2-6 is found to have diverse changes in power density, with

bands of increasing and decreasing power density that stretch across the entire body of

water. However, under SSP5.8-5, the change in power density Pacific Ocean is less

stratified, in particular at the end of the century, where nearly the entire North pacific

has an increasing power density greater than 0.05 kW/m^2. Similar results are also seen in the Atlantic and Indian Ocean.

4.4.2 Wave

For the three time periods considered under SSP1.2-6 the global average wave power density is found to increase in the near term by 0.004 kW/m^2, and by 0.002 kW/m^2 in the middle of the century. At the end of the century, the global average decreases by -0.002 kW/m^2. Under SSP5.8-5 the global average wave power density is shown to decrease in the near term by -0.008 kW/m^2 and increase at the end of the century by 0.001 kW/m^2. In general, the global distribution of the change in power density was small. The interquartile range (the difference between the 75th and 25th percentile values) of the global change in wave power density under SSP1.2-6 is found to be 0.008 kW/m^2, 0.004 kW/m^2, and 0.011 kW/m^2 for the three time periods considered. Likewise, under SSP5.8-5, the interquartile range is found to be 0.011 kW/m^2, 0.006 kW/m^2, and 0.025 kW/m^2, for the respective time periods.

The small distribution of the change in wave power density is also reflected spatially. Overall, Figure 4-2 reflects this trend, with the majority of coastlines showing no increase or decrease in wave power density. However, there are notable exceptions, such as coastal regions of the United Kingdom, where it is found in the near-term under SSP1.2-6, the wave power density decreases by magnitudes of -0.001 kW/m^2 to -0.020 kW/m^2. However, under SSP5.8-5, the power density was found to increase by magnitudes up to 0.05 kW/m^2.

Also notable is the wider spread decrease in wave power density at the end of the century under SSP5.8-5, with most coastal regions having decreases of -0.005 kW/m^2, to -0.020 kW/m^2. This is especially true for the northern hemisphere at the end of the century, where the only locations with increasing wave power density are coastal portions off of Alaska and Norway have increasing wave. Conversely, the southern

hemisphere is found to have more regions with increasing wave power density, such as southern areas off of Africa, South America, and Australia.
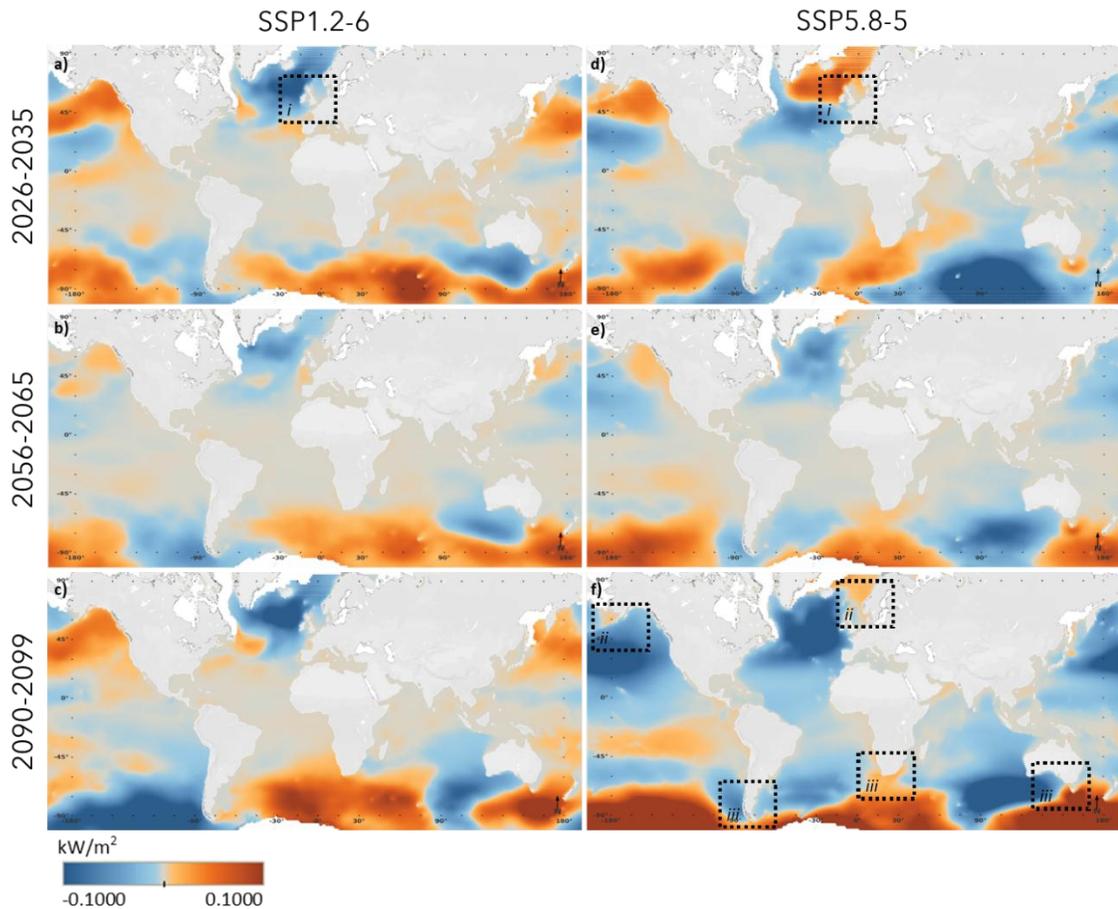
Figure 4-2 | Anomaly in future wave power density (in kW/m^2) compared to the average power density between the years 2016-2025. This Figure shows two emissions scenarios (SSP1.2-6 and SSP5.8-5) are considered for three different time periods: The near-term (2026-2035 subplots a. and d.), middle of the century (2056-2065 subplots b. and e.), and end of the century (2090-2099 subplots c. and f.). Blue data points represent a decrease in power density and red datapoint represent an increase. Noted results are labelled and boxed as: i) United Kingdom ii) Norway, iii) southern portions of Africa, South America, and Australia

4.4.3 Reference Wave results

For reference, the possible change in wave power density was also approximated in

kW/m. These results are a scalar adjustment to the standardized wave power density

results, and as such there is no change in the spatial results. The average change in power density for each emission scenario and time period is summarized in Table 4-2.

Table 4-2 | Global average anomaly in future wave power density using the reference wave results approximated in kW/m.

	Near-Term (kW/m)	Middle of Century (kW/m)	End of Century (kW/m)
SPP 1.2-6	1.4	0.7	-0.7
SPP 5.8-5	-2.7	0.0	0.3

The interquartile range or the global change in wave power density under SSP1.2-6 is found to be 2.7 kW/m, 1.4 kW/m, and 3.8 kW/m for the three time periods considered. Likewise, under SSP5.8-5, the interquartile range is found to be 3.8 kW/m^2, 2.1 kW/m^2, and 8.6 kW/m^2, for the respective time periods.

4.4.4 Marine currents

For the three periods considered under both SSP1.2-6 and SSP8.8-5, there is effectively no change in the global power density for tidal and marine currents energy. The only exception was the near-term under SSP1.2-6, with an average decrease in E_{tmc_a1} of -0.001 kW/m^2. Specific regions, however, did show notable changes in power density. For example, coastal waters off South-east Asia have changes in the power density of +/- 0.15 kW/m^2 depending on the time period and SSP considered. Other regions with similar magnitudes of change can be seen in Figure 4-3 and include off the east coast of North America, the southern tip of South Africa, portions of eastern Australia and the coasts of the Nordic countries in Europe.

Also of note is the variation in power density along the equatorial currents. While most of these equatorial locations are far from any coast, coastal regions near the equator have changes in tidal and marine current power density of +/- 0.10 kW/m^2. Overall, for the locations listed above, there is a trend of power density increasing over time. These increases are also, in most cases, amplified under SSP5.8-5. Exceptions to this include

regions along the northern coast of Brazil, and off the coast the Arabian Peninsula; in these regions the power density is projected to either decrease or not change.
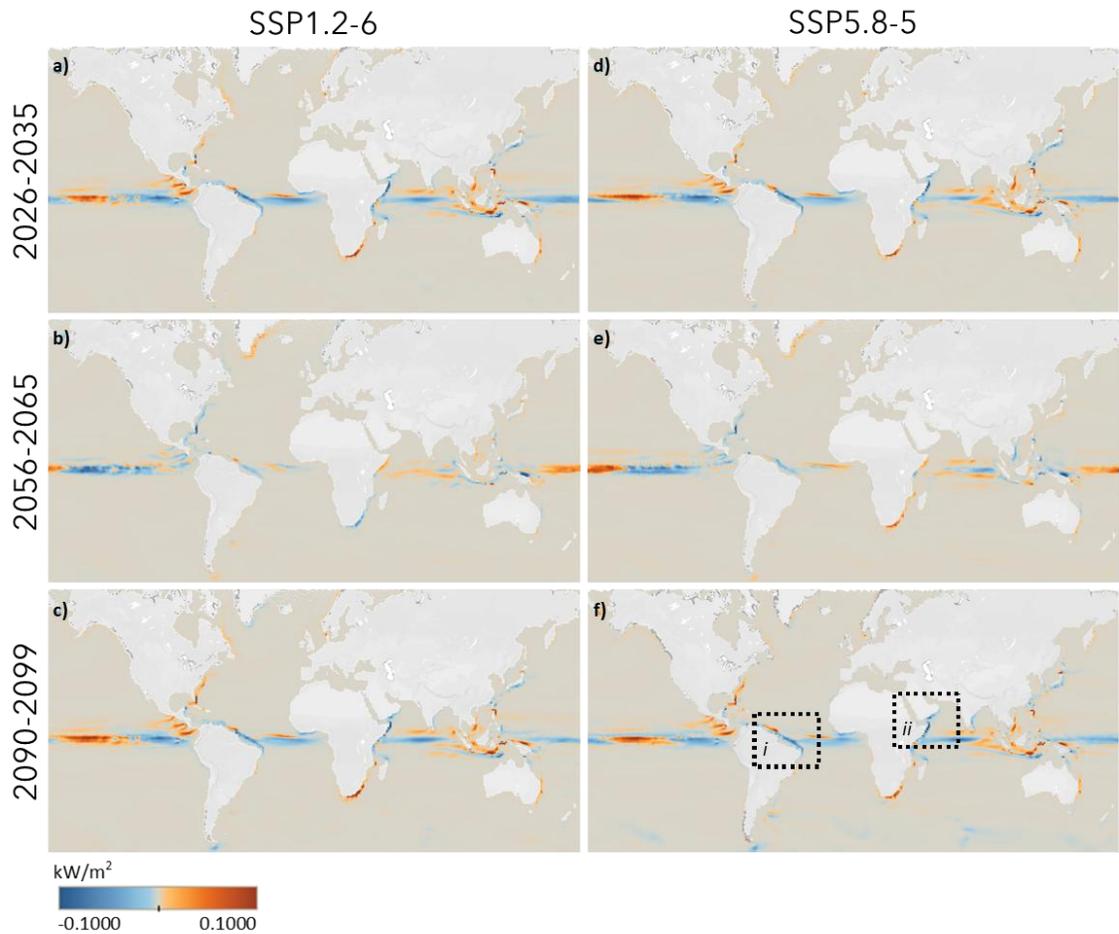
Figure 4-3 | Anomaly in future tidal and marine current power density (in kW/m^2) compared to the average power density between the years 2016-2025. This Figure shows two emissions scenarios (SSP1.2-6 and SSP5.8-5) are considered for three different time periods: The near-term (2026-2035 subplots a. and d.), middle of the century (2056-2065 subplots b. and e.), and end of the century (2090-2099 subplots c. and f.). Blue data points represent a decrease in power density and red datapoint represent an increase. Noted resulted are labelled and boxed as: i) Brazil, ii) Arabian Peninsula

4.4.5 Solar

Under SSP1.2-6 the global average change in solar power density is projected to be less than 0.001 kW/m^2 for all three time periods. Under SSP5.8-5, the power density in the near-term (E_{sl_a1}) is found to decrease by -0.001kW/m^2, in the middle of the century

(E_{sl_a2}) the power density increases by 0.001 kW/m^2, and then decreases by -0.002 kW/m^2 at the end of the century (E_{sl_a3}). While the global average change in solar power density is comparable to the other MRE resources, the regional variations are less. A maximum Inter-Quartile Range of 0.009 kW/m^2 is projected for the end of the century un SSP1.2-6. For reference, the Inter-Quartile Range was 0.004 kW/m^2 or less for all three time periods under SSP1.2-6.

Like the result found for wind, the change in solar power density is projected to have different regional variation for the two emissions scenarios, as seen in Figure 4-4. For example, off the coast of India under SSP1.2-6, the power density in the near-term (E_{sl_a1}) shows an increase of 0.003 kW/m^2, in the middle of the century (E_{sl_a2}) an increase of 0.002 kW/m^2, and at the end of the century (E_{sl_a3}) a decrease of -0.004 kW/m^2. In contrast, for SSP5.8-5, E_{sl_a1} shows an increase of 0.005 kW/m^2, E_{sl_a2} shows a decrease of -0.005 kW/m^2, and E_{sl_a3} shows an increase of 0.007 kW/m^2. Other regional examples (to different degrees of magnitude) which are projected to have a similar pattern of power density changes switching from an increase to decrease include ocean waters off China/Japan, the Mediterranean Sea, and coastal waters off eastern Africa, among others.

Also similar to the trend found for wave power density, at the end of the century under SSP1.2-6, the solar power density is found to predominately decrease, or not change, in the northern hemisphere. Only a select few regions have an power density that increases, such as off the eastern coast of Canada or the waters off Iceland (Figure 4-4i). The southern hemisphere for the same period under high emissions however has a solar power density that either increase or stay the same for all coastal regions, with the exception of a portion of coastal Chile (Figure 4-4ii).
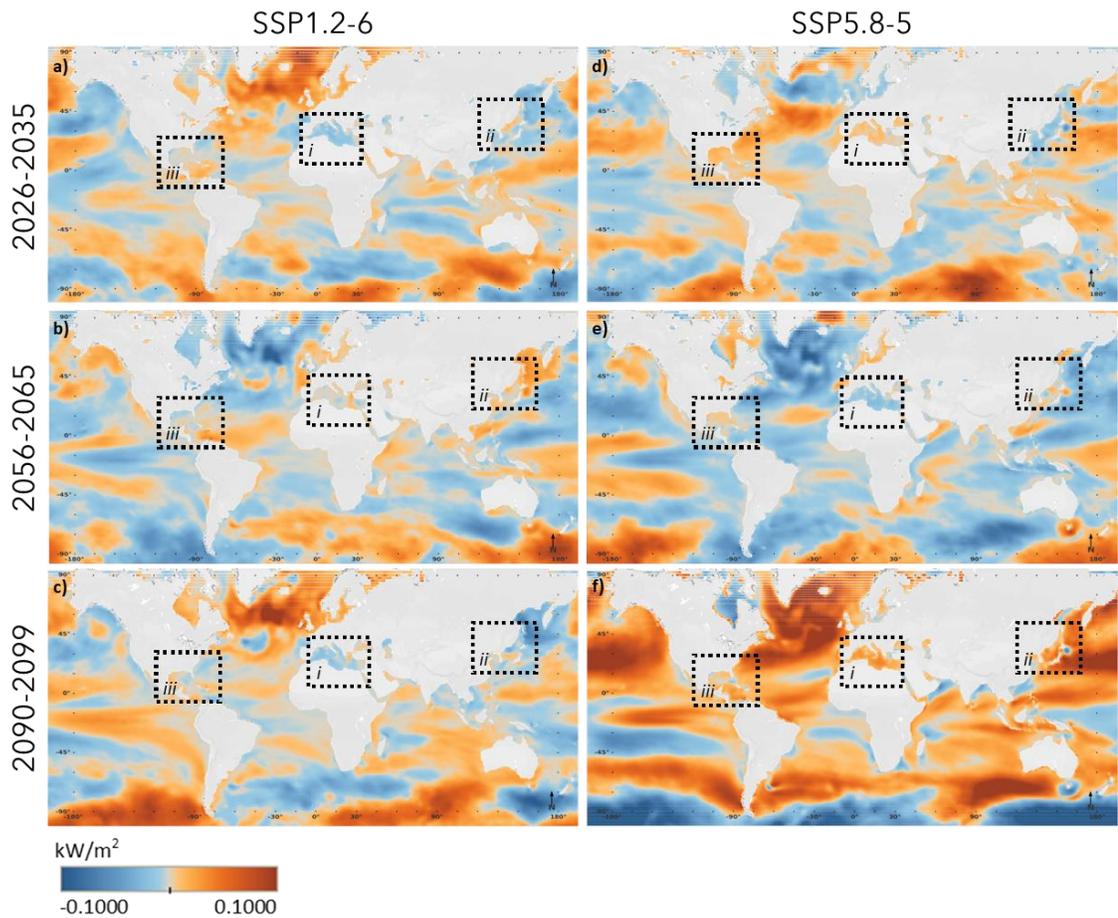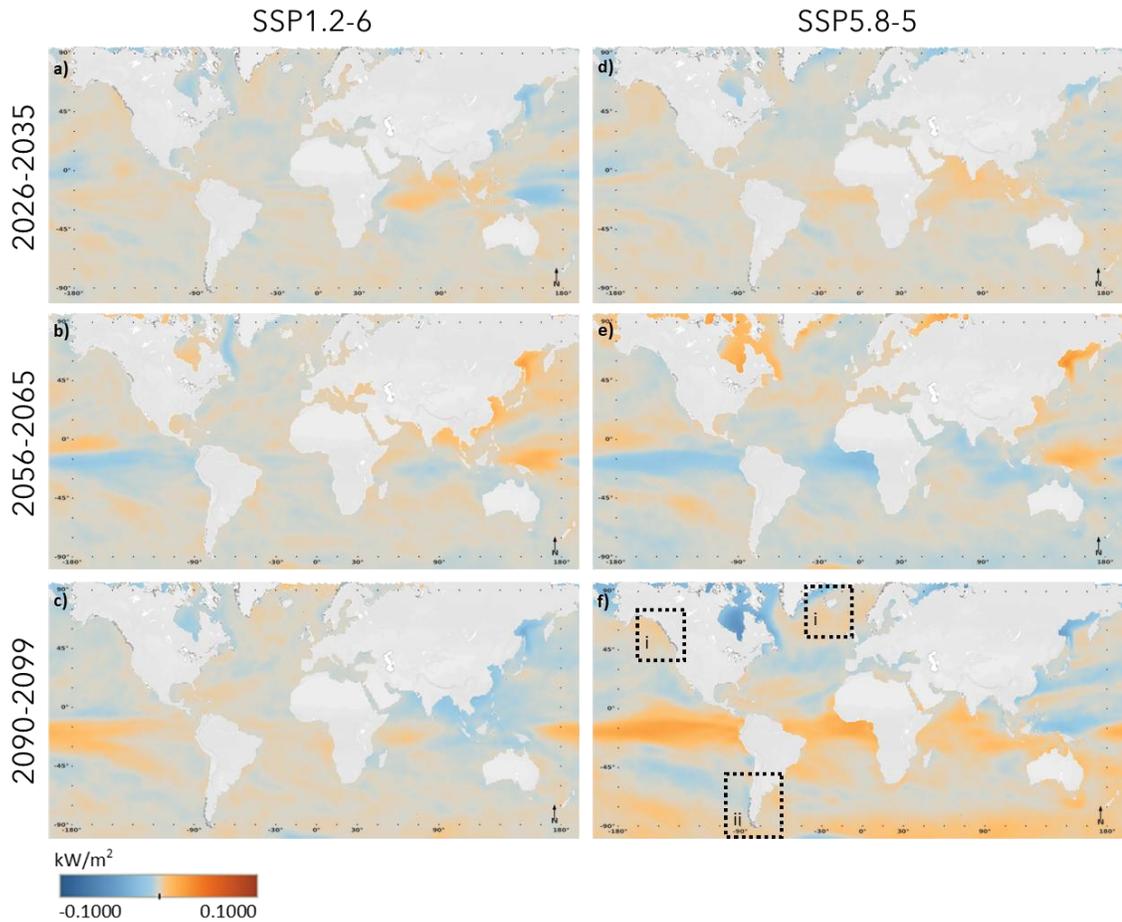
Figure 4-4 | Anomaly in future solar power density (in kW/m^2) compared to the average power density between the years 2016-2025. This Figure shows two emissions scenarios (SSP1.2-6 and SSP5.8-5) are considered for three different time periods: The near-term (2026-2035 subplots a. and d.), middle of the century (2056-2065 subplots b. and e.), and end of the century (2090-2099 subplots c. and f.). Blue data points represent a decrease in power density and red datapoint represent an increase. Noted resulted are labelled and boxed as: i) eastern Canada & Iceland, ii) Chile

4.4.6 OTEC

The power density for OTEC is projected to decrease on average for all time periods under SSP1.2-6. In near-term, E_{ot_a1} is -0.012 kW/m^2, in the middle of the century E_{ot_a2} is -0.005 kW/m^2, and at the end of century E_{ot_a3} is -0.168kW/m^2. Under SSP5.8-5 however, the OTEC global average power density is projected to increase in the later time periods. In the near-term E_{ot_a1} is less than -0.001 kW/m^2, middle of the century E_{ot_a2} is 0.005

kW/m^2, and at the end of the century E_{ot_a3} is 0.003 kW/m^2. Because OTEC is only viable in locations with warmer sea surface temperatures, the regions with a changing OTEC power density are limited to the lower latitudes, as show in Figure 4-5.
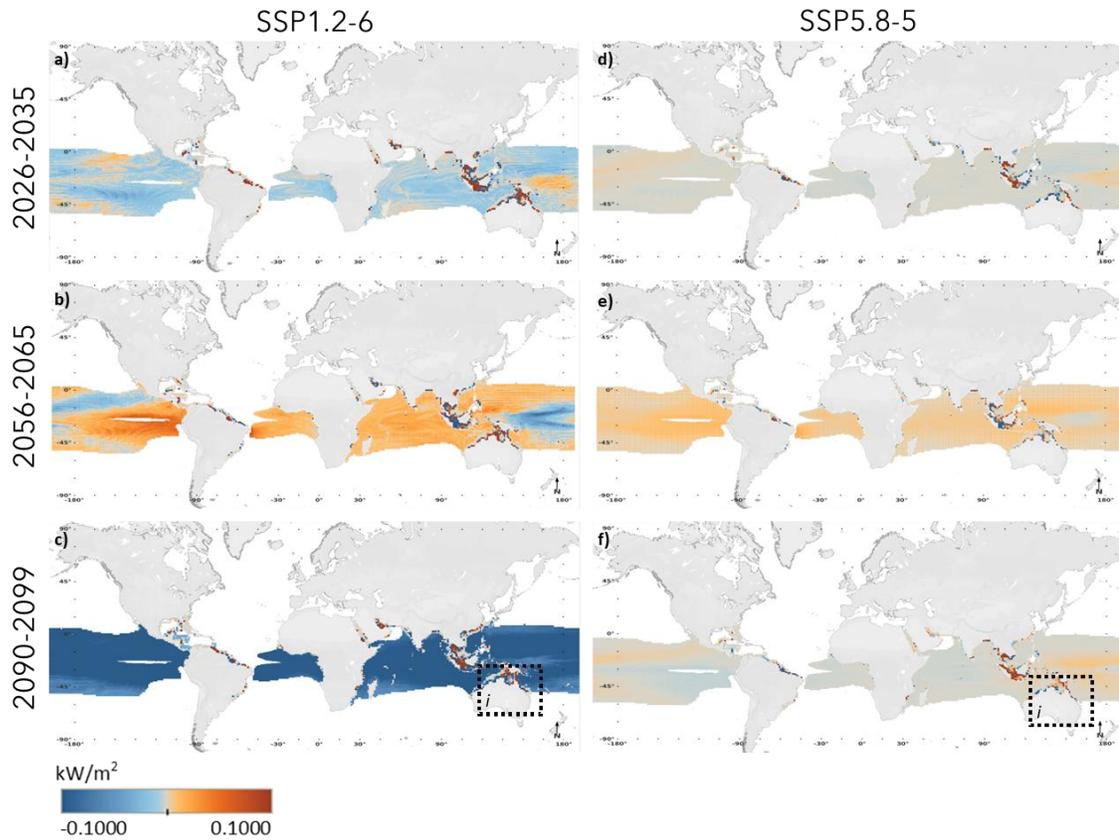
Figure 4-5 | Anomaly in future OTEC power density (in kW/m^2) compared to the average power density between the years 2016-2025. This Figure shows two emissions scenarios (SSP1.2-6 and SSP5.8-5) are considered for three different time periods: The near-term (2026-2035 subplots a. and d.), middle of the century (2056-2065 subplots b. and e.), and end of the century (2090-2099 subplots c. and f.). Blue data points represent a decrease in power density and red datapoint represent an increase.

Further, regional trends emerged over time. For both SSP1.2-6 and SSP5.8-5, the middle of the century is projected to have the most regions with an increasing OTEC power density. But for the near-term and end of the century, more regional variation is shown. Figure 4-5i shows adjacent locations across a 500 km portion off the northern coast of Australia are projected to have the power density at the end of the century (E_{ot_a3})

change by: 0.14 kW/m^2, 0.05 kW/m^2, -0.30 kW/m^2, -0.07 kW/m^2, and 0.50 kW/m^2 under SSP1.2-6. Under SSP5.8-5 however, these same locations are shown to have the power density (E_{ot_a3}) change by less than 0.009 kW/m^2, -0.02 kW/m^2, 0.02 kW/m^2, 0.01 kW/m^2, and 0.07 kW/m^2, respectively. Other regions that exhibited this high degree of spatial variability include ocean waters between Malaysia and Indonesia, ocean waters off the eastern coast of Brazil, and ocean waters adjacent to the Arabian Peninsula.

4.4.7 Cross-resource assessment

Looking at the change in power density for each MRE resource together reveals how climate change may impact the energy mix of MRE. The box plots in Figure 4-6 show that under SSP1.2-6 OTEC is found to have the widest range, and most volatile changes in power density, with 75% of locations having a decrease in power density in the near-term, in the middle of the century the opposite is found, with over 75% of locations having an increase in power density. However, by the end of the century, nearly 100% of all locations are found to have decreases in power density.

The wind and wave resources do have changes in the power density, but they are notably smaller. In the middle of the century, the interquartile range is shown to decrease, with approximately 50% of locations globally have changes in power density less than +/- 0.005 kW/m^2, by the end-of the century changes are found to be in the magnitude of 0.01 kW/m^2. For tidal and marine currents, there is almost no perceptible change in the resources.
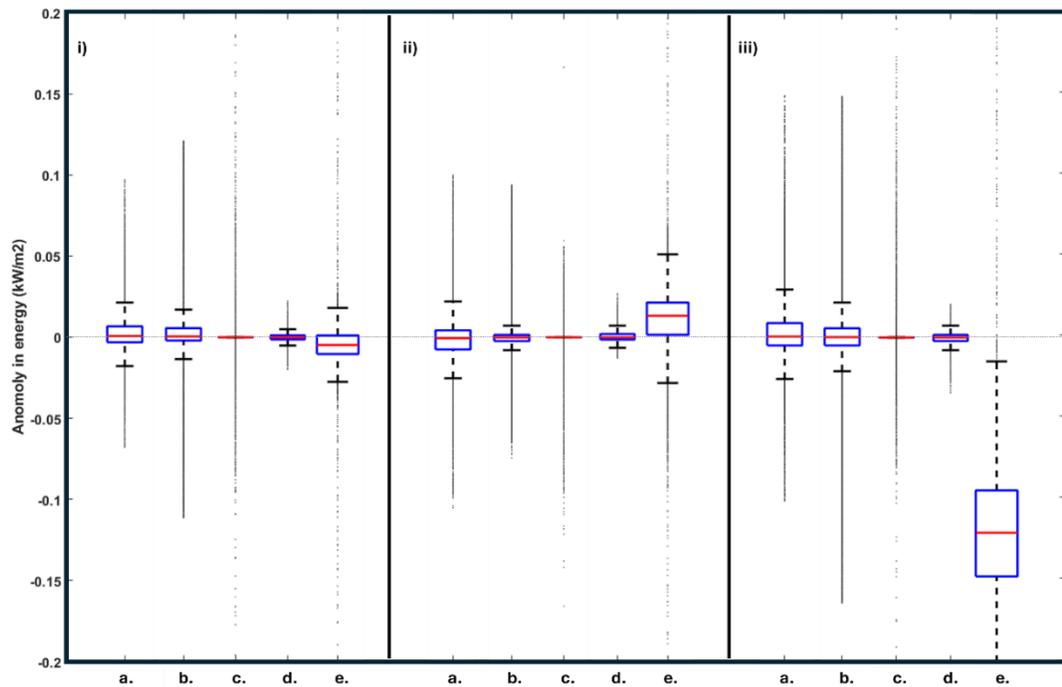
Figure 4-6 | Box plot showing the distribution of global change in power density for MRE for emission scenario SSP1.2-6. This Figure shows three time periods: i) the near-term 2026-2035, ii) the middle of the century 2056-2065, iii) the end of the century 2090-2099. The MRE resources are labelled as a. wind, b. wave, c. tidal &marine currents, d. solar, e. OTEC. The blue box shows the inter-quartile range, and outliers are shown as lines beyond the whiskers.

The cross-resource change in power density under SSP5.8-5 is found to have more variation. For example, in the near-term, the wind and wave change in power density have similar global distributions, with first, second and third quartiles in the magnitude of 0.01 kW/m^2. However, as seen in Figure 4-7, the middle of the century results the inter-quartile range of the distribution of power density change for wind nearly doubles, while for wave this value decreases to near zero. At the end of the century, the range of change in wind power density is shown to increase again, with 50% of locations seeing power density changes between -0.02 kW/m^2 and 0.025 kW/m^2. For wave power density, the distribution also got larger but was skewed towards a decreasing power density, with over 50% of locations seeing a decrease in power density between 0.01 and 0.025 kW/m^2.

OTEC, on the other hand, is not found to have an increase or decrease in the rage of the distribution, however, in the middle of the century, the distribution shifts towards more an increasing power density, with over 50% of locations showing increasing power density. Another noteworthy result evident is the relative stability of the marine currents and solar resources. Across all time periods under SSP5.8-5 and SSP 1.2-6, the resources are found to have minimal change. The only exception to this is solar, which had a slight increase in the interquartile range of the distribution of the change in energy, in an order magnitude of 0.005 kW/m².
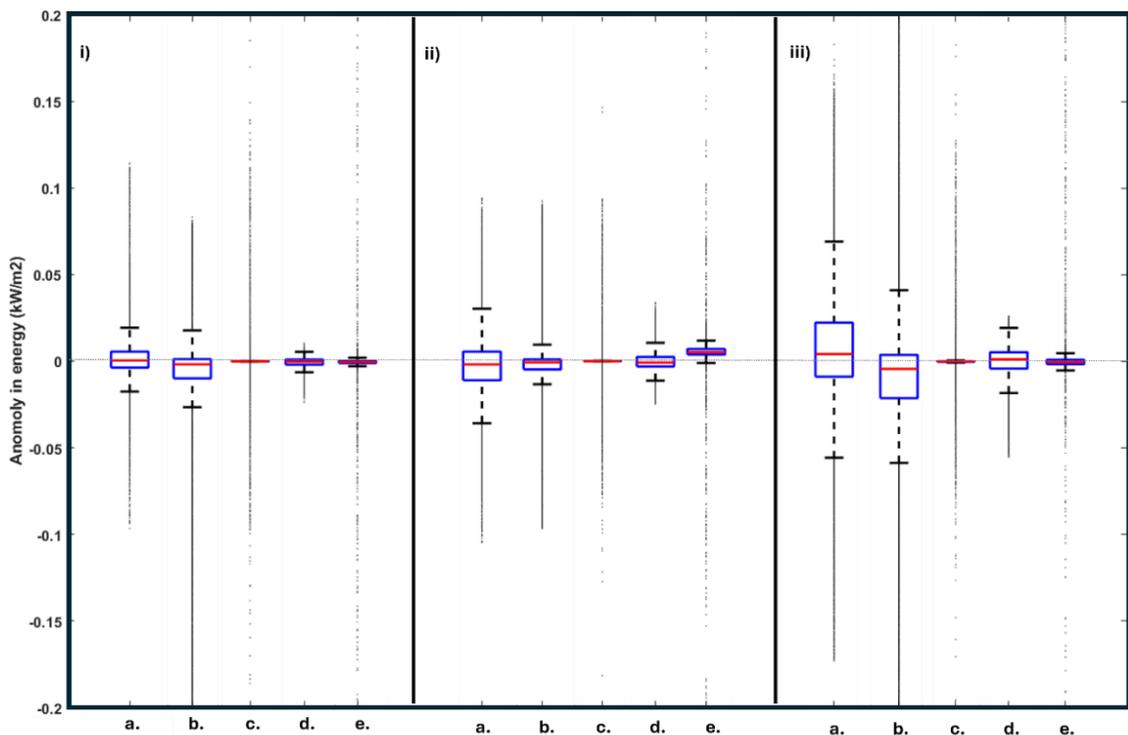
Figure 4-7 | Same as for Figure 6, but for SSP5.8-5

4.4.8 Case study comparing MRE resources future change

To demonstrate the how a standardized cross-resource assessment can inform decision makers, a case study considering solar, wind, and wave resources was completed. The case study assessed the change in future power densities for the three MRE resources

around the United Kingdom (U.K.) coastal waters (Figure 4-8). The case study assumed the low-emissions scenario (SSP1.2-6) in the near-term and provide the results both low- and high-emissions scenarios (SSP 1.2-6 and SSP 5.8-5) in the middle of the century. This configuration simulated how a decision-maker could approach understanding what resource should be developed in these regions.
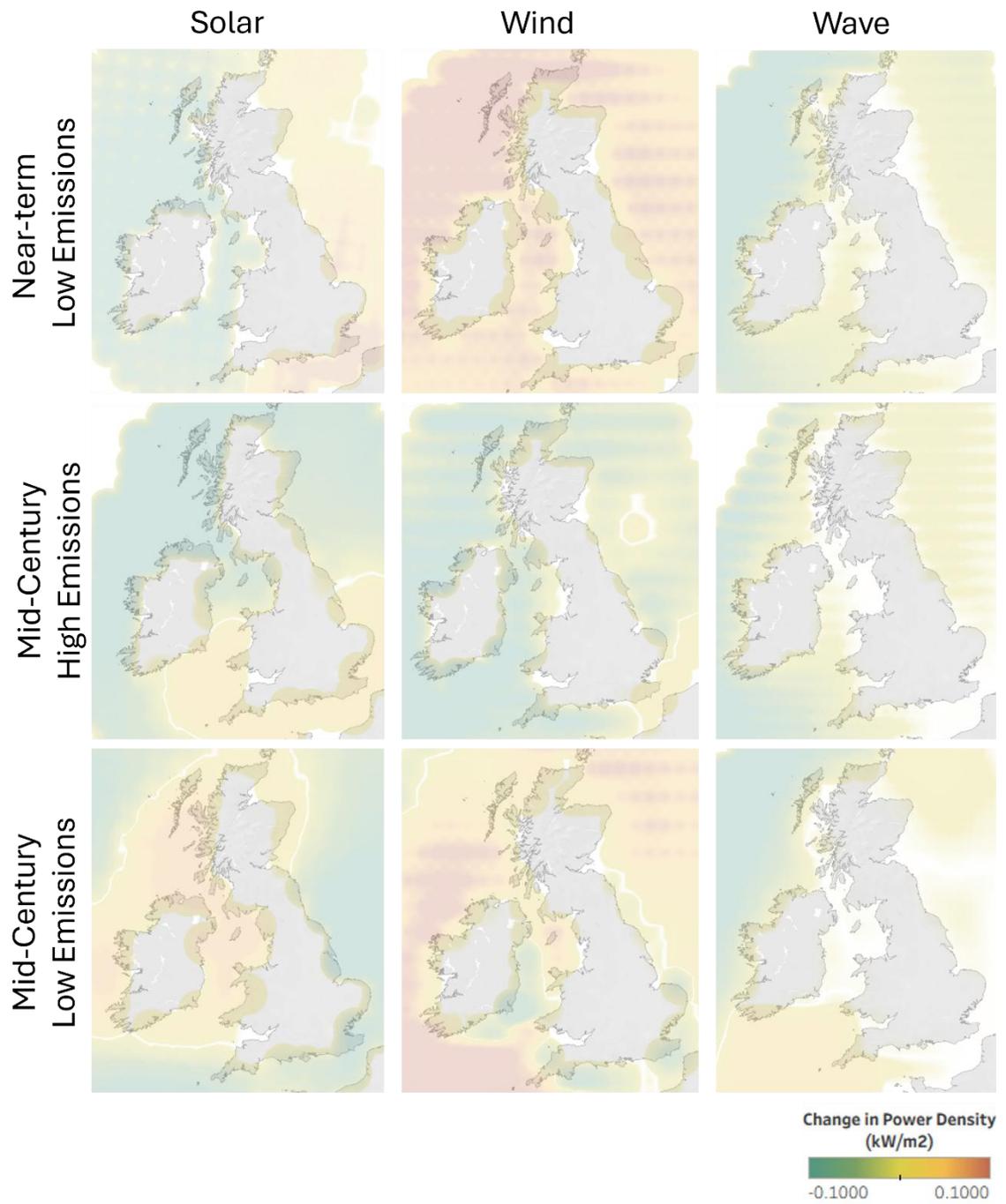
Figure 4-8 | Case Study of the future change in solar, wind, and wave power densities under a low emissions scenario (SSP 1.2-6) and a high emissions scenario (SSP 5.8-5) for the United Kingdom.

In the first case study, the near-term wind power density was found to have an average increase on both the eastern and western shores of the U.K., by 0.024 kW/m^2 and 0.033 kW/m^2, respectively. The average wave power density however is shown to decrease by -0.028 in the eastern UK shores and by -0.044 kW/m^2 in the U.K. western shores. The solar power density did not have a consistent increase or decrease, with the eastern U.K. shores average power density found to decrease by -0.001 kW/m^2 and increase by 0.001 kW/m^2 on the western U.K shores. These results suggest that developing some combination of wind throughout the U.K. waters, and solar along the eastern shores could maximize the amount of available energy.

In the middle of the century, under a low-emissions scenario, wind was found to have the most beneficial change to the power density. The wind power density increased on average by 0.007 kW/m^2 across all the U.K. waters. The average power density of solar and wave resources was shown to have slight decreases, less than -0.001 for solar, and less than -0.005 for wave power densities along the U.K. west coast. Under this scenario, pursuing the development of wind and solar resources in both the near-term and the middle of the century would provide the opportunity to maximize the amount of available energy.

However, if a high-emissions scenario is considered in the middle of the century, these results change, with all three resources found to have power densities that decrease. Wind had the greatest average decrease of -0.015 kW/m^2 in the western U.K. offshore regions and -0.006 kW/m^2 in the eastern U.K. offshore regions. The average wave power density decreased by -0.007 kW/m^2 in the western U.K. waters, and by -0.001 in the eastern U.K. waters. The average solar power density had the smallest decrease of -0.001 across the entire the U.K. offshore region. Under this scenario, development of wave and solar resources may limit any loss of available energy as due to wind resources power densities dropping and could be candidates for repowering former wind farms when they are decommissioned.

4.5 Discussion

While a change in energy ranging between 0.001 kW/m^2 and 0.01 kW/m^2 may seem to be trivial, the impact of this change could be substantial. For context, if only 10 percent of the exclusive economic zone of the United Kingdom were to have a 0.05 kW/m^2 increase in power density, this would represent an approximate total increase 340,000 kW (340 MW) in available energy (Stewart, 2016). That amount of energy is the equivalent of more than the electric demand from 175,000 homes in the UK (EDF, 2023; Fankhauser, 2020; MacKay, 2016). On the regional and global scale this change in power density could have profound impacts.

As shown by the results from this study, the power density of MRE resources is going to change in the future, by how much and where this change is expected to happen however will be dependent on the climate response to the socioeconomic decisions made in the near-term. This is exemplified by the change in power density OTEC found in this work. Intuitively, it would be reasonable to expect the power density for OTEC to increase by a larger margin if climate warming continues and have less change if climate change is mitigated. This expectation is in part met by results of this work, with more than 50% of locations globally found to have an power density increasing under SSP5.8-5. However, under SSP12-6 at the end of the century, the OTEC energy is found to decrease in more than 75% of locations. This average decrease in OTEC power density is a magnitude larger than the change for any other MRE resource under either climate scenario or time period considered. While contrary to what may be expected, this unexpected result is not unprecedented, as recent work has shown under SSP 1.2-6 the warm trend of sea-surface tends may actually be reversed between the middle and the end of the century (Azarian et al., 2023; Iyakaremye et al., 2021). This work did not explore the driving reasons for this decrease in OTEC power density, but mechanisms such as delayed timing of melting polar ice sheets, reduced ocean heat transport, and decreased vertical mixing from wind

and waves could be possible influences (Gao et al., 2023; Mecking & Drijfhout, 2023; Wei et al., 2020).

Understanding and improving predictions of how the power density will change will become a pressing matter for policy makers and MRE developers as the first generation of MRE systems (predominately wind) will reach the end of their lifespan within the next decade (Irawan et al., 2019; Winkler et al., 2022). Assuming that the five MRE resources considered in this work (wind, wave, tidal & marine currents, solar, and OTEC) will all be commercially viable in the next decade, there will be increased competition for viable sites that MRE can be developed on (Bhattacharya et al., 2021b; Liguo et al., 2022). In addition, understanding how each MRE resource will change in the future can enable decision makers and stakeholders to invest in and develop technologies which can optimally harness the total power density available from all the MRE resources.

In practice, using 30-year time scales, as done in this study, decision makers and developers can assess if a different MRE resources will have more energy at locations where existing MRE systems will be decommissioned. Likewise, the same determination can be made for new locations not yet developed. Determining how the optimal mix of MRE resources, with regards to the total power density, may change in the future now can allow stakeholders and decision makers to invest in R&D in the MRE technologies that will allow for future optimal MRE development.

The United Kingdom, for example, is expected to have a near-term average increase in wind power density of 0.04 kW/m^2 under SSP1.2-6, and under SSP5.8-5 have an average decrease of less than -0.009 kW/m^2. In the middle of the century, however, the wind energy is projected to decrease on average by -0.002 kW/m^2 and -0.005 kW/m^2 under SSP1.2-6 and SSP5.8-5, respectively. These results suggest that in the near-term development of offshore wind turbines may be optimal, but, in the middle of the century when these turbines would be decommissioned, switching to a different MRE resource

might be optimal. In this case, tidal and marine currents could be considered as a middle of century option as the total power density in the United Kingdom is estimated to be equal to 11% of the electricity demand, and, as demonstrated in this work, the absolute change power density is projected to be less than +/-0.001 kW/m^2 for both SSP1.2-6 and SSP5.8-5 (Coles et al., 2021).

This type of development could also lend itself to a co-generation electric system, where multiple MRE technologies are deployed in the same region. This could have added benefits in addition to optimising the total MRE resource potential such as load balancing, operations, and maintenance flexibility, and improving grid resilience, and lowering operations and maintenance costs (Aktaş & Kırçiçek, 2020; Bhattacharya et al., 2021c; Clemente et al., 2021). To better enable these benefits, future work can downscale the approach used in this study for specific regions determine future, site-specific changes in power density in MRE resources. For near-term planning, future work could also consider other energy quantification methods, such using the technical or economic power density.

As highlighted by the U.K. case study, how the MRE resources change will depend on the amount of future emissions. This presents a challenge for planning a resilient and dependable energy system. By using a cross-resource approach, decision makers can identify which MRE resources can maximize the available power in different locations. This also provides the ability to plan to switch to another MRE resource at the end of a developed MRE system's lifespan and increase the available power at that site (Boopathi et al., 2021). For example, given that wind could have the most available energy in near-term, decision makers could pursue maximizing the amount of offshore wind development right away as that technology is commercially mature. However, knowing that solar and wave resources are likely to have less decreases in power density in the middle of the century under a higher-emissions scenario, the decision maker could also direct funding towards continuing research to commercialize solar and wave energy

conversion technologies, with the intent on developing these systems when the wind farms reach the end of their useful life. This proactive approach can optimize the amount of clean energy is produced from MRE develop and improve the electric systems resiliency to continued climate change (Khurshid et al., 2024).

4.6 Conclusions

This work has identified – on a global scale – how five MRE resources (wind, wave, tidal and marine currents, solar, and OTEC) may change given two potential future climate scenarios. Compared to the other MRE resources, wind and OTEC were shown to have the greatest change in power density globally as well as the largest regional variation. For wind, increases of up to 0.040 kW/m^2 were projected at the end of the century under SSP5.8-5 for portions of the North Atlantic and North Pacific. For OTEC, the largest power density increase projected was 0.50 kW/m^2 in the North Pacific occurring in the middle of the century under SSP1.2-6. Also evident is the general decrease in power density across multiple MRE resources in the middle of the century. Wind and marine current have a global average power density that are projected to decrease under both SSP1.2-6 and SSP5.8-5. Solar and marine current were shown to have smallest amount of change in power density globally; however, in some regions the power density changed by up to +/- 0.02 kW/m^2. For wave and solar resources at the end of the 21st Century under SSP-5.8-5, a notable change becomes apparent with increasing power density in the southern hemisphere but decreasing in the northern hemisphere.

Given the magnitude of these projected changes, a cross-resource perspective that assess the power density of different MRE resources commensurately can enable a wide-range of stakeholders including researchers, developers, investors and policymakers to accelerate the adoption of MRE systems that are optimised to the available resource. This type of renewable energy development can, in turn, help accelerate transitioning the electricity generation sector to net zero and contribute to the international emission goals set out by the Paris Agreement.

Chapter 5 Minimising uncertainty in marine renewable energy assessments

Preface

This chapter has been prepared for submission to a journal. As such, it is structured as a paper with an abstract, introduction, methods, results and discussion. This chapter addresses the following research question (presented in Chapter 1.2, Table 1-1):

RQ.4   How can uncertainty in assessing and interpreting the power density of MRE be minimised?

This chapter aims to determine the amount of uncertainty that results in the variables used to quantify power density of MRE. It expands the MRE power density database provided in Chapter 1 to include the methodologies used in previous resource assessments and presents a framework which stakeholders can use to determine the range which a reported power density may deviate from the given value.

5.1 Abstract

To avoid consequences of climate change, a rapid transition to clean energy in the near term is paramount, and marine renewable energy is a promising field which is being pursued by nations globally to accelerate development of renewable energy. A growing subset of research supporting the development of marine renewable energy are coined resource assessments. These studies quantify the power density of a marine renewable resource and provides critical information needed in planning renewable energy development. However, the influence of uncertainty from different data types, spatial resolutions, temporal resolutions of the data used to administer these assessments, and the impact this has on the calculated power density, is largely unknown. This study builds on a database of marine renewable energy resource assessments to quantify the uncertainty associated with the different variables used in prior studies. A framework is also developed that stakeholders can use to determine the likely range a given power density may deviate from the reported value. Results of this work demonstrate how to account for uncertainty in existing and future resource assessments, which can better inform decision makers and in turn help accelerate development of marine renewable energy.

5.2 Introduction

In the last two decades there has been rapid growth in renewable energy, but there is an urgent need for further development to avoid irreversible and potentially catastrophic consequences of climate change (Rogelj et al., 2015; Y. Wang et al., 2023). Globally the installed capacity of renewable energy systems has increased by 50% between 2015 and 2020, and by the end of 2021, 290 gigawatts of renewables had been installed which corresponded to 12.8% of that year's global electricity production (Ashraf et al., 2024; Yolcan, 2023). However, to achieve the international emissions reduction target of net-

zero CO_2 anthropogenic emissions by 2050 set by the Intergovernmental Panel on Climate Change (IPCC), renewable energy will need to comprise 66% of the total electric demand by 2030 (International Energy Agency, 2021; (IPCC), 2022). Marine Renewable Energy (MRE) is a nascent field with high power density and is gaining growing interest as an option to accelerate renewable energy production (Collombet & Cagney, 2022). For example, in 2023 the European Commission announced targets of 61 GW of MRE by 2030 (60 GW of which are coming from offshore wind), and an additional 40 GW of MRE (all non-wind) developed by 2050 (European Commission, 2023).

Underpinning this interest is an increasingly robust field of research assessing the amount of energy available from MRE, typically called resource assessments. The taxonomy of resource assessments has varied over time with changing nomenclature used to define how energy is quantified. For example, a U.S. Department of Energy report broke resource assessments into four categories: *Resource Potential*, *Technical Potential*, *Economic Potential*, and *Market Potential* (Brooks, 2022). However, a separate U.S. National Renewable Energy Laboratory study used three categories: *Theoretical Resource*, *Technical Resource*, and *Practical Resource* (Kilcher, Fogarty, & Lawson, 2021b).

In addition to inconsistent naming conventions, a multitude of different variables are used in MRE resource assessments. This includes options in the data type (e.g., in situ or model output), spatial resolution (e.g., 100 km^2 or 50 acres (0.2 km^2)), temporal resolution (e.g. 12 hours or daily), and length of data (e.g. 6 months or 2 years) used in resource assessments. There are further variations in how results are presented, both within a single MRE resource, and especially across different MRE resources (Cox et al., 2018; International Renewable Energy Agency, 2013). These differences make it difficult to compare the results between resource assessments and draw meaningful conclusions when comparing the power density of MRE resources (Widén et al., 2015b). This challenge is highlighted in recent research which showed there are differences of multiple magnitudes between the results published in different resource assessments for

the same MRE resource (Liu et al., 2021). These differences in results could be due to the influence of the different variables used in the quantification of power density. However, the extent of this possible impact remains unknown, and is largely unaccounted for in most resource assessments.

Research in MRE addressing this gap typically focus on model comparisons applicable to a single resource (Peters et al., 2020; Robertson et al., 2016a). Of the few studies that do consider multiple MRE resources, those reviews typically assess the variables in units typical to each individual resource (Widén et al., 2015c). This leaves open a question on how to best interpret the influence of different variables options on the results of MRE resource assessments.

This research aims to examine how the different variables used in MRE resource assessments influence reported power density across six MRE resources: wind, wave, marine current (including both tidal and other near surface ocean currents), tidal range, ocean thermal energy conversion (OTEC), and solar. By analysing a comprehensive dataset of over 800 studies, this work evaluates the impact of different variable selections and methodological approaches on energy estimates in comparison to the existing literature.

To further the application of this research, this study develops a framework to account for uncertainty in variables used in MRE resource assessments. Two case studies are presented that apply the developed framework demonstrating how stakeholders can utilize it to confidently interpret reported power densities reported in resource assessments. Overall, the findings of this work provide insights into the variability introduced by different assessment techniques, helping researchers and policymakers critically evaluate current and future MRE resource studies.

5.3 Methods

To address the primary aim of this research, the MRE power density database developed by (Spalding et al., 2025) was expanded to include the different variables used in MRE resource assessments. A quantitative empirical analysis was implemented in this analysis to determine deviations in power densities that used different variable options (Nowell et al., 2022; Onwuegbuzie & Combs, 2010; Ryś et al., 2009). The six MRE resources considered (wind, wave, marine current, tidal range, OTEC, and solar) were chosen as the conversion technologies for these resources are currently, or expected to be soon, mature (L. Wang et al., 2023; J. Zhang, 2024). To allow for a commensurate evaluation across different MRE resource types, this study evaluated four variable options used in MRE resources assessments. The first category variable considered is data type and was grouped into four options, detailed below:

- Remote sensed – includes all data measured using remote sensing technology (e.g. satellite altimetry or LiDAR) (Avtar et al., 2019; McCann, 2019)
- Hindcasts – includes all data generated using retrospective models (typically hindcast or reanalysis data sets) (Baatz et al., 2021; Sharmar et al., 2021)
- In Situ – all data measured with instruments at specific locations (e.g. weather stations or buoys)
- Forecast – includes all data generated with forward looking models (e.g. SWAN wave model) (Lavidas & Venugopal, 2018; Sweeney et al., 2020; Ying et al., 2023)

The second variable evaluated was spatial resolution, which were the options used for the spacing represented as a square grid between data points. Examples of different spatial resolution used in MRE resource assessments include kilometres-squared, hectares, and square-miles. The third variable considered was temporal resolution options used, which is the sampling frequency, and can range from hours to months to years. The last variable evaluated was the length of data considered in the study, which

was the different options used for the total length of time between the start and end of the data used.

These four variables were selected for this evaluation because they are frequently included in MRE resource assessments and are often the limiting factors in a study's robustness (Gaetani et al., 2015; Gils et al., 2019). The rest of this section describes the analytic approach of this research to quantify the influence of uncertainty in these variables.

5.3.1 Database of MRE power density and variables

This study expands upon the MRE resource assessment database created by (Spalding et al., 2025). The database includes standardised power densities reported in over 800 MRE resource assessments. The variables options used in the MRE resource assessments included in the MRE power density database were extracted for post-processing. All spatial resolutions were converted to units of kilometres (km), all temporal resolutions were converted to hours (h), and length of data converted to years (y).

For ease of interpretation, the different options of spatial resolutions, temporal resolutions, and length of data used in the resource assessments were grouped into ranges, with the lower bound being inclusive and the upper bound exclusive. The distributions were selected to level the number of datapoints in each range, while still providing useful bounds. For example, all spatial resolutions less than 3 km^2 and greater than or equal 1km^2 are grouped together. In some cases, a specific location, or specific point in time, was used in the original resource assessments. In these cases, the spatial or temporal resolutions were recorded as a zero for categorization purposes only. For studies that did not report on a specific variable, a value of "N/A" (not available) was entered in the MRE power density database.

5.3.2 Evaluation of the influence of variables

To assess the influence of non-commensurate variables, this study built off approaches used in medical research and behavioural science which often are underpinned with nonhomogeneous data. This included using a non-statistical comparative analysis, allowing for substantive inferences to be made based on how individual results in the MRE power density database compared to the database as a whole (Onwuegbuzie & Combs, 2010; Ramlo, 2024). In practice this entailed taking each power density estimates from the database, categorized by the corresponding variables used in that specific resource assessment, and finding the difference to baseline determined for each MRE resource. The ranking criteria methodology commonly used in multi-decision criteria analysis (Stanujkic et al., 2023), was adapted to determine a baseline weighted mean based on the number of variables reported in each included MRE resource assessment (Chittaranjan, 2015; Hozo et al., 2005; S. Khan, 2020). For each power density included in the MRE power density database, a weighted score is applied to associated power density based on if the study reported the following methods: data type, data source, model selection or analytic approach used, spatial resolution, temporal resolution, length of data, data start-date, and data end-date.

As shown in equations 5-1 through 5-3, the possible deviation range for each MRE resource and variable options combination was calculated by first finding the weighted score (W_x) for each entry in the database (Eq. 5-1). The weighted score is based on the number of variables (M_n) each study reported of the nine possible variables considered in the research. Then for each variable category and corresponding MRE subcategory (sb_x) the sum of the product of each power density (E_{sb_x}) and associated weighted score is found and divided by the number of values (W_{nx}) taken in that sum giving a reference weighted mean ($\bar{x}_{f\_sb}$) for each subcategory (Eq. 5-2). The last step was determining the divergence of each power density (Ed_{sb_v}) in the database associated with each option for each variable category. This was found by subtracting the

corresponding MRE baseline from the average power density of each corresponding MRE resource and variables option combination considered in the MRE power density database (Eq. 5-3). Variables options with fewer than 20 datapoints were not included to avoid the possibility of outlier data skewing results. The results were presented as a percent change for simplified interpretation.

$$W_x = \frac{M_n}{9}$$ (Eq. 5-1)

$$\bar{x}_{f\_sb} = \frac{\sum E_{sb\_x} * W_x}{\sum W_{nx}}$$ (Eq. 5-2)

$$Ed_{sb\_v} = \frac{\sum E_{sb\_v}}{\sum N_{sb\_v}} - \bar{x}_{f\_sb}$$ (Eq. 5-3)

This approach serves as a proxy for the widely accepted principle in the scientific community that greater transparency in reporting of methods and variables is typically associated with higher rigor and study quality (Streiner & Norman, 2006). While this research does not determine the accuracy of any individual result, this work provides a measure of confidence in existing resource assessments based on the variables used.

5.4 Results

5.4.1 Power density baseline and variable breakdown

This section presents the weighted baseline which is used to assess the influence of data type, spatial resolution, temporal resolution and length of data variables in MRE resource assessments in the subsequent results sections. The reference weighted mean calculated for each MRE resource type are shown in Table 5-1. Tidal range has the largest power density weighted baseline of 1.55 kW/m^2 and wave had the second highest at 0.331 kW/m^2. Notably there was insufficient data to provide result for solar.

Table 5-1 | Reference weighted mean for each MRE resource

Results Category	Power density Baseline (kW/m²)
Wave	0.331
Wind	0.049
Marine Current	0.057
Tidal Range	1.550
OTEC	0.038
Solar	*Insufficient data*

The distribution of the variable 'data type' used in the resource assessments included in the MRE power density database is shown in Figure 5-1 and Figure 5-2. For wave and tidal range, hindcast and in situ data were the most common data types, used in 66% and 82% of the total resource assessment studies for each, respectively. Other resources, like wind, had a more even distribution with 27% using remote sensed data, 38% using hindcast data, 26% using in situ data, and 8% using forecast data.
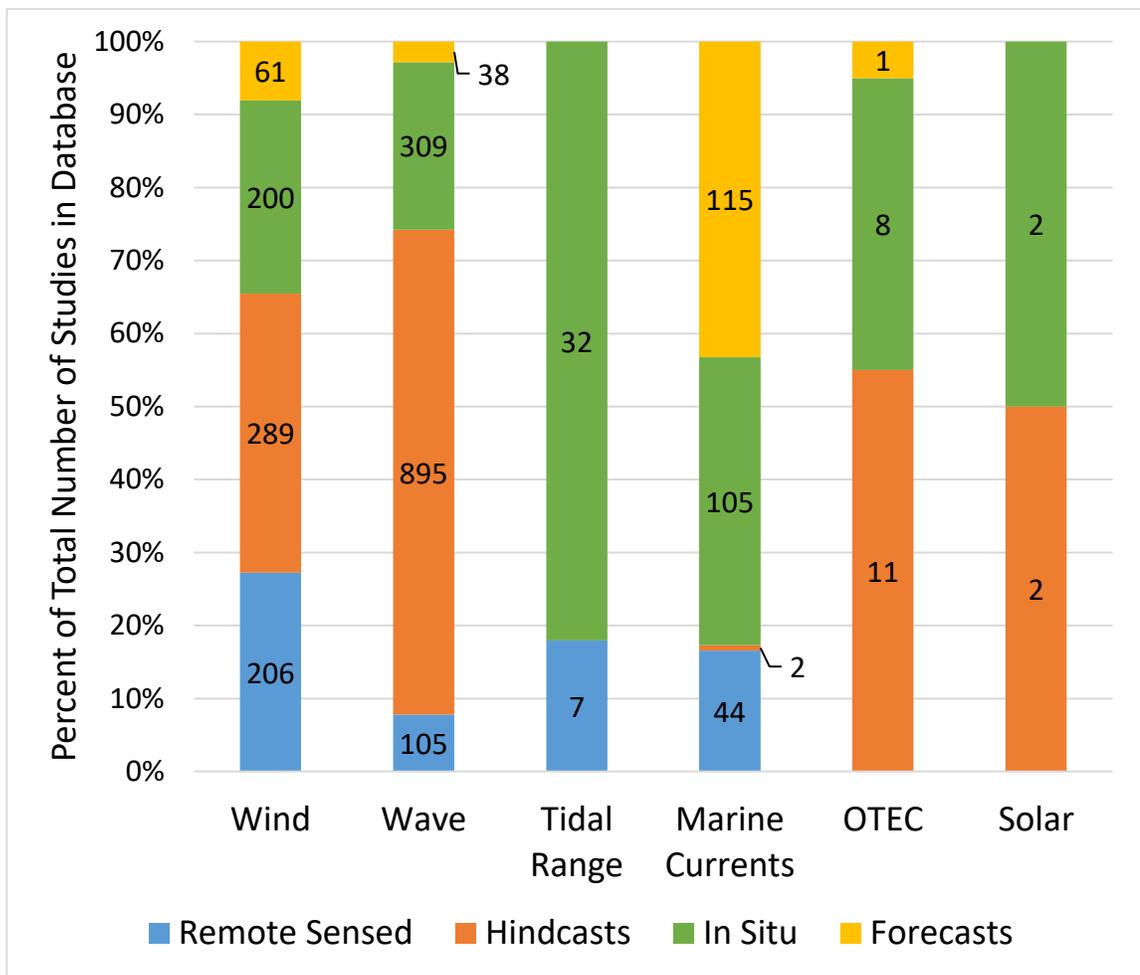
Figure 5-1 | Count of resource assessments using different variables by MRE resource type. The bar height represents the percent of the total by MRE resource type, the total number of studies is labelled within each bar.

The distribution of the number of studies using different spatial resolutions, temporal resolutions and length of data is shown in Tables B-2 through Table B-8 available in Appendix B. Figure 5-3 shows the different spatial resolutions used globally. Wind and wave studies are conducted across a range of scales, with the highest representation in the 3 km^2 to 1 km^2 range (29% for wind, 27% for wave). In contrast, tidal range studies predominantly use the lowest spatial resolution group, with 81% of studies falling into the 0 km^2 category (representing a study considering a single point) and no studies use resolutions greater than 10 km^2. Marine current resource assessments are similarly concentrated at coarser resolutions, with 49% of studies using spatial resolutions less

than 1 km². OTEC studies also rely primarily on low-resolution data, with 65% of studies in the 1 km² range. Solar resource assessments are more evenly distributed, with notable representation in the mid-range resolutions, including 25% between 10 km² and 5 km², and 25% between 3 km² and 1 km².

Figure 5-4 shows the global temporal resolutions used in resource assessments, wind energy featured 86% of studies using data in the 12-to-5-hour range and 14% in the 5-to-1 hour range. Wave and tidal range studies are more evenly distributed, though they are most frequently conducted at sub-daily resolutions, with 43% of tidal range studies using temporal resolutions between 12 and 5 hours, and 31% between 5 and 1 hours. Marine currents are similarly concentrated at higher temporal resolutions, with 55% of studies using temporal resolutions in the 5 to 1-hour range and 18% below 1 hour. OTEC studies, in contrast, use a wider range of temporal resolutions, notably with highest concentration of resource assessment on daily timescales (23% used temporal resolutions greater than 24-hours).

For length of data, shown in Figure 5-5, wind and wave studies tend to use longer datasets, with 35% of wind studies and 30% of wave studies in the 20- to 10-year range. Tidal range studies, however, rely primarily on short datasets, with 53% of studies in the 5-to-1 years range and 20% using data less than one year in length. Marine current resource assessments similarly depend on shorter records, with 65% of studies using datasets less than one year in length. OTEC resource assessments follow a similar pattern, with 79% of studies between 5-to-1 year range. Solar studies primarily rely on mid-length datasets, with 60% of studies in the 10 to 5-year category and no representation beyond 30 years.
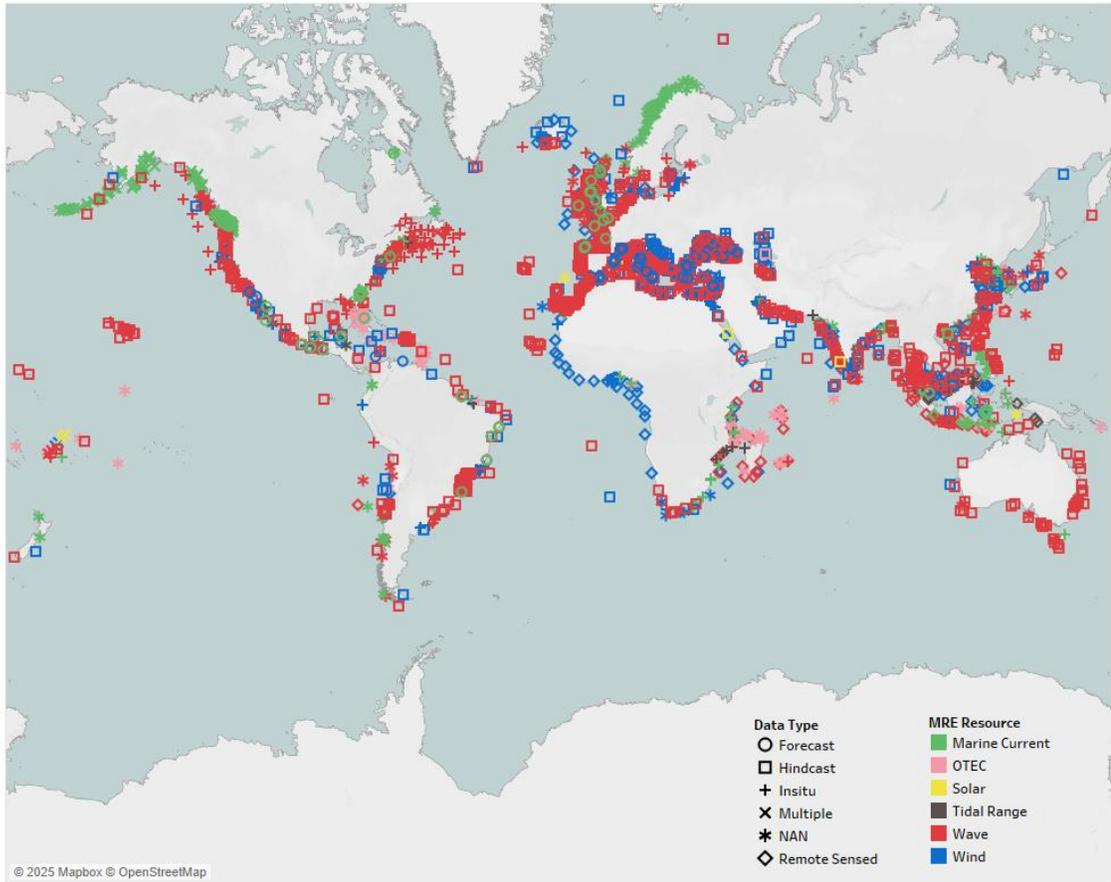
Figure 5-2 | Map of the global distribution and value of different data types (unitless) used in MRE resource assessments. Interactive version available online (see section 5.7 Data availability)
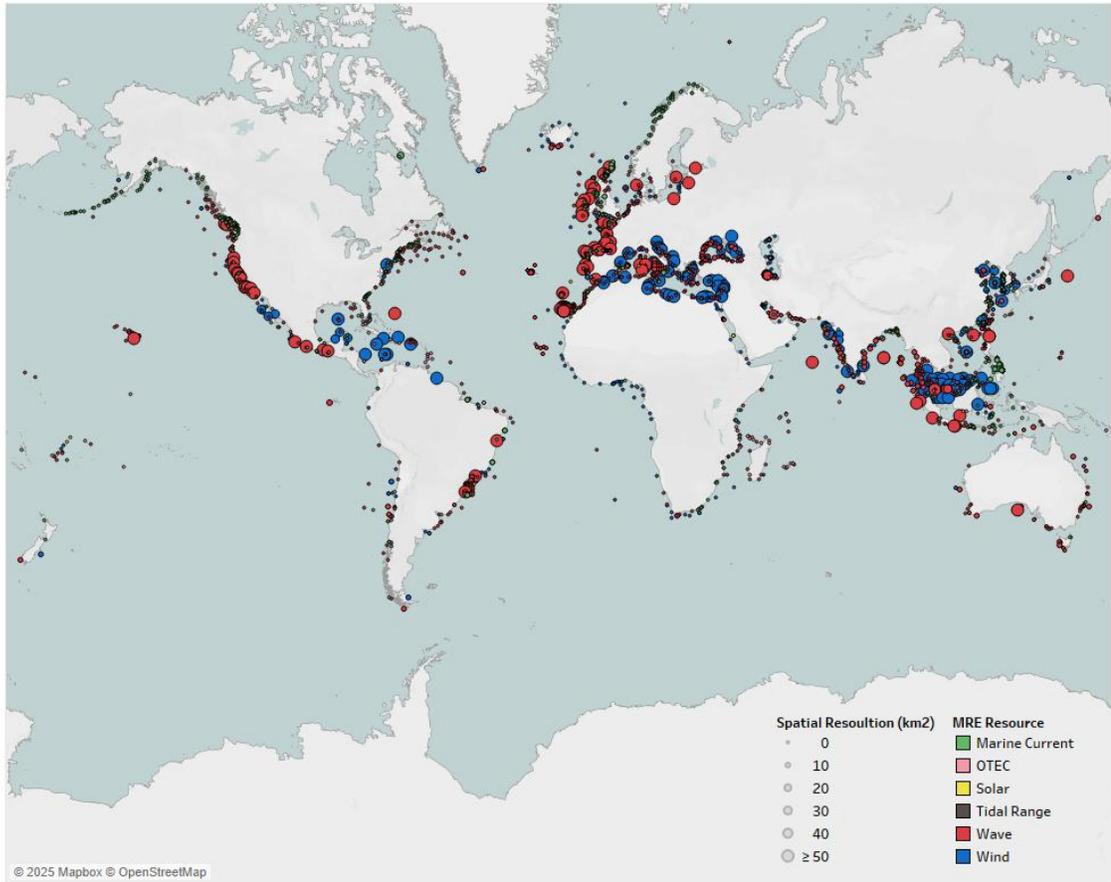
Figure 5-3 | Same as Figure 5-2, for spatial resolution (km²)
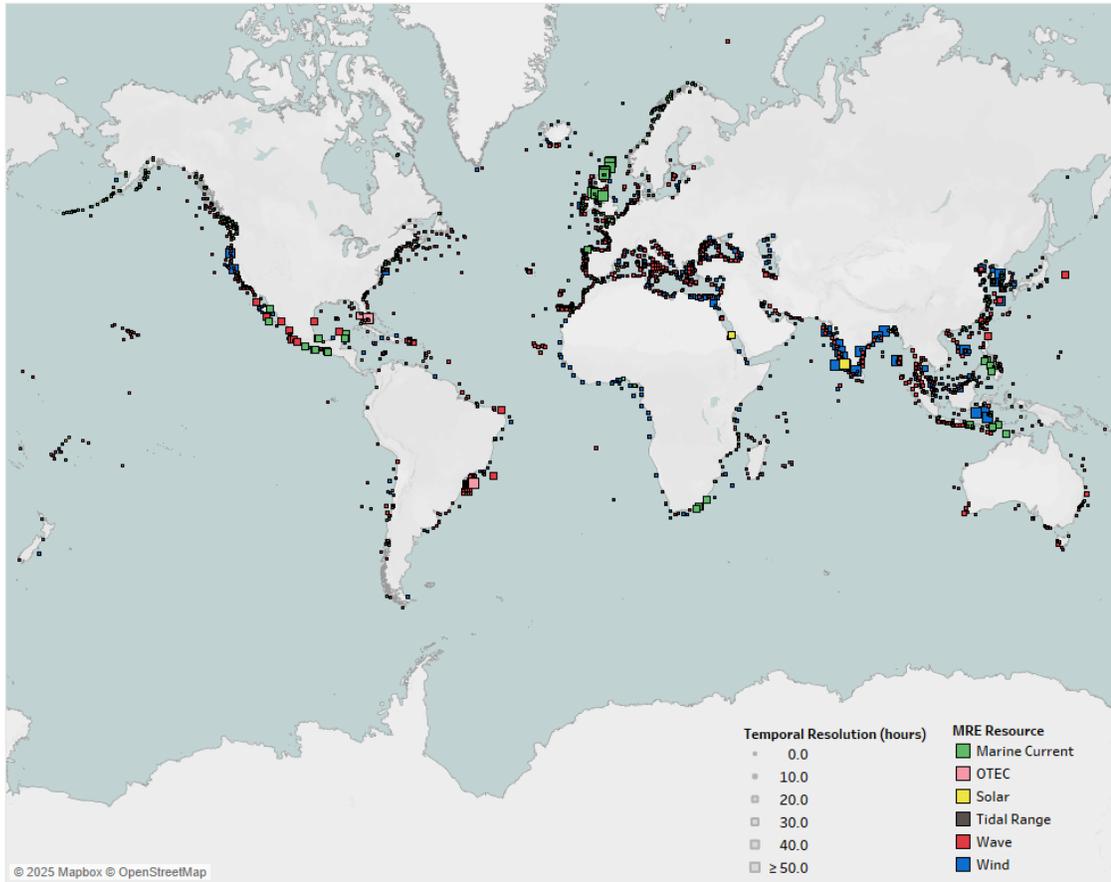
Figure 5-4 | Same as Figure 5-2, for temporal resolution (hours)
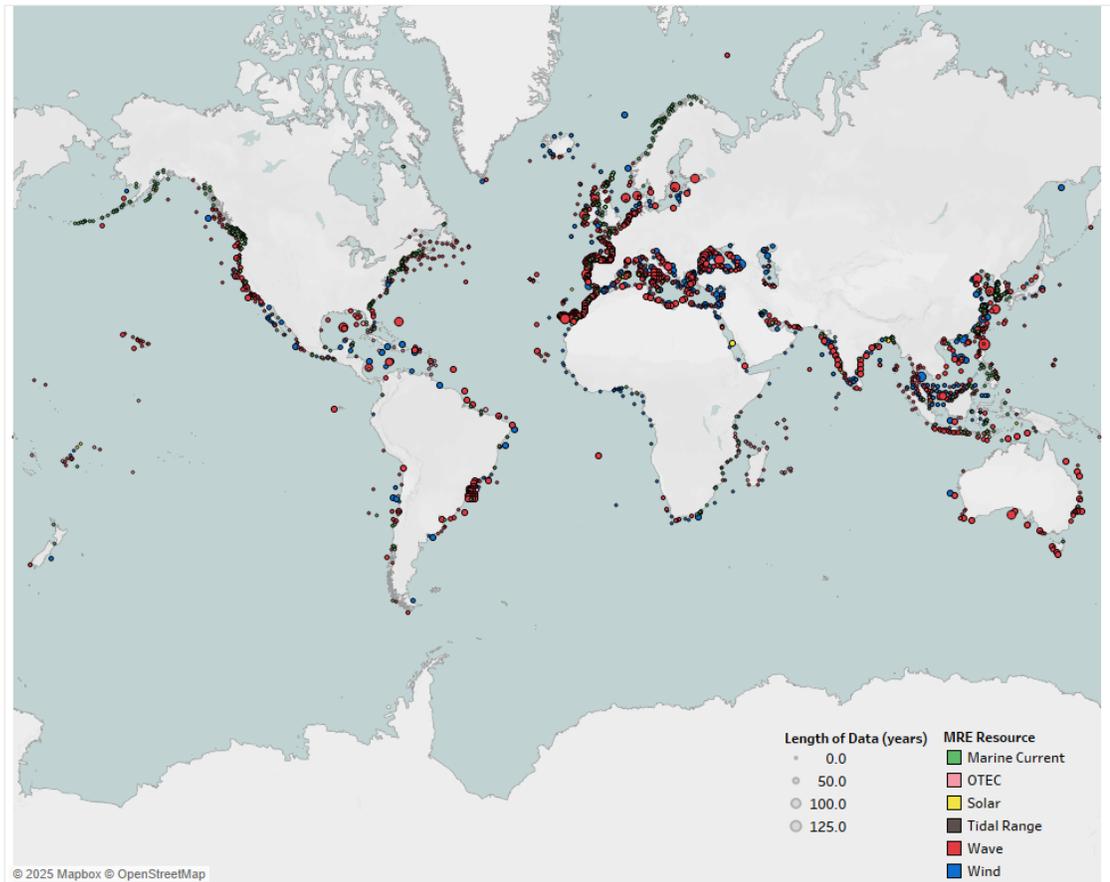
Figure 5-5 | Same as Figure 5-2, for length of data (years)

5.4.2 Global assessment by MRE Resources

This section evaluates how variables such as data type, spatial resolution, temporal resolution and length of data influence the power densities reported in MRE resource assessments for each MRE resource type globally. Compared to other MRE resources, wind studies have the smallest variations across different data types. This can be seen in Figure 5-6a by the dark blue line representing wind, which stays near to the dashed black line representing the power density baseline. The largest deviation from baseline for wind studies was found in resource assessments that used remote sensed data, with average power densities 23% smaller than the baseline. As seen in Figure 5-6a, all other

data types used in wind resource assessments have average power densities that deviate from the baseline less than 15%, with in situ having the smallest change of 1%.

Wave studies had more variation between data types. In wave power density results that used hindcast and in situ data the average energy estimate is 4% larger than the wave baseline, while results using remote sensed data and forecast data are 27% and 56% smaller, respectively.
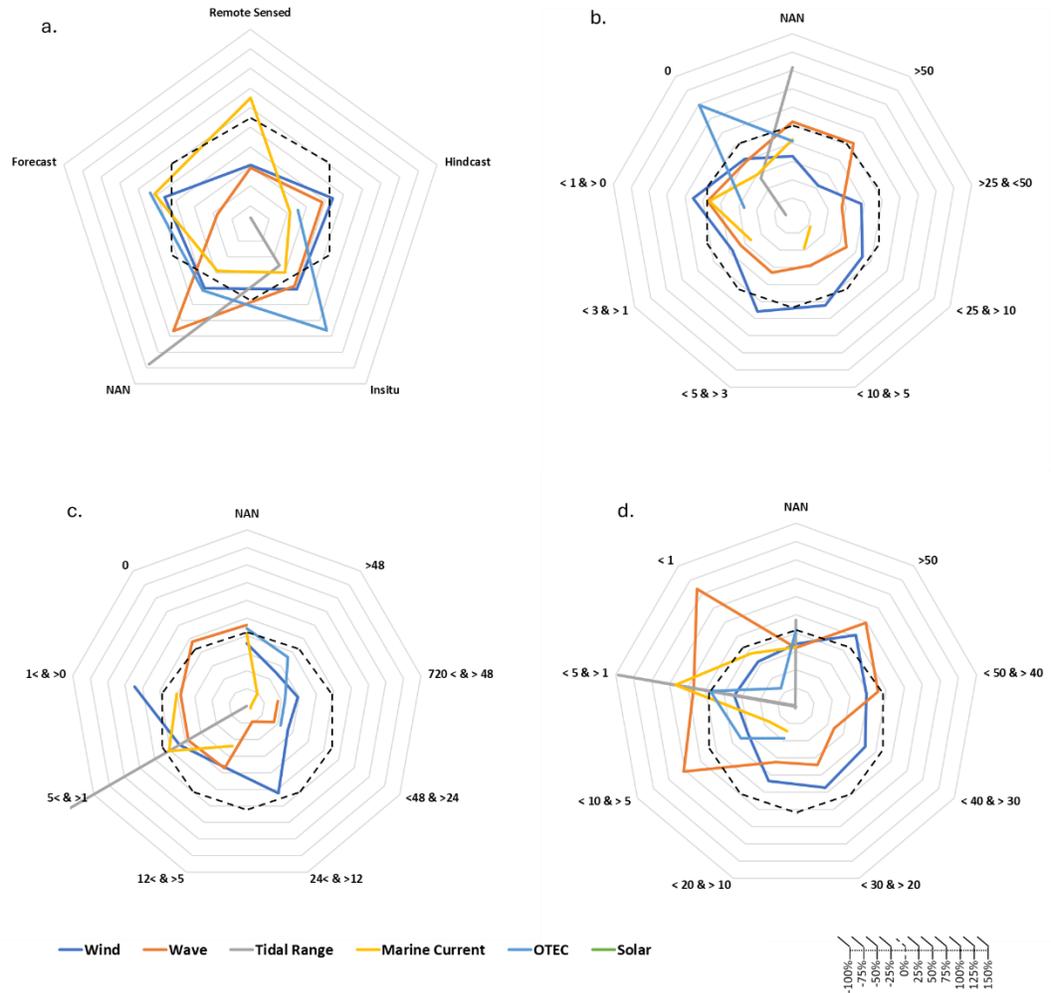
Figure 5-6 | Radar plots of the comparative percent change of energy results from MRE resource assessments. Results grouped by a. data type, b. spatial resolution, c. temporal resolution, d. length of data. The dotted dashed line represents no change from the weight baseline, results in the smaller rings represents variables which gave power density results less than the weighted baseline and results in bigger rings represent variables with power densities larger than the weighted baseline

For marine current and OTEC, different data types gave substantial and opposing deviations from baseline in energy estimates. For example, for marine current resource assessments using remote sensed data, on average the resulting energy estimates are

63% larger than the marine current baseline, while studies using hindcast data are 47% smaller. In the case of OTEC, studies that use in situ data found power density averages that are 65% larger than the OTEC baseline, while results using hindcast data are 37% smaller.

The tidal range resource assessments included in the MRE power density database only reported remote sensed data and in situ data, which on average are 91% and 37% smaller than the tidal range baseline, respectively. There is an insufficient number of studies to assess data types used in offshore solar energy. When data types are not reported, or multiple data types used, serval MRE resources had deviations from the relevant baselines that are more than double other results. For example, in tidal range studies not reporting data types, the average energy estimates are 119% larger than the baseline.

When considering how spatial resolution impacts the quantification of power density, as shown by Figure 5-6b, discernible patterns were less prevalent, but some notable results are still present. For example, wind, wave and tidal range studies that considered a single point had the smallest deviations in average power density from the respective baselines (3%, -2%, and -33%, respectively) compared to the other spatial resolutions used. Another trend is apparent for marine currents, where power density quantifications progressively deviate from the baseline as spatial resolutions get larger, ranging from 16% larger for results using resolutions less than 1 km^2, and reaching 72% smaller for results using resolutions between 25 km^2 and 10 km^2.

Overall, studies using shorter temporal resolutions had the smallest variation to the baselines (Figure 5-6c). For wave, temporal resolutions less than 12 hours had average power densities ranging between 7% and 5% smaller than the wave baseline. For wind studies using temporal resolutions from 12 to 5 hours, and 5 to 1 hours, average results in power densities are 8% smaller and 10% larger than the baseline, respectively. Across all MRE resources (except tidal range and solar which had insufficient data), resource

assessments using temporal resolutions greater than 24 hours all had results smaller than the respective baselines, ranging from 10% (OTEC) to 94% smaller (marine currents).

As with spatial resolutions, there are less discernible trends of the influence from different lengths of data. Nearly all marine currents, tidal range, OTEC, and solar studies use length of data greater than 20 years. Wind and wave have more studies using other lengths of data, but as seen in Figure 5-6d, no trend is seen of increasing or decreasing length of data that correspondingly minimises the divergence from the baseline. For example, in wave assessments the length of data option that minimised the difference to the baseline is between 40 and 50 years (smaller by 2%), but the biggest divergence is for studies using 50 years or more of data (larger by 27%).

5.4.3 Framework to assess MRE resource assessments

To allow for more confident and robust interpretation of MRE resource assessments, a framework was developed to determine how much an power density presented in a resource assessment could deviate due to the variable options used in that study. The framework is provided in Figure 5-7. This framework uses the deviations in power density associated with of specific variables (presented in Section 5.4.2). The results from Figure 5-6 are consolidated and converted to a present change from baseline in data matrices for data types, spatial resolutions, temporal resolutions (available in Appendix B, Tables B-2 through B-9).

i. Input Variables

Data Type:___   Spatial Resolution:___   Temporal Resolution:___   Length of Data:___

Resource Type:_____   Reported Energy:_____

ii.

B. Data Type Matrix

	Remote Sensed	Hindcast	In-situ	Not Reported	Forecast
Wind	-0.230	0.105	0.007	-0.005	0.152
Wave	-0.269	-0.039	-0.041	0.670	-0.557
Tidal Range	-0.906		-0.367	1.193	
Currents	0.627	-0.472	-0.251	-0.283	0.283
OTEC		-0.368	0.652	0.028	0.344
Solar					

C. Spatial Resolution Matrix (km²)

	Not Reported	>50	>25 & <50	<25 & >10	<10 & > 5	<5 & >3	<3 & >1	<1 & >0	0
Wind	-0.180	-0.452	-0.039	0.110	0.310	0.395	-0.054	0.382	0.026
Wave	0.295	0.306	-0.308	-0.149	-0.279	-0.169	-0.185	0.182	-0.015
Tidal Range	1.045							-0.906	-0.328
Currents	0.051			-0.715	-0.528		-0.342	0.162	-0.252
OTEC	0.031				-0.368			-0.326	0.987
Solar									

D. Temporal Resolution Matrix (hours)

	Not Reported	>48	720< & >48	<48 & >24	24< & >12	12< & >5	5< & >1	1< & >0	0
Wind	-0.105	-0.370	-0.269	0.310	-0.084	0.096	0.613		-0.105
Wave	0.149		-0.557	-0.774	-0.068	-0.042	-0.050	0.195	0.149
Tidal Range	-0.055					18.661	-0.998		-0.055
Currents	0.035	-0.773	-0.940		-0.405	0.269	0.009		0.035
OTEC	0.106	-0.096	-0.451			-0.359			0.106
Solar									

E. Length of Data Matrix (hours)

	Not Reported	>50	<50 & >40	<40 & >30	<30 & >20	<20 & >10	<10 & >5	<5 & >1	< 1
Wind	-0.150	0.272	-0.021	0.095	0.177	0.082	-0.249	-0.144	-0.201
Wave	-0.199	0.484	0.139	-0.398	-0.148	-0.189	0.774	0.419	1.096
Tidal Range	0.182					-0.975	-0.998	1.466	-0.986
Currents	-0.191					-0.641	-0.582	0.674	-0.053
OTEC	0.032			-0.370		-0.536	-0.130	0.184	-0.683
Solar									

iii.

$$1 + \left(\frac{b.}{1+\|b.\|}\right) = f_1$$

$$\times$$

$$1 + \left(\frac{c.}{1+\|c.\|}\right) = f_2$$

$$\times$$

$$1 + \left(\frac{d.}{1+\|d.\|}\right) = f_3$$

$$\times$$

$$1 + \left(\frac{e.}{1+\|e.\|}\right) = f_4$$

$$= F.$$

iv.

$$b. + c. + d. + e. = g.$$

v.

$$A_f = F. \times g.(+/-)1$$

vi.

$$E_a = E_i \times A_f$$

vii.

$$R_e = E_i - E_a$$

Figure 5-7 | Framework to determine the deviation range of resource assessment energy estimates based on the variability from existing studies. Matrices $B. - E.$ provides the associated percent change (as a decimal) for each variable option and corresponding MRE resource. These percent changes are combined in step $iii.$ these terms are combined into a single adjustment term ($F.$). In panel $iv.$ the sign of the sum of the matrices ($g.$) is determined and carried to panel $v.$ which calculates an adjustment factor (A_f). This adjustment factor is multiplied by the power density from a given resources assessment (E_i), as shown in panel $vi.$ to find adjusted bound of energy the power density (E_a). The likely range (R_e) which the power density could likely deviate from the reported value is finally calculated in panel $vii.$

The framework begins by identifying the key reported variables: data type, spatial resolution, temporal resolution, and length of data in Panel i from a given resource assessment. This information is then cross-referenced with the matrices in Panel ii (b) to (e) giving the percent change in power density from baseline found for each data variable and MRE combination.

Next, in Panel iii, the framework combines these percent changes into a single term ($F_.$) by applying a simplified factorial scalar transformation and subsequently multiplies results together (Varin, 2023). Because the factorial scalar transformation removes any negative values, the sign of the sum of each percent change ($g_.$) is quantified in panel iv. In panel v the sign of that value is multiplied into the combined percent change value ($F_.$) giving the adjustment factor (Z_a).

In panel vi this adjustment factor (Z_a) is multiplied by the reported power density (E_i) from a given resource assessment to provide the outer energy bound (E_a) which is how much the reported power density could deviate from baseline. The difference between the initial power density (E_i) and the outer energy bound (E_a) provides the deviation range over which the power density could deviate (R_e), shown in panel vii. In the case where the subtraction of the outer energy bound (E_a) would give a negative number, the lower bound of power density is set to zero.

5.4.4 Case study assessing the range of deviation in MRE resources

Two case studies are presented demonstrating the use of the framework. The first case study uses data from three resource assessments off Cozumel Mexico, one for wind, one for wave, and one for marine current (Alcérreca-Huerta et al., 2019; Gross & Magar, 2015; Hernández-Fontes et al., 2019). The second case study takes data from two marine current resource assessments off Australia (Perez et al., 2019; Schaeffer et al., 2020). Figure 5-8 demonstrations the application of the framework to the wind resource assessment in case study 1.

i. Input Variables
Data Type: Hindcast   Spatial Resolution: 25km^2 Temporal Resolution: 6 hours   Length of Data: 27 years
Resource Type: Wind   Reported Energy: 0.4 kWm^2

ii.

B. Data Type Matrix

	Remote Sensed	Hindcast	In-situ	Not Reported	Forecast
Wind	-0.230	0.105	0.007	-0.005	0.152
Wave	-0.269	-0.039	-0.041	0.670	-0.557
Tidal Range	-0.906		-0.367	1.193	
Currents	0.627	-0.472	-0.251	-0.283	0.283
OTEC		-0.368	0.652	0.028	0.344
Solar					

C. Spatial Resolution Matrix (km^2)

	Not Reported	>50	>25 & <50	<25 & >10	<10 & > 5	<5 & >3	<3 & >1	<1 & >0	0
Wind	-0.180	-0.452	-0.039	0.110	0.310	0.395	-0.054	0.382	0.026
Wave	0.295	0.306	-0.308	-0.149	-0.279	-0.169	-0.185	0.182	-0.015
Tidal Range	1.045							-0.906	-0.328
Currents	0.051			-0.715	-0.528		-0.342	0.162	-0.252
OTEC	0.031				-0.368			-0.326	0.987
Solar									

D. Temporal Resolution Matrix (hours)

	Not Reported	>48	720< & >48	<48 & >24	24< & >12	12< & >5	5< & >1	1< & >0	0
Wind	-0.105	-0.370	-0.269	0.310	-0.084	0.096	0.613		-0.105
Wave	0.149		-0.557	-0.774	-0.068	-0.042	-0.050	0.195	0.149
Tidal Range	-0.055					18.661	-0.998		-0.055
Currents	0.035	-0.773	-0.940		-0.405	0.269	0.009		0.035
OTEC	0.106	-0.096	-0.451			-0.359			0.106
Solar									

E. Length of Data Matrix (hours)

	Not Reported	>50	<50 & >40	<40 & >30	<30 & >20	<20 & >10	<10 & >5	<5 & >1	< 1
Wind	-0.150	0.272	-0.021	0.095	0.177	0.082	-0.249	-0.144	-0.201
Wave	-0.199	0.484	0.139	-0.398	-0.148	-0.189	0.774	0.419	1.096
Tidal Range	0.182					-0.975	-0.998	1.466	-0.986
Currents	-0.191					-0.641	-0.582	0.674	-0.053
OTEC	0.032			-0.370		-0.536	-0.130	0.184	-0.683
Solar									

iii.

$$1 + \frac{0.105}{1+0.105} = 1.09$$

X

$$1 + \frac{0.11}{1+0.11} = 1.10$$

X

$$1 + \frac{0.096}{1+0.096} = 1.09$$

X

$$1 + \frac{0.177}{1+0.177} = 1.15$$

F. = 1.51

iv.
0.105
+
0.11
+
0.096
+
0.177

g. =

v.
1.51 = 1.51 X (+)1

vi.
0.6 = 0.4 X 1.51

vii.
0.2 = 0.60 - 0.40

Figure 5-8 | Application of the framework on a resource assessment of offshore wind in Cozumel, Mexico. The variables options used in the resource assessment are shown in panel *i.*, and the corresponding variability highlighted in matrices *B.- E.* The framework calculations are shown in panels *iii.* and *iv.*, and the final adjustment factor, adjusted energy bound, and variability range highlighted in panels *v.*, *vi.*, and *vii.* respectively.

Table 5-2 and Table 5-3 show the starting data taken from the MRE power density database and the resulting outputs from applying the framework

Table 5-2 | Results from application of the framework to determine the range of variability of wind, wave, and marine current resource assessments in Cozumel, Mexico

Case Study 1 – Cozumel Mexico

Location 1

Resource Type	Wind
Data Type	Hindcast
Spatial Resolution	25 km^2
Temporal Resolution	6 hours
Length Data	27 years
Adjustment factor	1.289
Initial Energy	0.400 kW/m^2
Adjusted Energy Bound	0.516 kW/m^2

Location 2

Resource Type	Wave
Data Type	Hindcast
Spatial Resolution	1.3875 km^2
Temporal Resolution	24 hours
Length Data	10 years
Adjustment factor	-1.589
Initial Energy	0.330 kW/m^2
Adjusted Energy Bound	0.0 kW/m^2

Likely Power density Divergence

Lower Bound	**0.400 kW/m^2**
Upper Bound	**0.602 kW/m^2**
Variability Range	**0.202 kW/m^2**

Likely Power density Range

Lower Bound	**0.000 kW/m^2**
Upper Bound	**0.330 kW/m^2**
Variability Range	**0.330 kW/m^2**

Location 3

Resource Type	Marine Currents
Data Type	Hindcast
Spatial Resolution	25 km^2
Temporal Resolution	6 hours
Length Data	27 years
Adjustment factor	1.276
Initial Energy	0.200 kW/m^2
Adjusted Energy Bound	0.255 kW/m^2

Likely Power density Range

Lower Bound	**0.200 kW/m^2**
Upper Bound	**0.255 kW/m^2**
Variability Range	**0.055 kW/m^2**

In Case Study 1, wind was shown to have the largest power density with 0.400 kW/m^2, wave had the second highest power density of 0.330 kW/m^2, and marine currents had the least power density at 0.200 kW/m^2. After following the framework, wind and tidal range had power density adjusted bounds that increased up to 0.516 kW/m^2 for wind and 0.255 kW/m^2 for marine currents. The adjustment for wave power density resulted in a decrease larger than the initial power density, resulting in the lower bound of the energy deviation range being set at 0 kW/m^2. This also gave the largest variability range for power density of waves (0.333 kW/m^2), while marine currents had the smallest variability range at 0.056 kW/m^2. These result show, for these three resources, offshore wind has the highest opportunity for the maximum amount of energy, but marine currents may provide the most reliable source of energy.

Table 5-3 | Results from application of the framework to determine the range of variability of two marine current resource assessments in Australia

Case Study 2 Results - Australia

Location 1

Resource Type	Marine Currents
Data Type	In Situ
Spatial Resolution	0.000 km^2
Temporal Resolution	0.083 hours
Length Data	0.417 years
Adjustment factor	0.914
Initial Energy	0.850 kW/m^2
Adjusted Energy Bound	0.777 kW/m^2

Location 2

Resource Type	Marine Currents
Data Type	Hindcast
Spatial Resolution	15 km^2
Temporal Resolution	24 hours
Length Data	2 years
Adjustment factor	-0.017
Initial Energy	0.500 kW/m^2
Adjusted Energy Bound	0.000 kW/m^2

Likely Power density Range

Lower Bound	**0.777 kW/m²**
Upper Bound	**0.850 kW/m²**
Variability Range	**0.073 kW/m²**

Likely Power density Range

Lower Bound	**0.000 kW/m²**
Upper Bound	**0.500 kW/m²**
Variability Range	**0.500 kW/m²**

Case Study 2 applied the framework to two assessments of marine current in two locations in Australia. The first assessment, based on in situ data, reported an power density of 0.850 kW/m^2 and had an adjustment factor of 0.914 kW/m^2, yielding an

adjusted upper bound of 0.850 and a lower bound of 0.777 kW/m^2. The second assessment, derived from hindcast data, had a reported power density of 0.500 kW/m^2. After applying the adjustment factor, the adjusted bounds for power density gave a negative number, which is overwritten as 0 kw/m^2. This implies the actual power density for this location has a higher degree of uncertainty and could have average power densities lower than reported in the assessment. Together, the results from applying the framework show that that the first location has both the higher power density and the lower variability range, making it a less risky location for marine current MRE development.

5.5 Discussion

The results from this study show that different options of data sources and spatial and temporal data resolutions and durations used in MRE resource assessments can have disproportional influence on the power density quantification. Trends suggest that use of certain variables options result in precise energy estimates, while other options result in larger deviations from the reported power densities in resource assessments. These deviations, however, depend on the MRE resource considered. These trends are substantive inferences and are based on data extracted from the existing body of literature. As such, this study does not investigate the causation of these trends, however considering adjacent research in energy quantification for an MRE resource with the results of this study can provide insight into the cause of data influences on energy quantifications due to variable choice.

For example, this study shows that marine current energy estimates that use spatial resolutions greater than 1 km^2 have deviations of power density that progressively decrease from the baseline with increasing spatial resolutions. This may be because of the typical size of locations that are favourable for marine current energy. Research has shown that favourable locations are those with coastal characteristics like a channel, which effectively act as a funnel for incoming and outgoing tides, intensifying water

velocities and in turn increasing the power density (Bryden & Melville, 2004; Owen, 2008). In evaluations of channels in the United Kingdom and Norway, the typical widths at locations with strong power densities for tidal and marine currents are all typically less than 1 km (Garcia-Oliva et al., 2017; Grabbe et al., 2009). These results together suggest it is likely that larger spatial resolutions include more open water, which will have slower current velocities, and therefore decrease the average power density calculated. Therefore, when considering resource assessments for marine current, those studies using finer spatial resolutions will likely have more precise results.

Similarly, this work shows that marine current energy estimate using temporal resolutions greater than 12 hours give results that are up to 94% smaller than studies using shorter temporal resolutions. In research investigating the relationship between tidal phase and marine current energy, it has been found that the semidiurnal (M2) harmonic, with a periodicity of 12.42 hours, is typically the largest constituent globally (Iyer et al., 2013; Kowalik, 2004). Therefore, it is possible that studies using temporal resolutions greater than 12 hours are capturing instances between maximum tidal currents and therefore the current velocities are lower than reality, in turn lowering the calculated power density (Neill et al., 2016). Knowing this, readers can have more confidence in the results of resource assessments of marine currents that use temporal resolutions of less than 12 hours.

In this work no trends are present in the spatial resolutions or temporal resolutions of wind studies. Likewise, conflicting studies exist on the influence of spatial resolution on wind related assessments. For example, (Pryor et al., 2012), found that using finer spatial resolutions does not improve model results, while (Alvarez et al., 2014), found the opposite, with results showing finer spatial resolution did improve wind model results. This suggests that either there is a lack of understanding in the underlying mechanisms that link spatiotemporal variations to wind resource assessments, or these variables may have less influence on offshore wind energy.

On the other hand, results from this study suggest length of data and data type use in wind studies may have strong influence in energy quantification. For example, results showed in that using length of data less than 10 years had energy estimates which were underestimated when compared to the baseline (by 14% to 25%), while studies using longer data has smaller deviations. This matches other research which has found that longer data measurements improve the study accuracy (Murthy & Rahi, 2017). All together this suggests that readers of wind resource assessments should expect studies with longer lengths of data to be the most precise, and to consider the spatial and temporal resolutions used carefully in these studies.

In the case of wave power density, results from this study imply that forecast model data on average underestimate power density while in situ and hindcast data provide more precise energy estimates (each +/- 4%). This implication aligns with comparative wave model studies, such as (Robertson et al., 2016), who found certain wave forecast models can give energy estimates 14% lower than measured buoy data. Also evident from this work is the possible influence spatial resolutions can play on wave power density estimates, with studies using larger spatial resolutions having energy estimates on average up to two times smaller. Ongoing research has highlighted the challenge in quantifying the nearshore topology effects on waves, which together suggests that studies using larger spatial resolutions do not capture this behaviour which could drive the smaller energy estimates (Bowen & Huntley, 1984; Smith et al., 2013). Therefore, wave resource assessments which use hindcast data with finer spatial resolutions will likely give the most reliable results.

Temporal resolution is shown to have a possible influence on wave power density, with all studies using resolution greater than 12 hours reporting energy estimates on average smaller by 56% to 77%. Contrary to this, no clear pattern was shown from length of data. While these results are seemingly contradictory, looking at the individual needs of wave energy converters and the driving mechanisms of waves can provide insight. State-of-the

art wave devices are sensitive to time series changes, with some studies measuring the effects on a scale of minutes, highlighting the short-term variation inherent to the wave resource (N. Li et al., 2020; Xiao & Wang, 2024). However, longer term annual variability in wave power density has been shown to be low, in part because the wave energy resource is driven in part by the atmospheric-ocean system, where changes occur on the scale of decades (Fairley et al., 2017; Portilla et al., 2013b; Reguero et al., 2015b).

These results highlight the complexity and nuances between the different variables used in energy quantification of MRE which can lead to uncertainty when interpreting resource assessments. Further, while this research has provided an assessment of the influence of different variables, pulling together this information to make informed decisions remains challenging. To address this issue, this study presented a framework which can be used to interpret the results from resource assessments and determine the range which the actual average power density may divert from the reported values.

Prior studies have emphasized the importance of uncertainty quantification in marine renewable energy planning (Clark & DuPont, 2018; Klousakou et al., 2018), and the developed framework contributes by providing a standardised approach to account for non-homogeneous methodological variability. By considering the likely deviations in power densities reported in resource assessments, policy makers can ensure procurement targets align with realistic energy availability, allowing policymakers to optimise resource allocation while mitigating the risk of underperformance. For developers and financiers, this framework provides a method of carefully evaluating the underlying data and variables used in resource assessments before making investment decisions. This provides a standardised approach to quantify this variability, reducing the risk of overestimating available energy and allowing for the optimisation of developed resources.

Recent research has noted the need for optimal development of renewable energy resources to ensure net-zero targets are reached (Bogdanov et al., 2021; Sarjiya et al., 2023). For stakeholders involved in site selection, the framework enables a direct comparison of different assessments, ensuring that decision-making accounts for variability in different variables rather than relying solely on reported values. By applying this approach, developers can prioritize locations with lower uncertainty, which can ensure optimal development of MRE resources. Additionally, financiers can better assess risk, supporting investment decisions that align with expected energy generation rather than idealized estimates.

While this research is based on a comprehensive review of literature, it is limited by the number of studies included in this work. There is a sizeable number of studies that did not report some or all of the data types, spatial resolutions, temporal resolutions and lengths of data used (28% of the total number of the possible number of variables in the MRE power density database). To allow for rigorous interdisciplinary studies, it is imperative future research report all methodologies used in a transparent and robust manner. Further, the disproportionate amount of research conducted by MRE resource type may also limit the extent that conclusive findings can be made. As more research becomes available for resources like OTEC and solar, additional conclusions that could impact interdisciplinary assessments of MRE may be ascertained.

5.6 Conclusions

This research presents a comprehensive assessment of the different variables used in MRE resource assessments and evaluates the influence of the variable options on the reported energy estimates. Results of this research show the different variable options can, on average, lead to over- or under-estimations of power densities. Clear trends are seen when looking at how the different variable options influence the power density when compared to a baseline by MRE resource. These influences are likely in part driven by the inherent, natural mechanisms related to each MRE resource, limitations of current

methodologies, and limited amounts of data reported in the energy quantification of MRE.

The results of this work also underscore that there is wide variability in power density results from existing work that is non-uniformly influenced by the variables used in any given study. These complex relations make a confident cross-comparison of MRE technologies challenging. To help address the uncertainty that arises from over and under estimations associated with different variables, this study presented a framework which stakeholders (such as developers and policy makers) can use to interpret MRE resource assessments by determining the upper and lower bounds which the power density may be over/underestimated compared to the global baseline for that resource. The proposed framework provides a systematic approach for interpreting the range the power density results from resource assessments may deviate from those reported. and an accessible approach which stakeholders can use to reduce uncertainty and risk in research, development, and deployment of MRE. This in turn can accelerate the decarbonisation of the energy-sector and substantially contribute to meeting international net-zero emission targets.

5.7 Data availability

External data is used from CPIM6, EC-Earth5, and CRISO and is available from their respective websites.

Interactive versions of the maps in Figure 3-5 through Figure 3-7 are available online at the following links:

https://public.tableau.com/views/VariationinMarineenergyPotentialCoorespondingtoDataType/Dashboard1?:language=en-US&publish=yes&:sid=&:redirect=auth&:display_count=n&:origin=viz_share_link

https://public.tableau.com/views/VariationinMREEnergyPotentialCoorespondingtoData
SpatialResolution/SpatialRes?:language=en-
US&publish=yes&:sid=&:redirect=auth&:display_count=n&:origin=viz_share_link

https://public.tableau.com/shared/2JD2RSWCD?:display_count=n&:origin=viz_share_li
nk

https://public.tableau.com/shared/CGQBJ6YCQ?:display_count=n&:origin=viz_share_li
nk

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

Chapter 6 Discussion

6.1 Research outcomes and implications

As international efforts work to decarbonise the electricity sector, maximising the available clean energy resources is imperative. Globally, MRE is a largely untapped resource that can considerably contribute to these decarbonisation efforts. Understanding how much energy there is and how it is allocated between the different MRE resources is essential to maximise the contribution from the future development of these resources. However, notable knowledge gaps exist, such as the lack of comparability of resource assessments (Baumann et al., 2019; Yavor et al., 2021c), inconsistent methods and reporting (Doukas et al., 2010; Perujo et al., 2003), and uncertainty in data (de Vries et al., 2007; Sgobbi et al., 2016) are impeding MRE research and development. Wider renewable energy issues such as grid integration also persist slowing the adoption of MRE (Bhattacharya et al., 2021d; Zhao et al., 2024). To address these knowledge gaps, the goal of this thesis was to provide comprehensive understanding of the power density for MRE resources, how they compare to one another, and to assess the impact of future climate change on MRE and address inherent uncertainty.

The novel methods presented in Chapter 3 in this thesis were used to create the MRE power density database which is the foundation of that allows for a direct comparison to be made between previously published research that was incomparable. The MRE power density database is open access and available online (DOI: 10.15129/10ff203b-a19a-4fc8-b0da-e806c038e5a7). Chapter 3 also advances prior work included in the MRE power density database by comparing every power density to historic averages of each MRE resource at the same locations previously studied. By then presenting a projection of how the power density could change as a range of outcomes (Chapter 4) and a framework to quantify the uncertainty in resource assessments (Chapter 5), this research

provides a complete assessment the of how the power density of MRE compares. This approach aligns with related research (Dutta et al., 2022) and provides stakeholders across multiple disciplines the ability addresses the questions of optimal resource allocation, long-term energy planning and policy development, and financial risks related to renewable development (Giglio et al., 2023; Helistö et al., 2019).

The value of this approach is demonstrated using two case studies presented in Chapter 5. By using the developed framework developed shown in Figure 5-7 the case studies demonstrated how determining the range of uncertainty in published resource assessments can help address pressing issues such as the reliability of energy security in island nations (Barone et al., 2021) and the strategy for renewable energy procurements (Ayele et al., 2024). In the case of renewable energy procurement, the framework was applied to three MRE resource assessments off the coast of Cozumel, Mexico and identified that while wind had the highest reported power density, it also has a larger range of uncertainty. Conversely, marine current had a smaller reported power density, but the range of uncertainty was more than a factor of ten smaller compared to wind. By applying the framework to assess existing resource assessments in a standardised manner and accounting for underlying uncertainty, policymakers can prioritise government funding for MRE resources and manage risks related to project success.

From a global perspective, the standardised comparison of existing MRE resource assessments to the historic power densities of other MRE resources (Chapter 3) showed a clear misalignment between prior research motivations and the actual power density in MRE. Offshore wind, for example, has received extensive investment, policy backing and subsequent development globally (Jansen et al., 2022; Musial et al., 2023). This is reflected in the MRE power density database developed in Chapter 3, with 27% (816) of the reported power density from the included studies considering wind. Other resources like marine currents and solar combined comprise less than 20% of studies. However, when those studies are compared to the other MRE resources at the same locations,

wind, on average, displayed only the third largest power density of the different MRE resources studied. This implies that research and investment priorities have been guided more by technological maturity and policy momentum than by maximising the available power density. These findings in Chapter 3 support research in (Komor & Bazilian, 2005) that found there are multiple – and at times conflicting – goals between different stakeholder groups. Consequently, MRE technologies that have received less research, such as marine currents or offshore solar, present the possibility of under-utilisation of offshore energy resources.

Further supporting the possibility of an under-utilisation of offshore energy resources is the determination of a conservative upper limit for the global power density of solar and marine current resources in Chapter 3. Results showed that if just 10% of every location studied in the MRE power density database also included the power density of solar, an additional 1,628 kW/m^2 could be harnessed globally. This aligns with research, (López et al., 2020b), that found the combined wind and solar power density to be 10 times larger than the energy from an offshore wind farm alone. Similarly, Chapter 3 found a conservative upper limit for the marine current power density to be 1,091 kW/m^2, which is a 188% increase from the total power density from all studies included in the MRE power density database. These results suggest that prioritizing research and development towards the highest-power density resources, such as solar and marine currents, could increase the amount of carbon-free energy available and accelerate the decarbonisation of the electricity sector.

Given the long lead-times required for MRE research and development (Khojasteh et al., 2023; Parkison & Kempton, 2022), together with the ongoing impacts of climate change on renewable energy resources (Gernaat et al., 2021), assessing how the power density may change for each MRE resource is necessary to inform long term MRE planning. The projected range of possible future changes in MRE power density in Chapter 4 indicates the impacts of climate change on MRE power density does not follow linear or easily

predicted trends. For example, recent research has found that even under the 'best-case' SSP 1.2-6 emissions scenario, the global wind power density is likely to decrease because of ongoing climate change (Koletsis et al., 2016; S. Zhang & Li, 2021b). Results from this thesis agree with these findings, showing that globally the power density could decrease by -0.002 kW/m^2 between now and middle of the century. Given these results. However, the range of possible changes across multiple emission scenarios (see Figure 4-1), showed that under both the lowest 'best-case' scenario and the highest 'worst-case' scenario, the global average wind power density could increase up to magnitude larger than current values by the end of the century. This aligns with findings in (Martinez & Iglesias, 2024b)), which found that no linear trend can be expected for how climate change will impact future wind power density.

Results in Chapter 4 also showed that projections for the change in OTEC power density diverge from the expected impacts of climate change on sea surface temperatures. Given that OTEC relies on the temperature differential between warm surface waters and cold deep waters, and it is largely expected that with higher emissions scenarios (associated with rising global temperatures) the OTEC power density will increase due to warmer surface water temperatures (Aresti et al., 2023). This conclusion is supported by the notable lack of research on how climate change will affect the future power density of OTEC. The few studies that do discuss the future power density of OTEC (e.g., (Du et al., 2022)) the technical power density is quantified based on simplified OTEC plant, and the theoretical power density is not considered (Nihous, 2005c). Chapter 4 address this gap and shows that the possible change in OTEC power density is region dependent. For example, in a 100 km^2 region off the northern coast of Australia, the power density for OTEC at the end of the century was found to was both increase and decrease at adjacent locations under both emissions scenarios.

Even under high emissions scenarios, frequent decreases in power density could occur in the middle of the century, particularly in parts of the Pacific and Indian Oceans. One

possible explanation for the expected change in power density diverting from changes in sea-surface temperature is the impact of additional glacier melting under higher emissions scenarios, which after entering global ocean circulation, lowers surface water temperatures and the overall thermal gradient (Eayrs et al., 2021; Kostov et al., 2017). Other possible explanations could relate to increased rainfall events, which are predicted to occur with greater frequency as climate change continues (Cai et al., 2022), or the reversal of thermohaline circulation which is likely to occurs with current climate trends (Nihous, 2007).

Not all MRE resources were found to have the same variability in future power density. For example, marine currents were found to have minimal changes from the different scenarios. The largest global average change in all time-periods and emissions scenarios considered was equal to or less than 0.001 kW/m^2. This minimal impact from climate change on the power density of tidal currents aligns with the established understanding that velocities from tides are predominately driven by planetary gravitational forces, which are independent of climate-related influences (Pugh et al., 2014). Other non-tidal marine currents are driven by deep-water global circulations that are also less sensitive climate and atmospheric influences (Scott et al., 2008). However, localised, minor fluctuations in marine current power density are possible, and one possible explanation is how the coastal and channel dynamics of ocean current velocities may change with rising sea levels (Khojasteh et al., 2021). This consistency, when compared to other MRE resources, suggests marine currents may be the most reliable and resilient MRE resource available and highlights the importance of using a cross-resource approach when assessing energy systems. The results from Chapter 4 could inform policymakers and developers in specific regions how to best invest in research and development of MRE resources such to minimize the risk of underutilization in available energy resources.

Beyond evaluating historical and projected future power density, meaningful comparisons between MRE resources require addressing the underlying uncertainties

associated with any assessment of power density. Research has highlighted that uncertainty in power density assessments can be notably high, regardless of the data or methods used. For example, (Frandsen & Christensen, 1992) found wind energy estimates can vary from real-world wind farm production by up to 30%. More recent research has shown continued uncertainty in energy modelling, such as (Gualtieri, 2022), which determined that more recent hindcast and reanalysis models do not always have more accurate results compared to older versions.

Chapter 5 furthers the understanding of uncertainty in power density assessments by identifying how uncertainties can compound when cross-comparing MRE resource assessments. For example, wave resource assessments are found to have the smallest range of uncertainty when utilising in situ or hindcast data, with spatial resolutions between 25 and 10 km^2, temporal resolutions less than one-hour intervals, and data lengths spanning between 40 and 50 years. However, applying the same set of variables to other MRE resources yields notably larger uncertainty ranges. Using the framework shown in Figure 5-3 and the same set of variables applied to wave, the expected range of uncertainty would increase by more than 200% in wind resource assessments but decrease by -12% in marine current resource assessments. This complexity highlights the importance of quantifying uncertainty in a standardized manner and can allow stakeholders to minimize the risk in future research and development investments towards MRE.

Using a cross-resource approach that evaluates the current and future power densities of MRE, this thesis has indicated a misalignment between power density and development priorities. The standardised assessment of MRE power density and determination of future impacts of climate change demonstrates how recent calls for the need for a reassessment of funding strategies and technology selection can be addressed (Gatto & Drago, 2021; Zeng & Yue, 2022). This approach can inform stakeholders to ensure that the resources included in planned development maximise the available

power density. Additionally, the assessment of the impacts of climate change on MRE highlights the importance of understanding the range of possible outcomes for energy planning. By understanding the range of possible change, energy planners can avoid assumptions that could lead to inefficiencies or failed investments (Gatto & Drago, 2021; M. Kumar & Ng, 2022; Zeng & Yue, 2022).

The results of this thesis have implications for energy system planning and long-term decarbonisation strategies. Taken together, this thesis demonstrates how proactive planning of MRE research and development can maximise clean energy production, helping reach net-zero goals. This cross-resource, standardised approach can inform policymakers, aid developers, and minimise risks for investors, bridging the gap between science and application.

6.2 Broader contribution to science

The methodology and results presented in this thesis can influence the broader international goal of the net-zero transition, including the transformation of the electric supply and distribution system (Amani & Jalili, 2021; Cuadra et al., 2015), shifting climate policies (Burgess et al., 2024; Shang et al., 2022), and strategic development of all renewable energy technologies (Burgess et al., 2024; Qadir et al., 2021; Shang et al., 2022). For the transformation of the electricity supply and distribution systems, the rise of intermittent renewable resources, particularly wind and solar, has exposed the systems to a greater likelihood of system outages, underscoring the need for reliability improvements (Al-Shetwi et al., 2020; Erdiwansyah et al., 2021). Multiple sources of energy generation is one possible solution proposed; this thesis has demonstrated an approach that can be used to develop a diverse and carbon emissions-free system of electric generators (Al-Ghussain et al., 2021; Alqahtani et al., 2024).

Adopting a cross-resource perspective when evaluating options for improving reliability, similar to the approach of this thesis, would also underscore that several MRE resources

have reliability advantages. For example, marine currents are expected to not only have high power density, which can help meet demand, but they are also predictable, allowing grid operators to match supply to demand better (Khare & Bhuiyan, 2022; Uihlein & Magagna, 2016). Further, as demonstrated in Chapter 4, marine currents will likely see minimal changes from climate change; if developed, marine energy could provide greater reliability and resilience in electricity supply. Likewise, certain wave energy converters and tidal turbines can submerge to increase their survival rate during extreme weather events (L. Chen & Lam, 2015; B. Zhou et al., 2024). This resilience provides a key advantage as the expected increase in the frequency and severity of extreme weather events will likely result in a proportional increase of both land-based renewable and conventional energy systems being taken offline by this extreme weather (Gonçalves et al., 2024; L. Xu et al., 2024). As shown in Chapter 3 of this thesis, a cross-resource approach can identify under-utilised resources (such as marine currents and offshore solar) which, if developed, can improve the reliability and resilience of the electric supply and distribution system.

Looking at climate policy and planning, this thesis has shown that climate change will not only likely alter the distribution of available clean energy, but that these changes may not follow linear trends with increased carbon emissions. This identifies a key research gap as there are very few assessments of energy system planning that consider the impacts of climate change (Yalew et al., 2020). While energy planning models exist, there are limitations in assessing the impacts of climate change and a lack of flexibility in choosing decarbonisation pathways (Fodstad et al., 2022; Lopion et al., 2018). This research gap was addressed in Chapter 4 (Figure 4-6 and 4-7), which showed range of change in power density under different climate change scenarios. This work identified marine currents and solar will be impacted the least from future climate change. Understanding this range of possible change can allow energy planners, research and developer funders, and other stakeholders to select resources, such as marine currents and solar, which will maximise

future energy supply. Failing to incorporate these projections into energy system modelling and policy design could lead to lost investments and increased electric system instabilities (Peter, 2019; Totschnig et al., 2017).

Perhaps most notably, this thesis can inform the future development and comparative assessment with land-based renewable energy technologies. Land-based renewable energy resources, such as wind, solar, geothermal and bio-energy, face similar issues addressed in this thesis, including inconsistent energy quantification methodologies, variations in reported units, and differences in technology maturity (Ang et al., 2022; Kerschbaum et al., 2025). Like MRE, prior to this research, these issues make cross-comparing land-based renewable resources challenging. Additional complexities are present for onshore renewables which amplify this challenge, such as competing land uses and environmental impacts (Milbrandt et al., 2014; Rahman et al., 2022). Given these complexities optimising the technology choice and site selection is critical for maximising clean energy production.

The approach used in this study, which standardises power density assessments across diverse renewable resources, incorporates climate change projections, and systematically quantifies uncertainty, can also be used to optimise onshore renewable energy deployment. By applying cross-resource comparisons and uncertainty analysis, policymakers can develop more strategies to maximise clean energy production while minimising risk, in turn accelerating progress towards the net-zero transition.

6.3 Implications for industry and research applications

The results presented in this thesis have direct implications for the different MRE industry and fields of research. Renewable technologies like solar and wind have reached commercial maturity, and several other forms of clean energy (such as battery energy storage systems) are nearing commercial maturity (Bashi et al., 2022; Sun et al., 2023). As more technologies become ready to enter the market, there will be increased

competition for funding, project siting, and marketplace operations. By using a cross-resource approach to evaluating renewable resources commercial project developers can minimize risk, diversify their portfolios, and gain market competitiveness. Reduced risk can be achieved by having a confident understanding of how the power density of a resource will change before developing the actual system. This understanding can minimize the likelihood of diminishing power reduction from climate related changes and stranded assets (Boopathi et al., 2020; Rajaram et al., 2021). This same approach can allow commercial developers to achieve diversified portfolios. By looking at the resources which will have future favourable powder densities in the same regions as existing assets and planning for hybrid/co-located development, commercial developers can get optimal energy availability while minimizing development costs, even if those technologies aren't yet commercially today (S. Y. Tao et al., 2021; Yan et al., 2025). These types of diversified portfolios give commercial developers greater market leverage from having multiple dispatch options from different resources and more stable power production (Kim et al., 2024; Oskouei & Yazdankhah, 2015).

For researchers and technology innovators, this thesis has demonstrated how a cross-resource standardized approach to quantifying the energy of MRE can identify key factors which can accelerate technology development. For example, technology developers and researchers for marine current turbines can identify the locations where there are high power densities, and focus investment efforts in those regions. This approach also decreases issues that can arise with resource characterisation at project sites, as well as raise awareness of the number of global locations eligible for research and development with favourable power densities (MacDougall, 2017). This can result in identifying unknow sites that are favourable for marine currents, which in turn can promote additional research occurring. All together these factors can accelerate achieving technology maturity for marine current devices.

Additionally, by using standardized units, MRE researchers can more effectively communicate the benefits of MRE compared to other energy resources. By providing the energy quantification in a single set of units that can be directly compared to other resources, the discussion of MRE as a viable energy resource for development will become more approachable to a wider audience. By simplifying the conversation about energy quantification, researchers and technology developers both can more easily raise awareness of the benefits of MRE among the public, governments, and funding bodies (Palm et al., 2025). This in turn can provide additional research and development opportunities for MRE, which ultimately can accelerate commercialization of MRE technologies and result in a more rapid reduction of global emissions.

This thesis has also provided tangible resources that can benefit research and development of MRE. The database of MRE resource assessments provide a centralized library of peer-reviewed resource characterization assessments. This allow rapid access to determine what the power density for these resources may be at any given location across the globe. Using this in conjunction with the framework presented in Chapter 5 can allow stakeholders with or without subject matter knowledge to take any number of studies and compare the powder densities reported. This practice can allow for streamlined decision making at the policy and legislative level – allowing the drafters of those regulations and laws to incorporate MRE provisions without commission specific studies.

Another example of how the applicability of these resources is for commercial MRE developers. The detailed data on the methods and variables used in prior studies can be used to inform actual project design. For example, understating the temporal resolution and range associated with any given assessment can enable developers to estimate annual energy production from a power density. Further, understanding the range of possible variation from use of these methodologies can allow commercial developers to account for uncertainty sooner in the design process. While actual modelling of the site

and system will be required in all MER design, this approach can provide early-stage design answers, such as the minimum number of MRE turbines that would be required to achieve a desired annual energy production.

6.4 Limitations

The findings of this research should be considered within the limitations of the data that underpins the analysis. As with any power density assessment, the accuracy and applicability of the results depend on the quality and availability of input data, modelling assumptions, and computational limitations. Specifically, this relates to the creation of the MRE power density database in Chapter 3, and the projections of power density change in Chapter 4. When the MRE power density database was created it used the most up-to-date research available up to 2021; the results of this thesis are derived from the results of that research. A notable amount of the referenced work did not report the data and methods considered in this thesis. Specifically, 28% of the total possible number of variables that could have been extracted from each study were not available reported. The absence of these variables was not assessed in this thesis.

Another limitation of this work related to the MRE power density database is the disparity in the amount of previous research in each MRE resource. As discussed throughout this thesis, OTEC and marine currents have notably fewer published assessments than wind and wave, while solar has received comparatively a negligible amount of research. This uneven data distribution may introduce biases in cross comparing the power density of MRE, particularly when applying standardisation methods to resources with different levels of technological maturity (Rexhäuser & Löschel, 2015).

Likewise, the qualification of the uncertainty metrics in Chapter 5 is based on the MRE power density database presented in Chapter 3. As there are fewer studies for solar, OTEC and marine current resources, the determined uncertainty for these resources is less

robust than for wind and wave resources. In the case of solar, the uncertainty metrics for some data type, spatial resolution, temporal resolution and length of data variables were not calculated as there were not a sufficient number of available studies to calculate significant results.

An additional limitation is the model data used in climate change projections presented in Chapter 4. The underlying data is taken from specific climate models (CMIP6) which have documented biases and inherent uncertainties (Moseid et al., 2020; Z. Xu et al., 2021). These biases are not accounted for in the analysis of this thesis.

6.5 Recommendations for future work

This thesis has provided a comprehensive global comparison of the historical, current and future power density for MRE. While this research has demonstrated how a standardised cross-resource approach can identify resources, maximise clean energy production and accelerate progress toward net-zero goals, the following recommendations have been identified that can further the progress towards optimal clean energy development:

1. Further research can continue to add new research to the MRE power density database developed in Chapter 3 (DOI: https://doi.org/10.15129/10ff203b-a19a-4fc8-b0da-e806c038e5a7). Continuing to collate new research will allow for further cross-resource evaluations and identification of trends in how the scientific community's understanding of MRE power density is changing.

2. The approach used in Chapter 4 to project changes in power density of MRE could be downscaled to regional applications and perform local bias correction to the underlying climate model data. This work can provide a refined understanding of how climate change will impact regional MRE resources and evaluate how this impacts the cross-resource comparison of these resources.

3. Throughout this thesis, the theoretical power density was used in line with the goal of identifying how the total energy of MRE compares and informing future research and development to optimise the total available offshore power density. In the actual development of these MRE systems, however, more precise quantification of energy will be needed, such as determinations of the technical, practical or economic power densities. Future research could build on the standardised approach presented in this thesis to calculate downscaled energy qualifications in commensurate units. This would provide an updated picture of the optimal MRE resource for different locations globally.

4. Future should also apply the cross-resource approach demonstrated throughout this thesis to other sectors of renewable energy, such and land-based renewables. This approach will allow lesser adopted technologies, like bio-renewables, geothermal, and energy storage to be compared to more traditionally adopted technologies like wind and solar. A cross-resource approach can assist in the development of optimal renewable energy development that will benefit energy reliability and resilience, while also reducing carbon emissions.

Chapter 7 Conclusions

7.1 Summary of research aims

The primary aim of this thesis was to inform renewable energy stakeholders considering the future development of MRE on how to optimise the available energy from MRE. This was addressed through four research question (provided in Table 1-1 of Chapter 1), which are concluded below.

RQ.1   Based on current knowledge, which MRE resources have the highest power density both for different regions and globally?

To address this research question, a MRE power density database of resource assessments was created in Chapter 3. The reported power densities were standardised to allow for a commensurate comparison to be made between the different MRE resources. The MRE power density database contained of over 800 published MRE resource assessments and represents the status of the total energy available offshore. This database showed marine currents have the highest global average power density, at 1.53 kW/m². This was substantially larger than the other resources which had a global average power density of 0.327 kW/m² for wind, 0.081 kW/m² for solar, 0.69 kW/m² for tidal range, 0.05 kW/m² for wave, and 0.039 kW/m² for OTEC.

RQ.2   How does the power density of MRE as understood today compare to historic averages?

Chapter 3 used hindcast data compare how each power density reported in the MRE power density database compared to the power density of the other MRE resources at the same locations. Results showed notable regional variation in which MRE resource had the largest power density. For example, in in the western North Atlantic the average historical wind power density was found to be 0.1 kW/m² larger than wave

power densities in the MRE power density database, while in the southern hemisphere, the opposite relation was seen with power density of wind being on average -0.01 kW/m^2 smaller the wave power density reported in the MRE power density database.

RQ.3   Will climate change increase or decrease the power density for MRE resources and which MRE resources will change the most?

To address the gap in knowledge relating to the possible impacts of climate change on the cross-resource power density of MRE, Chapter 4 evaluated the range of possible change in MRE under a low emission (SSP 1.2-6) and a high emissions (SSP 5.8-5) future climate scenario. Wind and OTEC are found to have the highest variation in average power density changes, with an increase of 0.040 kW/m^2 project for wind under high emissions at the end of the century in the portions of the North Atlantic and North Pacific. For OTEC, power density increases of 0.50 kW/m^2 are found in the North Pacific under low emissions. Marine currents were shown to be the least impacted by climate change, with maximum global average increase of 0.001 kW/m^2 occurring at the end of the century under SSP 5.8-5.

RQ.4   How can uncertainty in assessing and interpreting the power density of MRE be minimised?

Uncertainty is unavoidable in energy quantification for renewable energy and the Chapter 5 provided a quantification of this uncertainty so it can be accounted for in energy planning. Results show the impacts of this uncertainty can be substantial. For example, marine current studies using temporal resolutions greater than 12 hours give results that are up to 94% smaller than studies using shorter temporal resolutions. Notably, Chapter 5 identified there is a lack of understanding in the underlying mechanisms that link spatiotemporal variations used in resource assessments, particularly those for wind and wave studies. To address this gap and the persisting uncertainty in energy quantification, a framework was provided in Chapter 5 that can

be applied to any MRE resource assessment to determine the bounds which the reported power density could deviate from the given value.

7.2 Final remarks

This thesis presents a cross-resource assessment of the power density of MRE resources. This research aimed to provide a comprehensive understanding of how the total offshore energy is distributed between MRE, how climate change will influence this distribution of energy, and how much uncertainty there is when comparing these different resources. By comparing this MRE power density database to historical averages of power density for MRE, this thesis identified that marine current and offshore solar might be underutilised resources based on the comparatively lesser amount of existing research and larger power densities. The determination of the range of possible change in MRE power density from future climate change and quantification of uncertainty provides a complete picture of what the available energy offshore could be in the near term and long term. It was shown the impacts from climate change, and the uncertainty across different energy quantification variables, have non-linear impacts on resulting power density.

The results of this thesis, taken together, can allow developers, policymakers, researchers, and other MRE stakeholders to proactively plan for energy research and development that accounts for climate change allowing for optimised offshore energy deployment and accelerate decarbonisation of the electric sector. This approach bridges the gap between available science and actionable information, providing an accessible foundation to address the pressing issues in climate change and energy security the world is facing. Further application of the standardised, cross-resource approach used in this thesis can be applied in downscaled applications and in other sectors such as onshore renewables. Continuation of this work in this manner can allow researchers, policy

makers, investors, and developers to employ strategies that optimise future clean energy production, minimise risk, and accelerate progress toward net-zero climate goals.

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Appendices

Appendix A – Chapter 3

Table A-0-1 | 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

Title	Year	Authors	Energy Type
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
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 Power density in the Croatian Part of the Adriatic Sea and Comparison with Wind Power density	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 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, Monica Fossati, Sebastian Solari, Luis Teixeira	Wave, Ocean Current
Wind and wave power density 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 Power density 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

	2016	Christina Kalogeri, George Galanis, Christos Spyrou, Dimitris Diamantis, Foteini Baladima, Marika Koukoula, George Kallos	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 power densities 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

Appendix B – Chapter 5

Table B-0-2 | Number of studies in database by data type used, grouped by MRE resource

MRE Resource	Remote Sensed	Hindcasts	In Situ	Forecasts
Wind	206	289	200	61
Wave	105	895	309	38
Tidal Range	7	0	32	0
Marine Currents	44	2	105	115
OTEC	0	11	8	1
Solar	0	2	2	0

Table B-0-3 | Number of studies in database by spatial resolution used, measured in km^2 in the database, grouped by MRE resource

MRE Resource	>50	> 25	< 25	< 10	< 5	< 3	< 1	0

		& < 50	& > 10	& > 5	& > 3	& > 1	& > 0	
Wind	108	46	8	59	61	206	35	190
Wave	87	31	7	224	35	315	172	295
Tidal Range	0	0	0	0	0	0	7	30
Marine Currents	0	0	12	13	0	19	120	80
OTEC	0	0	0	1	0	0	13	6
Solar	0	0	0	1	0	1	0	2

Table B-0-4 | Number of studies in database by temporal resolution used, measured in hours in the database, grouped by MRE resource

MRE Resource	>720	720 < & > 24	24< & >12	12< & >5	5< & >1	1< & >0	0	>720
Wind	12	15	12	6	227	204	46	0
Wave	0	18	18	17	316	502	49	63
Tidal Range	0	0	0	0	0	1	1	0
Marine Currents	10	22	22	0	3	29	74	0
OTEC	2	1	1	0	0	10	0	0
Solar	1	1	1	0	0	6	0	0

Table B-0-5 | Number of studies in database by length of data used, measured in years in the database, grouped by MRE resource

MRE Resource	> 50	50 < & > 40	40 < & > 30	30 < & > 20	20 < & >10	10< & >5	5< & >1	<1
Wind	6	53	129	55	263	85	152	7
Wave	24	95	252	156	386	90	248	46
Tidal Range	0	0	0	0	3	1	8	3
Marine Currents	0	0	0	0	19	25	99	261
OTEC	0	0	2	0	1	1	19	1
Solar	0	0	1	1	0	6	2	0

Table B-0-6 | Percent change power density compared to the MRE baseline categorized by data type used

MRE Resource	Remote Sensed	Hindcast	In situ	Not Reported	Forecast

Wind	-23%	11%	1%	15%	-21%
Wave	-27%	-4%	-4%	-56%	304%
Tidal Range	-91%	N/a	-37%	N/a	N/a
Marine Currents	63%	-47%	-25%	28%	6%
OTEC	N/a	-37%	65%	34%	N/a
Solar	N/a	N/a	N/a	N/a	N/a

Table B-0-7 | Percent change power density compared to the MRE baseline categorized by spatial resolution used, measured in km^2 in the database

MRE Resource	>50	> 25 & < 50	< 25 & > 10	< 10 & > 5	< 5 & > 3	< 3 & > 1	< 1 & > 0	0
Wind	-45%	-4%	11%	31%	39%	-5%	38%	3%
Wave	31%	-31%	-15%	-28%	-17%	-18%	18%	-2%
Tidal Range	N/a	N/a	N/a	N/a	N/a	N/a	-91%	-33%
Marine Currents	N/a	N/a	-72%	-53%	N/a	-34%	16%	-25%
OTEC	N/a	N/a	N/a	-37%	N/a	N/a	-33%	99%
Solar	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a

Table B-0-8 | Percent change power density compared to the MRE baseline categorized by temporal resolution used, measured in hours in the database

MRE Resource	>720	720 < & > 24	24< & >12	12< & >5	5< & >1	1< & >0	0	>720
Wind	-37%	-27%	-33%	31%	-8%	10%	61%	N/a
Wave	N/a	-56%	-56%	-77%	-7%	-4%	-5%	19%
Tidal Range	N/a	N/a	N/a	N/a	N/a	1866%	-100%	N/a
Marine Currents	-77%	-94%	-94%	N/a	-41%	27%	1%	N/a
OTEC	-10%	-45%	-45%	N/a	N/a	-36%	N/a	N/a
Solar	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a

Table B-0-9 | Percent change power density compared to the MRE baseline categorized by length of data used, measured in years in the database

MRE Resource	>50	< 50 & > 40	< 40 & > 30	< 30 & > 20	< 20 & > 10	< 10 & > 5	< 5 & > 1	< 1
Wind	27%	-2%	9%	18%	8%	-25%	-14%	-20%
Wave	48%	14%	-40%	-15%	-19%	77%	42%	110%
Tidal Range	N/a	N/a	N/a	N/a	-98%	-100%	147%	-99%
Marine Currents	N/a	N/a	N/a	N/a	-64%	-58%	67%	-5%
OTEC	N/a	N/a	-37%	N/a	-54%	-13%	18%	-68%
Solar	N/a	N/a	N/a	N/a	N/a	N/a	N/a	N/a