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Wave and tidal current energy – A review of the current state of research beyond technology

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ABSTRACT

The oceans of the earth offer vast amounts of renewable energy. Technologies to harness the power of the seas are at an early stage of development. Even the most advances technologies, namely tidal current and ocean wave still face considerable barriers and many obstacles remain. Research, development and innovation can help overcome those barriers. This review provides an overview over the current state of research in the field of ocean energy. In particular, the authors focus on research beyond technology or technological improvements. This article also highlights areas where research gaps exists and where future research efforts should be directed to.

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1. Introduction

The oceans of the earth represent a vast source of renewable energy. In general, ocean energy can be divided into six types of different origin and characteristics: ocean wave, tidal range, tidal current, ocean current, ocean thermal energy, and salinity gradient [1–3].

Currently, all ocean energy technologies except tidal range can be considered at an early stage of development from conceptual up to demonstration stage [2]. Ocean wave and tidal current energy are the two types of ocean energy which are most advanced and are expected to contribute significantly to the supply of energy in future [2]. Thus, the authors will focus on those two types ocean energy in this paper.

The ocean energy industry has made significant progress in recent years but is still at very early stage with some advanced prototypes that are currently being tested [4]. Existing challenges include further development of the technology to prove reliability and robustness and to reduce costs but also deployment and risk reduction. This is reflected in the current research themes funded e.g. by the EU with 68% of the funds being directed to technology development (Fig. 1). However, other not technology-related knowledge gaps and barriers exist [4].

The aim of this review is to provide an overview over the current state of research in the field of wave and tidal current energy. Further research and innovation in the area of technology is the prerequisite to tap the full potential of ocean energy. According to [5], technological barriers represent the most important issue that the ocean energy sector needs to address in the short-medium term. Priority topics include e.g. technology advancement, reliability demonstration, sub-system development and optimisation, pre-commercial array sea trial and demonstration, predictive maintenance systems, and array electrical systems [4].

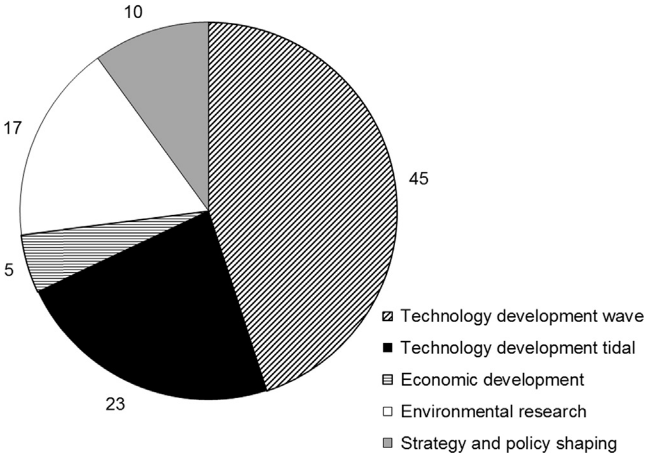

Fig. 1. Research themes financed by EU funding in 2011 according to [132].

However, also other areas require attention but they are tackled to a minor extend partly. This article will focus on research beyond technology or technological improvements (for those, the authors would like to refer to technology-oriented studies and reports such as [4,6–8]) and identify areas where research gaps exists and where future research efforts should be directed to. The review is based on a literature review and desk-based research. Areas that will be covered in greater detail have been identified according to [2,7,9].

The article is structured as follows: Section 2 presents the state-of-research of resource assessment and forecasting; Section 3 will present research on environmental impacts. Section 4 covers socio-economic impacts and Section 5 grid integration. Section 6 discusses the current literature on array configuration, installation, operation and maintenance while in Section 7; some relevant works on regulatory and legal affairs will be presented. Section 8 contains some conclusions.

2. Resource assessment and forecasting

An important initial step towards market deployment of ocean energy is the characterisation and mapping of ocean energy resources. The assessment of wave energy resources includes the identification of areas with high wave energy, the quantification of average energy resources (e.g. total annual wave energy) and the description of the resource by using parameters such as significant wave height, wave energy period and mean wave direction [10]. Precise estimates and description of available wave energy resources at high spatial and temporal resolution are needed for proper planning and the optimisation of the design of ocean energy converters [11,12]. This will help to optimise device performance in terms of power produced. For example, the power output of a Oscillating Water Column device at a certain location has been studied [13]. The current state of technology development will determine how much of the resource can be exploited with the main technical parameters to be improved being device efficiency and capacity factor [10,14] . Reducing uncertainties concerning the available resources will also increase the confidence of investors as it allows a better determination of the value of investments and minimising risks [15,16]. In the following sections, an overview of current state of wave and tidal current energy resource assessment and forecasting is presented.

2.1. *Ocean wave*

2.1.1. *Resource assessment*

During the last years, ocean wave energy resources have been assessed for various regions in the world. The first wave energy resource assessments have been made using buoy data limited to local conditions [12]. The second generation of assessments included buoy data in combination with deep water numerical models which can assess offshore wave resources which helped overcoming the limitations of first generation assessments, namely the limited time period of the buoy measurements and the uncertainties of extrapolating local data to other locations [12]. Recent tools incorporate radar measurements and allow modelling wave generation and propagation also in coastal regions [11,17]. Usually, wind and bathymetry data are used as an input for such models. Typical output parameters are: significant wave height, mean wave period, peak wave period, and mean wave direction.

Ocean wave energy resource assessments have been performed on global, regional and local level. In Table 1, a non-exhaustive list of wave energy resource assessments is presented. Other coasts and areas that have been studied include California, Argentina, Australia, Portugal, Sweden, Korea, Spain, Iran, and the Atlantic coast of the United States [18].

2.1.2. *Forecasting*

Wave forecasting is performed by statistical techniques or physics-based models [19,20]. An example for a wave forecast system based on physical models is the wave model WAM that is incorporated into the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) [19]. The ECMWF model forecast includes up to a maximum of 48 h ahead in 3 h steps. Similarly, the National Oceanic and Atmospheric Administration (NOAA) and the National Weather Service (NWS) use WAVEWATCH-III based on wind information from the Global Data Assimilation Scheme (GDAS). WAVEWATCH-III produces forecasts of up to 180 h in 3 h steps. Other wave forecast include regional forecasts for the Gulf of Mexico (using SWAN and wind forecasts from NOAA) and forecast from private companies such as Oceanweather which uses a privately developed spectral wave model.

Statistical approaches include neural networks, regression-based techniques and genetic programming [20–25]. Some authors have tried to combine both methods [19]. It seems that statistical models are more accurate for short time horizons (up to 6 h) while physics-based model perform better for longer time horizons and a combination of both methods leads to more accurate results [19]. Statistical models might be sufficient for to be used for electricity utilities for generating and trading.

2.2. *Tidal current*

2.2.1. *Resource assessment*

Similar to wave energy, tidal current energy resources have been assessed since a number of years. Often, direct measurements have been performed on-site. Since some years, 2D and 3D modelling techniques have been applied to assess tidal current energy resources by modelling current velocities. More recent publications assess also the hydrodynamic effects of power extraction and consider for example change to the flow field, change in water surface elevation, or disturbances in tidal dynamics [26,27].

According to [14], tidal current energy is calculated as function of seawater density velocity, velocity availability factor, neap/spring factor, and peak spring-tide velocity. However, it is not possible to convert all tidal current energy power due to Betz' law and mechanical losses in the turbines. These limitations are accounted via the power coefficient.

Tidal energy resource assessments have been performed for many regions and coastal areas of the world. Table 2 shows examples for studies in the field.

2.2.2. *Forecast*

Tidal current forecasts are usually readily available [28]. For example, NOAA Current Predictions allows forecasts up to 48 hours, one week and annual predictions, which are available online.

The German Federal Maritime and Hydrographic Agency provides current predictions of up to 3 days [29]. The model used is a 3D model that takes into account meteorological forecasts for the North Sea and Baltic Sea provided by the German Weather Service (DWD) [30], tides and external surges entering the North Sea from the Atlantic, as well as river runoff from the major rivers. The

Table 1
Examples of ocean wave energy resource assessments.

Region	**Parameters**[a]	**Modelling approach and tools**	**Reference**
Global	H_S, T_m, T_p, P	WAVEWATCH-III using FNL wind data from the Global Forecast System (GFS). 19 buoys and satellite altimetry data used for model validation	[11]
Global	H_S, T_p, P	WAVEWATCH-III based on wind fields input from NCEP. Spatial resolution of 1.25° × 1.0°, 3 h intervals	[17]
Global	H_S, T_p, θ_m, P	WAVEWATCH-III. Spatial resolution 30′, temporal resolution 3 h	[15]
UK (Cornwall)	H_S, T_e, θ_m, P	Wave model SWAN, wave and wind input from ECMWF. Grid resolution 1.5° × 1.5°, 3 h temporal resolution. Validation with buoys measurements	[133]
Eastern Mediterranean and Aegean Seas	H_S, T_m, P	Spectral wave model (hourly) using wind data from ECMWF. Model calibrated using the wave measurements conducted at three different stations	[134]
Western French coast	H_S, T_p, T_m, P	WAVEWATCH III providing boundary conditions for SWAN. Wind input from ECMWF, compared and validated with measurements from three buoys	[12]
Azores islands	H_S, T_e, θ_m, P	Analysis of wave climate using remotely sensed and historical data. Model based on WAM for wave generation to provide boundary conditions for SWAN	[135]
Hawaii	H_S, T_e, P	WAVEWATCH-III model based on FNL wind data for far field, Hawaii WAVEWATCH-III model with high-resolution winds from WRF for local wave processes. SWAN model for coastal waters. Validation with measurements from satellites and buoys	[136]
Galicia	H_S, T_e, θ_m, P	Offshore buoy used as boundary condition. Wave propagation to coastline modelled with SWAN. Validation with offshore and coastal wave buoys	[10]
Black Sea	H_S, T_e, P	6-h wind fields from ECMWF as input for SWAN (1.3 × 1.83 km). Measurements from a wave buoy for verification	[18]
India	H_S, T_p	WAVEWATCH-III model combined with SWAN. IFREMER/CERSAT blended winds used as input. 1.133° × 1.133° spatial grid with 0.5 h temporal resolution. Validation with buoy measurements.	[137]

[a] H_S: significant wave height; T_m: mean wave period; T_p: peak wave period; T_e: wave energy period; θ_m: mean wave direction; P: wave power.

Table 2
Examples of tidal current energy resource assessments.

Region	Parameters	Modelling approach and tools	Reference
Ireland	Peak spring-tide velocity	2D depth integrated numerical model. Validated with measurements from Acoustic Doppler Current Profilers	[14]
Fiji	Marine current velocity	Measurements using current profilers and satellite data. Current recorded at intervals of 10 min averaged over 20 s. Also temperature and water level recorded	[138]
Iran	Surface velocity, flow power	Current data of measurement stations, 5-min intervals, interpolated to other points	[139]
Indonesia (Alas Street)	Current velocity	Princeton Ocean Model (POM) used to create a numerical model of the Alas Strait. POM is a 3D, time dependent, sigma-coordinate, free surface model. Values of tidal amplitude, tidal phase and angular speed for each constituent and each node on the boundary, were obtained using the Oregon State University Ocean Tidal Prediction Software (OSU OTPS). Validated with measurements from Acoustic Doppler Current Profilers	[140]
UK Southwest	Current velocity	2D finite element model. Turbine arrays modelled by means of a line sink of momentum	[26]
Canada, British Columbia	Tidal volume flux, extractable power	2D finite element model calculates tidal heights and currents	[9,141]
Norway	Kinetic energy flux	Current velocities gathered from DNL (mean maximum spring speed). Kinetic energy flux calculated from velocity and cross-section	[142]
Canada, Bay of Fundy	Tidal amplitude, tidal phase, theoretical turbine power	2D finite-volume model used (FVCOM). Model was run by specifying M2 phase and amplitude at open boundary	[143]
Taiwan, Kinmen Island	Current velocity, flow power density	3D semi-implicit, Euler–Lagrange finite-element model (SELFE) for simulation. Bottom topography data in the coastal seas from National Science Council, Taiwan. Validated with measurements from Acoustic Doppler Current Profilers and tide level measurements	[144]
UK, Pentland Firth	Water level amplitude, currents, extractable power	Depth-averaged numerical model. Actuator disc theory to model the effect of turbines on the flow, and to estimate the power available for generation after accounting for losses owing to mixing downstream of the turbines	[27]
US, South Carolina	Water level, mean flow velocity, maximum flow velocity, power density	Regional Ocean Modelling System (ROMS) used. 3D free-surface, terrain-following, numerical model. ADCIRC tidal database used to define tidal constituents on seaward boundary. Field measurements used to validate results. Model used to simulate impact of the dissipation of power due to the placement of extraction devices	[145]
China, Jiangsu	Flow velocity, power density	2D model built based on MIKE 21 to simulate tidal hydrodynamics. Time-dependent water elevation is provided along open-sea boundary. Validation of water elevation and current velocity with field measurements	[146]
Europe	Water level, current velocity, power density	European Tidal Database based on the Princeton Ocean Model (POM). Tide levels are forced at the model boundary with tidal components from the NAO99 dataset	[147]

forecasts for the sea computed by the operational circulation model cover 48 hours.

A number of commercial offers are available, mainly aiming at navigation (e.g. MaxSea [31]). They are mainly based on data available from public institutions such as NOAA or Meteorological Services.

2.3. Future research

According to [9], “further R&D is needed in the field of resource assessment, both on the measurement side (…), and on the development and validation of suitable modelling systems.” However, in the recent years, modelling approaches have become more sophisticated and have been performed for many regions of the world. What is still missing is a harmonisation of approaches. In Europe, the SI Ocean project aims developing a “harmonized and comprehensive pan-European wave and tidal power resource map”. Current activities of IEC TC 114 include the definitions of resource assessment requirement which will help in achieving harmonisation [32]. Going beyond pure resource assessment, it is necessary to connect resource assessment with local limitations from other activities in the marine environmental such as fishing, shipping, and offshore wind. Also other constraints are being included in resource assessments, for example protected habitats (Section 3.2), and the possibilities of grid connection (Section 5.2).

3. Environmental impacts

Ocean energy – as all other renewable sources of energy – can contribute to a more sustainable energy supply but it is not environmentally friendly per se. The activities involved in manufacturing, operation, maintenance and decommissioning of ocean energy devices will have various effects on the environment. Governments and society need a robust understanding of the environmental implications of ocean energy systems before ocean energy deployment takes place, and also to mitigate or adjust impacts to acceptable levels. While Environmental Impact Assessments (EIA) are performed to ensure that environmental implications of decisions are taken, Life Cycle Assessments (LCA) are used to identify and quantify the impact of industrial products on the environment.

The main direct expected environmental impacts of ocean wave and tidal current technology include impact on the benthic community (due to alterations in flow patterns, wave structures, sediment dynamics), species-specific response to habitat change, and the entanglement of marine mammals, turtles, larger fish and seabirds [33]. However, due to limited observations, the significance of environmental impacts of commercial deployment projects cannot fully be determined yet (see Section 3.2.1 on tidal currents and Section 3.2.2 on ocean wave). Future research in the area of environmental impacts should be focused on localised environmental impacts including e.g. electromagnetic field effects of subsea cables, flow alteration, sedimentation and habitat change of near generation devices. Examples of such efforts include [34,35] that model the impact on beach morphology exerted by wave energy farms or . Furthermore, it was stated that “comprehensive assessment, including both impacts and costs should be performed, applying the well-known Life Cycle Assessment (LCA) methodology to ocean energy generation” [9]. A new range of technologies, devices and sub-systems need in-depth analysis [9]. In addition, competing pressures and uses, e.g. climate change, fishing,

Table 3
Overview of LCA studies on ocean energy.

Type	Device	FU (kWh)	Scope	Impact categories	Results	Reference
Ocean wave	Wave Dragon	1	Cradle-to-grave	EDIP	Scores better in GHG, bulk waste, dangerous chemicals compared to national grid.	[148, 149]
	Pelamis P1	1	Cradle-to-grave	Energy CO_2	Energy and carbon intensities comparable to large wind turbines and very low relative to fossil-fuelled generation. Emissions about 23 g CO_2/kWh.	[150]
	Pelamis P1	1	Cradle-to-grave	EDIP 2003	Based on [150] but CO_2 expanded to GHG and more impact categories. GHG emissions about 30 g CO_2/kWh. Performs well in comparison to other renewable energies and fossil fuels.	[151]
	Oyster 1	1	Cradle-to-grave	Energy CO_2	CO_2 and energy demand calculated including operation and maintenance. Emissions about 25 g CO_2/kWh. Carbon intensity comparable to large wind turbines.	[152]
	Hypothetical WEC array	1	Cradle-to-grave	GHG ODP AP POCP EP	Environmental impact of wave power stems mainly from construction, in particular, production of steel parts. Large possibilities to improve the environmental performance. GWP between 32 and 152 g/kWh.	[40]
Tidal current	Seagen Turbine	1	Cradle-to-grave	Energy CO_2	Carbon intensity significantly lower than PV and slightly higher than offshore wind. Much better as fossil.	[153]
	Hypothetical TEC array	1	Cradle-to-grave	Energy CO_2	Assumptions based on Crest project. Tidal about 2 g CO_2/kWh. Better than wind, hydro and geothermal.	[41]
Wave and tidal	Range of literature	1	Cradle-to-grave	GHG	GHG emissions from wave and tidal less than 23 g CO_2 eq/kWh, with a median estimate of 8 g CO_2 eq/kWh for wave energy. In comparison to fossil energy, GHG emissions from ocean energy devices appear low	[2]

marine transport should be considered when looking at environmental impacts [9].

3.1. Life Cycle Assessment

The literature research shows that a small number of LCA on wave and tidal energy converters have been performed. The main focus was on devices at already more advanced stage of development (e.g. Pelamis, Oyster, Seagen, and Wave Dragon). So far, most of the studies addressed only energy and carbon as impact categories [36]. [2] concludes that there is a lack of studies of good quality, especially for tidal current, OTEC and salinity gradient devices. It is stated that “further LCA studies to increase the number of estimates for all ocean energy technologies are needed” [2].

Table 3 gives an overview of LCA studies on ocean energy found. Several studies have not been included due to a lack of quality. For example, estimates of life cycle carbon emissions and energy payback were given but device type, scope and boundaries of the assessment were not specified in [37]. Other studies included only the production of steel in the LCA for a wave energy converter and only looked at selected emissions [38,39].

All studies performed so far focused on the amount of electricity produced and did not look into issues like fluctuation, storage, or grid integration. Arrays have not been considered except for the studies of [40,41]. For a number of WEC types like point absorbers and marine current turbines, LCAs have not been compiled yet.

3.2. Environmental impact assessment and strategic environmental assessment

Until now, there are still gaps concerning the scientific evidence on the environmental effects of ocean energy technologies [2,33]. Existing data are very much dispersed amongst countries, researchers and developers [42,43]. Since wave energy and tidal energy technologies are at an early development stage, no data on environmental effects from arrays are available.

Environmental impact assessments (EIA) and strategic environmental assessments (SEA) have been undertaken so far, with a focus on Europe and North America. Reviews on the state of research have been published by several institutions. The IEA-OES has summarised available knowledge on environmental impacts of ocean energy devices in three areas: physical interactions between animals and tidal turbines; acoustic impact on marine animals; and effects of energy removal on physical systems [44,45]. Similarly, the SOWFIA project aimed at sharing and consolidating experience of consenting processes and environmental and socio-economic impact assessment best practices for wave energy [46].

3.2.1. Tidal current

In general, benthic habitats will be affected by tidal current energy converters and arrays due to the change of water flows, composition of substrate and sediment dynamics [33]. Potential other effects include mortality of fish passing through turbines (blade-strike) and the collision risk of marine mammals with tidal stream farms [33,47]. A study showed that change in sediment dynamics will most likely be observed following the installation of tidal arrays, impacting on bed morphology and benthic ecosystems [48]. This, in turn, could impact on floral and faunal species. Species of marine mammals and fish could experience distress and discomfort.

However, in their review, Frid et al. concludes that “there is little scientific literature to suggest that operation of underwater tidal stream energy devices will cause elevated levels of mortality to pelagic organisms such as fish and marine mammals” [33]. Also Lewis et al. mention that, “while current technologies have moving parts (rotating rotor blades or flapping hydrofoils) that may harm marine life, there is no evidence to date of harm from tidal current devices to marine life, such as whales, dolphins, seals and sharks“ [2]. A critical issue related to tidal energy converters relates to the noise disruption in turbulent waters, affecting in particular marine mammals, who may be severely affected by such instance [49].

3.2.2. *Ocean wave*

For some devices, an Environmental Impact Assessments has been carried out, including AquaBuoy and Wave Dragon [50]. Wave energy converters can potentially “alter water column and sea bed habitats locally and by changes in the wave environment” [33]. A modelling exercise showed that the installation of wave energy converter arrays can lead to significant changes in the inter-array and surrounding wave field [51].

According to Lewis et al., environmental impact from ocean wave energy devices might include “competition for space, noise and vibration, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution” [2]. As for tidal devices, the environmental impacts are considered comparably small [52,53]. Wave devices will represent a much lower collision risk compared to offshore wind devices but they could be the risk of underwater collisions for diving birds [54].

3.2. *Future research*

According to Lewis et al., “information on the environmental and social impacts is limited mainly due to the lack of experience in deploying and operating ocean technologies, although adverse environment effects are foreseen to be relatively low” [2]. In general, environmental impacts will very much depend on size of installation and the location selected [50]. Potential positive effects such as the creation of roosting sites and habitat enhancement for marine birds might occur as well [54].

The majority of the studies recommend that the first commercial scale installations of ocean energy technology should be accompanied by research studies on the local environmental impacts and for most installations, this will be covered by the EIA that is legally required.

Comprehensive LCA of ocean energy arrays are missing and an integration of aspects such as fluctuation of power output, storage, or grid integration would be very helpful. LCA of a number of major wave energy device types are still missing.

4. Socio-economic impacts

Socio-economic impact assessment addresses how a proposed development might affect the society as a whole or the local population. Various issues can be addressed ranging from well-being and quality of life to employment, income and economic power. For ocean energy, specific topics are negative effects due to visual impacts and the reduction of access to space for other users of the marine environment. Similar to the assessment of environmental impacts (Section 3), both positive and negative impacts of ocean energy deployment on society and economy needs to be studied in order to support evidence-based policy making.

Tools that are commonly used to assess socio-economic impacts are, for example, cost-benefit analysis or social impact assessment. Regional impacts or impacts on the whole economy can be assessed applying models such as computable general equilibrium models or empirical macro-economic models which also allow quantifying e.g. impacts on individual sectors, GDP, public budget, and household income. The FP7 project EquiMar aimed to deliver a suite of protocols for the equitable evaluation of marine energy converters (based on either tidal or wave energy) including economic assessment and cost modelling [55–57].

4.1. *Costs*

Many studies and reports have tried to estimate current and future costs of ocean energy. In general, there is a lack of data due to limited experience at commercial scale. The IEA-OES has published estimates for CAPEX and OPEX depending on the size of deployment (5–50 MW) and they have also addressed cost reduction pathways [42]. The SI-Ocean project has produced a report on cost of ocean energy in 2013 providing costs for early arrays and predictions for future costs by applying learning rates which was followed recently by a study from IEA-OES on the levelised cost of energy of ocean energy technologies [58,59]. Several recent journal articles have addressed specific issues by focussing on operation cost, costs for grid connection, or installation costs. Some examples are highlighted below.

An economic assessment of ocean energy has been performed by [60]. They highlight the lack of operational experience which means that operational costs have to be estimated. They provide a simulation model for operational costs and device availability to overcome these challenges. For the grid connection of an ocean energy array, Lopez et al. provide a preliminary cost estimate including a comparison of AV and DC transmission [61]. Cost components considered are offshore substation costs, cable costs, maintenance costs, and the costs for energy losses.

Morandeau et al. have developed a software tool for analysis and optimisation of marine energy installation [62]. The software incorporates metocean data, project information and vessel characteristics. It has been applied to a case study for two different types of installation vessels. An economic probabilistic model for marine offshore installations calculating CAPEX and OPEX and variation in LCoE of a hypothetical 250 MW wave array was developed by [51]. Their model captures effects of farm layout on energy productivity which allows optimisation of device siting.

An uncertainty analysis of financial aspects of wave energy farms was provided by [63]. The impacts of varying climate and wave conditions as well as feed-in tariffs on financial indicators such as IRR and NPV were quantified using a Monte Carlo method.

4.2. *Social impacts*

A main social impact that is usually addressed in studies on ocean energy is job creation. On national, European and global level, several estimates on the future potential for employment in the sector are available [64,65].

Other social impacts that have been addressed so far include CO_2 reductions [64], positive as well as negative impacts on other marine users [66] and local communities [67]; also the co-existence of fisheries and offshore renewable energy in the UK has been investigated [68]. It seems that other effects are difficult to quantify, including improvements to existing infrastructure; increased knowledge as a result of research and development in wave and tidal, improvements to energy security, health and quality of life.

4.3. *Cost–benefit analysis*

Only one cost–benefit analysis of a hypothetical tidal energy array in Nova Scotia was found in literature [69]. The case study was done for a hypothetical 300 MW farm and included several cost items (e.g. construction costs, operation and maintenance costs) and benefits (e.g. fuel savings, air quality, CO_2 emission reduction). In total, the net present value of the project was estimated to be negative due to the high initial capital costs. Unfortunately, no other cost–benefit analysis could be found to compare the results and findings, an especially to cover future installations including lower CAPEX due to learning curves.

4.4. Future research

Many studies address economic aspects of ocean energy including predictions of future costs of ocean energy. Still, there are improvements needed, especially in terms of operation and maintenance costs. Clearly, cost-benefit analyses including also aspects such as grid integration, energy security, and ecosystem services are missing. Social impacts are not well understood, when it comes to impacts beyond job creation such as welfare [70]. In particular, studies on the effects on national and EU level as well as coastal communities are needed [67,71].

5. Grid integration

The integration of ocean energy in the electricity grid poses various challenges. Firstly, ocean energy arrays have to be connected to the grid which can be very expensive since several components such as an array and subsea electrical system and a submarine cable connection to the shore are needed. Of course, grid availability in proximity to ocean energy arrays is a prerequisite for future developments [4]. Often, however, areas that offer good ocean energy resources are remote and often not connected with existing grid installation, thus requiring either grid upgrades or new-built capacity [5]. Grid integration is thus first of all an issue of electricity distribution and transmission and has also to be seen in the context of renewables integration at large [72].

Secondly, variability of electricity production from ocean energy devices might lead to issues such as grid congestion, weak grids, and voltage stability problems which is also related to technological development. Possible solutions and strategies to solve these problems are currently being researched and will be presented in the following sections.

5.1. Variability of resources

Ocean energy is a variable resource. Tidal current energy is periodic, and thus, resource forecasts are possible with a high reliability over long time horizons. Ocean wave energy can be considered a “stochastic” resource like wind energy [73]. For tidal currents, variability is very high on an hourly basis but limited for longer time horizons (e.g. monthly, yearly variation). On the contrary, variability for ocean wave energy is relatively low for short time scales (hours) but can be great for longer periods of time , for example on a seasonal or annual basis [2].

Reikard states that the forecast for wave energy is more precise than forecasts for wind and solar energy [20]. Still, the grid integration of ocean energy is of course influenced by the variability of resource availability. Several measures exist to accommodate for resource variability according to [74], including resource forecasting, intra- and inter-site smoothing, generation and load mix, and storage (e.g. pumped hydro, battery storage).

5.2. Grid connection and grid codes

In many cases, areas with great potential for ocean energy are located at regions with low population density with weak electricity networks. This may lead to a limitation of the electricity delivered to the grid due to quality of supply [75,76]. A reinforcement of transmission and distribution networks will most probably be necessary which implies high additional costs.

Grid codes for transmission and distribution networks specify parameters such as frequency stability, voltage, power factor, and harmonics that an electricity generating facility has to meet in order to guarantee the safe operation of the electricity grid. Usually, distribution system operators establish the local regulations in distribution codes while transmissions system operators define the main transmission grid regulations.

Currently, no European standard grid code exist but the various national system operators issue their respective grid codes and usually, the requirements differ between countries [77]. At the moment, a range of countries are updating grid codes or developing new grid codes dedicate to the accommodation of a growing share of renewable electricity [78]. The MARINET project, funded by FP7 of the European Union produced a report on grid integration and power quality testing and reviewed the national grid codes [79,80]. The project highlighted that employing state-of-the-art technology from wind energy, such as frequency converters, will likely allow for grid-compliant installations of ocean energy farms [80].

5.3. Power quality and control

The power quality of ocean energy converters has to comply with distribution and transmission grid codes. MacEnri et al. checked performance of the SeaGen device against EN 50160 [82] in their study [81]. It concluded that “SeaGen works very well from a power quality perspective and is fully compliant with EN50160” [81]. It was considered unlikely that power quality problems will occur when arrays of the device will be installed.

In the future, renewable energy producers will face increasing demands on power quality to contribute to system reliability and stability. A number of requirements will have to be met including e.g. voltage control and regulation, fault ride-through capabilities, active power control, and frequency regulation [78]. IEC TC 114 is working on defining the electrical power quality requirements for wave, tidal and other water current energy converters in working group PT 62600–30 which will increase harmonisation amongst developers [32,83].

Demands on the control ocean energy converters and arrays will be of high importance [76]. This includes voltage and power factor control as well as power conditioning [75]. Hong et al. present an overview of control strategies for ocean energy devices including oscillating water column, attenuators, and overtopping devices [84]. They argue that further research on control strategies are needed since they also offer the “potential to dramatically affect the absorbed energy and hence the economy of the devices”, which is also highlighted by [85]. Also Bacelli and Ringwood studied available control strategies for arrays of wave energy converters with respect to maximisation of energy absorption and conclude that performance can be increased by applying optimised control strategies [86]. The DTOcean project has a work package to identify, adapt and develop methods to optimise operational aspects of arrays of wave and tidal devices in terms of system control and operation [87].

Ongoing research tries to model impacts of ocean energy arrays on the grid by means of power flows and dynamic simulations. For example, Armstrong et al. studied the connection of hypothetical wave farms (one OWC farm and one heaving buoy farm) to the Western Interconnection (WECC) system [88]. Impacts on the transmission system were modelled in terms of voltage violations, loading conditions, congestion level, and substation performance. Impacts at the point of connection were quantified by assessing e.g. voltage level, flicker, harmonics, and low voltage ride through. It was shown that the integration of the wave energy farm would not pose any significant problems to the grid. Tedeschi and Santos-Mugica simulated the impacts of a wave farm (multi-MW point absorber) using the Spanish offshore testing facility Bimep as a real test case and studied different control options [89]. The model showed the importance of both wave and grid side energy wave energy converter control. In addition, centralised real-time control of the whole wave energy array reduced power variability and in consequence impacts on the grid.

5.4. *Future research*

Grid connection of ocean energy faces challenges due to weak electricity grids in rural areas. Reinforcement of grids will be needed which comes at high costs. The synergies with offshore wind farms need to be explored. At the moment, no single European standard grid code exists. Instead, the ocean energy sector – as other electricity producers – has to comply with the respective national or regional grid code. We will see increasing demands on power quality of renewable energy to contribute to system reliability and stability (e.g. voltage control and regulation, fault ride-through capabilities, active power control, and frequency regulation).

Most probably, the quality of power output from ocean energy arrays will meet the grid code requirements. However, adequate control systems for ocean energy converters and arrays have to be developed. Further research in the area of control strategies is needed since it offers a great potential for cost reduction due to increased absorbed energy while allowing meeting grid codes requirements.

6. Installation, operation and maintenance

The installation, operation and maintenance of ocean energy devices are relatively expensive. It is estimated that annual operation and maintenance costs of ocean energy devices can be as high as about 3.4–5.8% of capital expenditure compared to 2.3–3.7% for offshore wind [90]. One way to reduce those costs is to standardise equipment and procedures by industrial cooperation [4,6,91]. Other promising improvement options include the use of modelling tools to improve array layout and design which will lead to increased device and array efficiency and a reduction of costs.

6.1. *Array configuration*

Only few research papers have addressed issues of array configuration. One line of research looks at the impacts from ocean energy arrays on the hydrodynamic characteristics of the marine environment. One example of such a study is [48] who studied the effects of the configuration of a tidal array (turbine spacing and capacity) on water flows and water levels in the Shannon Estuary by means of a numerical model. They conclude that water flows and water levels will be affected, including a reduction in tidal range and a delay in high and low tides. Fallon et al. also develops suggestions for the optimisation of array spacing and location [48]. The FP7 project DTOcean ("Optimal Design Tools for Ocean Energy Arrays") has a dedicated work package on array layout. The project has already performed an assessment of capabilities of currently available tools studying the hydrodynamic interaction between the devices within the array but also with the resource and it will also determine how this affects the resource, power performance, cost uncertainties and environmental impact for selected scenarios [92]. It has to be noted, however, that array configuration will be highly dependent on the ocean energy device or technology chosen and flexibility will also be limited by the specific location chosen.

Going beyond impacts on hydrodynamics, some authors have tried to assess the influence of array configuration on power output as well. As an example [93], studied the impact of the shape and density of tidal current arrays (1000 × 10 m diameter turbines) on hydro-environmental parameters and the energy output in the Severn Estuary and Bristol Channel. They concluded that the layout of a turbine array can have significant impacts on power output and, to a lesser extent, on hydro-environmental parameters. Lee et al. [94] modelled ocean current flows to optimise tidal current turbine array layout. They found that turbine efficiency increased with distance between generators and a distance of three times the turbine diameter was appropriate. Similarly, for wave energy, studies shave addressed modelling and optimisation of power output of arrays [95–97].

6.2. *Installation*

So far, only a few full-scale devices have been installed and thus practical experience is limited [75]. However, the ocean energy sector can build on technology and know-how from other offshore energy technologies [69,75]. Installation equipment from the oil and gas industry might be used but it could be too expensive since for ocean energy projects, the installation costs are responsible for a high share of investment costs [62,98]. Installation of ocean energy devices has to be easy and fast in order to reduce costs for the installation process [69]. In the case of tidal devices, this is also an important prerequisite because installation has to be performed during slack tide which means a limited time period.

The installation process and costs for wave and tidal devices will significantly depend on the location. For example, shore based wave energy converters might need solid foundations and heavy infrastructure. The same is the case for bottom-mounted tidal devices which demand substantial foundations. The mooring of floating devices with drag-anchors seems to be a very economical solution while in some cases the sea-bed characteristics will demand other and more expensive mooring types such as pin piled moorings [98]. Only few papers have tried to establish models or tools to assess resource needs for installation requirements in terms of time and cost.

6.3. *Operation and maintenance*

Ocean energy devices will operate in harsh environments. Demands on survivability and reliability are high since the economic impacts due to failures can be significant. Maintenance costs for ocean energy devices will be high as for any other offshore technology and have a high share of lifetime costs [58].

The most common issues ocean energy devices will face are bio-fouling (moorings, floating or submerged parts of the device) and corrosion [75,99]. Research needs to develop special coatings that prevent bio-fouling and corrosion but also sealing materials and electric insulation materials for saline environments [75,100]. Developers aim at reducing maintenance intervals by creating very robust devices and designing devices for ease-of-maintenance.

Current research tries to model the reliability and possible failure rates of ocean energy devoices. For example, Thies et al. developed a methodology to simulate component reliability and failure rates under defined operational conditions [101]. Device testing in environments that can produce the same conditions as in real waters is a prerequisite for assessing device and component reliability [69]. Also array design parameters (e.g. device spacing) impacts on maintenance activities and costs and this is not very well understood so far.

An important aspect that has to be taken into account when designing ocean energy devices and developing ocean energy projects is that maintenance and repair activities can only be carried out in favourable weather conditions. Weather window analyses study the levels of access in terms of a number of weather characteristics (e.g. wave heights, wind speed). Inaccessibility of ocean energy devices for maintenance and repair might require other maintenance strategies such as onshore maintenance in order to ensure economic viability of projects [102].

6.4. Future research

Arrays of ocean energy converters have not been installed yet. However, models have been created that allow capturing the effects of arrays on hydrodynamics as well as power output. Since no long-term experience with devices is available concerning commercial operation and maintenance, there are only a few articles published that try to assess the resource needs for installation (e.g. time, cost). Array design parameters such as device spacing might have an impact on operation and maintenance activities and costs: this is not very well understood so far. Concerning reliability and performance, current research tries to model the reliability and possible failure rates of ocean energy devices.

7. Regulatory and legal affairs

Ocean energy is promoted by governments as a renewable source of energy that will help reaching climate targets and contribute to a secure energy supply. However, often not much attention is given to the existing legal framework and legal barriers may hinder the development of ocean energy [103,104]. It is thus important to study the legal framework to analyse the current legal situation, to identify best approaches and conflicting regulations [104,105].

7.1. Legal framework

The UN Convention on the Law of the Sea defines the main legal framework for the use of the oceans [106,107]. According to the Convention, territorial waters or territorial sea encompasses the coastal waters up to 12 nautical miles from a baseline which usually is the mean low-water mark. Territorial waters are sovereign territory of the state and give the full rights over water, sea bed and subsoil. The coastal country has the right to set laws, regulate the use of the ocean in its territorial waters [107]. The territorial waters are followed by an exclusive economic zone extending up to 200 nautical miles from the territorial sea baseline where a country possesses the rights to explore, exploit, conserve and manage the natural resources of the water column and seabed. Most ocean energy devices have and will be installed in territorial waters [107].

In many countries, there is no specific legal and regulatory framework for ocean energy in territorial waters [108]. For example, in the case of Ireland, existing environmental and maritime legislation applies to ocean energy including the following legislative instruments [103]:

- Foreshore acts (e.g. [109,110]);
- Electricity regulations (e.g. [111–113]);
- EU EIA Directive [114,115];
- EU Habitats and birds directive [116];
- EU SEA Directive [117];
- EU Renewable Energy Directive [118].

Legal and regulatory issues are a barrier towards ocean energy deployment. Leary and Esteban state that regulatory uncertainty appears to be the most significant non-technical barrier to the ocean energy sector [119]. They mention that in the USA, more than 23 federal and state regulatory agencies are involved in ocean energy projects. Often, approval processes are complex due to the large range of legislation and regulatory bodies. O'Hagan and Lewis mention Ireland as another example, where “management of all maritime sectors proceeds largely in an ad hoc, non- integrated manner with little formal inter-departmental communication” [103]. A comparison of national policy frameworks of the UK and France performed by the MERiFIC project showed that there are substantial differences between countries in terms of consenting procedures and "fragmentary evolution […] of consenting procedures for marine renewables" leads to complications [120].

The H2020 project RiCORE funded from the EU is a research project studying the legal framework for offshore renewable energy in EU Member States. It will support the improvement of consenting procedures by providing best practices [121].

7.2. Maritime and spatial planning

Marine spatial planning is considered as a solution to overcome problems with overlapping jurisdiction and to support ocean energy to tap the full potential [103,122]. According to [123], it can “help to avoid user conflicts, to improve the management of marine spatial claims, and to sustain an ecosystem-based management of ocean and seas”.

Maritime Spatial Planning (MSP) has not been fully introduced in all EU Member States so far [104,124]. In 2013, the European Commission has proposed a Directive on maritime spatial planning and integrated coastal management in 2013 which has been adopted by the European Parliament in April 2014 [125]. The Directive will make maritime spatial planning and integrated coastal management mandatory in the EU Member States. Maritime spatial planning is an important pillar in the Commissions' strategy for blue growth. It is hoped that over-regulation and administrative complexity can be reduced allowing for accelerated investment in the marine environment and generating economic gains [126,127].

Case studies using applying marine spatial planning for the ocean energy sector have already proven that it offers the potential of an integrated management of marine resource use [128,129]. In addition, it offers the potential to optimise siting location for ocean energy devices by accommodating the economic constraints for ocean energy production, conflicts with other marine users and for minimising environmental impacts.

7.3. Future research

The research in the area of regulatory and legal affairs that has been executed so far has focussed on consenting procedures and the approval process for ocean energy projects. In addition, the advantages of integrated management tools such as maritime spatial planning have been highlighted. Still, more detailed research is needed concerning regulations and legal frameworks [130]. Wright suggests comparing jurisdiction of some more advanced in order to identify the most optimal framework [131].

8. Conclusions

This study has reviewed the state-of-research in ocean energy, focusing on wave and tidal current, not directly associated with improvement to ocean energy technology and identified areas where future research efforts should be directed to.

Modelling approaches for resource assessment and forecasting are already very advanced and have been performed for many regions of the world. However, this should be widened to accommodate conflicting or competing use of the marine environment such as fishing, shipping, offshore wind, habitat protection and also technical limitations (e.g. grid connection).

Comprehensive Life Cycle Assessments of ocean energy arrays that would also include areas like fluctuation of power output, storage, or grid integration are still missing and for a number of individual WEC types, no Life Cycle Assessments are available so far. Another area which merits further research is the field of regulatory and legal affairs to define an adequate and optimal legal framework for ocean energy.

In terms of grid integration, the impacts of increasing demands on power quality of renewable energy to contribute to system reliability and stability should be discussed. Further research in the area of control strategies is needed since it offers a great potential for cost reduction due to increased absorbed energy while allowing meeting grid codes requirements. No long-term experience with devices is available concerning commercial operation and maintenance and few articles try to assess the resource needs for installation (e.g. time, cost). Array design parameters such as device spacing might have an impact on operation and maintenance activities and costs: this is not very well understood so far and should be addressed.

The most important areas, however, where future research should be focussing on are the economic and social impacts of ocean energy. A broad cost benefit analysis of ocean energy incorporating aspects such as grid integration and energy security could be very important. Economic aspects of ocean energy including predictions of future costs of ocean energy have been addressed but improvements are needed, especially in the area of operation and maintenance costs. Cost–benefit analyses that include also aspects such as grid integration, energy security, and ecosystem services are missing. Social impacts are not well understood, when it comes to impacts beyond job creation. In particular, studies on the effects on national and EU level are needed.

9. Disclaimer

The views expressed in this paper are purely those of the writer and may not in any circumstances be regarded as stating an official position of the European Commission.

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