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Effects and management implications of emerging marine renewable energy technologies

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ABSTRACT

Offshore renewable energy technologies are being tested and deployed around the world to mitigate climate change and to bring clean sustainable energy to remote locations. The trend is being led by the development of offshore wind, with energy from waves, tides, and large run of the river turbines also increasing. However, there are additional marine renewable energy technologies that will help to fill in gaps of availability and location for power production. These emerging technologies are generally less well known, including ocean thermal energy conversion, seawater air conditioning, power from salinity gradients, and floating solar photovoltaics (floatovoltaics). Coupled with each of these power production systems is the need for energy systems at sea to aid in storage and transport of the energy. There is little known about the potential environmental effects of these emerging technologies or undersea energy storage, or how they might best be managed. This paper describes the new technologies and explores the potential effects on the marine environment and wildlife and recommends approaches to their management.

1. Introduction

Offshore renewable energy is expanding across the globe with countries deploying offshore wind, wave, and tidal devices in nearshore and in coastal waters to generate power to augment national grid electricity (Copping et al., 2018). Smaller versions of wave and tidal devices are under development to power remote communities and islands, as well as to provide power at sea for ocean observation platforms, aquaculture facilities, seawater mining for critical minerals, and to develop methods for marine carbon dioxide removal (mCDR) (Cotter et al., 2021). These smaller scale offshore renewables often rely on storage and microgrids, adding security to the energy supply and minimizing intermittency (Green et al., 2019). Bottom-based offshore wind is a large commercial industry while wave, tidal, floating offshore wind are progressing towards large deployments (Mathijssen et al., 2020). Investigations of potential environmental effects of offshore renewables on marine animals, habitats, and ecosystem processes are ongoing, to meet statutory requirements for project development, as well as to address ongoing concerns from stakeholders and regulators driven by uncertainties of interactions (Garavelli et al., 2024).

Potential environmental effects from existing offshore renewables continue to be investigated and there remain questions about interactions with marine animals and seabirds, habitats, and ecosystem processes, particularly as larger arrays are deployed. At the same time emerging offshore renewable technologies are under development around the world. To date few of these emerging technologies have been deployed at scale and there is little known about the potential environmental effects of these technologies (Fig. 1). These emerging technologies include those that derive power from seawater gradients including thermal gradients - Ocean Thermal Energy Conversion (OTEC) and seawater air conditioning (SWAC), as well as from salinity gradients (Soukissian et al., 2023). Energy from solar radiation is under scrutiny

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with deployments of floating photovoltaic installations or floatovoltaics moving out of sheltered bays and reservoirs to the open sea. Investigations are ongoing into storing excess power produced at sea that is not transmitted to land by export cable or used onsite, through a range of energy storage media including battery banks, conversion and transport of hydrogen or ammonia. The potential for merging and co-locating several of these emerging technologies has led to investigations into multi-use platforms that may combine several technologies and end uses (e.g., the EU-project TROPOS: https://mcc.jrc.ec.europa.eu/main/dev.py?N=simple&O=300&titre_chap=%C2%A0&titre_page=TROPOS)

The energy efficiency, engineering details, and methodologies for installation, operation, and maintenance of these systems, and are well covered in the engineering literature, and are not within the scope of this study.

Each of the emerging technologies has specific siting and operating conditions that must be met. Few of each of these technologies have yet been deployed. Table 1 outlines the requirements for siting and operating each. Because few of these technologies have been deployed, there is little research on public perceptions and attitudes towards these installations.

This paper seeks to place the emerging offshore renewable technologies in perspective, to examine what is known about potential effects of these technologies on the marine environment at small and large scale, to explore knowledge gaps, and to recommend research and monitoring studies that will help clarify these effects. This information will be needed to responsibly develop emerging renewables and to provide a path forward for regulators and advisors to engage with project developers in the pursuit of low carbon power. A description of each of the emerging technologies will be presented, with a review of existing studies, and recommendations for research and monitoring that will clarify effects. An initial assessment of the likely risks posed by these technologies will be provided.

2. Methods

As there are few commercial scale deployments of emerging renewable offshore energy technologies, information for this study was taken from the scientific literature, from small pilot or demonstration projects, and from expert opinion as represented on the ICES workgroup on offshore renewable energy (https://www.ices.dk/community/groups/Pages/WGOre.aspx).

Table 1
Locations that are most appropriate for siting and operating emerging marine renewable energy technologies.

Emerging Technology	Criteria for Siting
OTEC	Tropical and subtropical areas where 20°C differential between warm surface and cold deep water can be maintained. Generally, water intake depths of 800–1000m
SWAC	Can be used in tropical, subtropical, and temperate/boreal areas where deep water is cooler than ambient air temperatures. Water intake depth can vary from the surface (in temperate areas) to 100s of m in the tropics.
Salinity gradient	Mouths of large freshwater rivers that discharge into saline waters, generally in tropical areas.
Floating PV	Year round generation in tropical, subtropical, and temperate areas with little cloud cover, seasonal generation in boreal areas.
e-fuels	Can be generated wherever offshore renewables are sited.
Energy storage	Storage can be situated on the sea surface, subsurface, or on the seabed, depending on type.

Commensurate with the scale of deployment, there are few well developed consenting and licensing processes that adequately address these emerging technologies in Europe (Galparsoro et al., 2022). There is a similar lack of documentation of existing consenting and licensing processes for emerging renewable technologies offshore in the Americas and Asia. Most applications for emerging (and even some more established offshore renewables) are viewed through a lens of offshore oil and gas development, or other offshore installations, although most nations are in the process of developing regulatory schemes that are better adapted to offshore renewables, particularly offshore wind. In evaluating the potential effects of emerging renewables on the ocean environment and its inhabitants, this study is taking a risk-based approach, evaluating each technology and its subsystems against the most likely marine animals, habitats, or ecosystem processes that may be affected. In keeping with the approach to environmental effects on more established offshore renewables, stressors such as risk of collision with rotating blades, effects of underwater noise from devices on animal navigation and communication, and others are lined up against each of the emerging technologies (Table 2) Some risks will be encountered across all the emerging technologies. These may include: construction

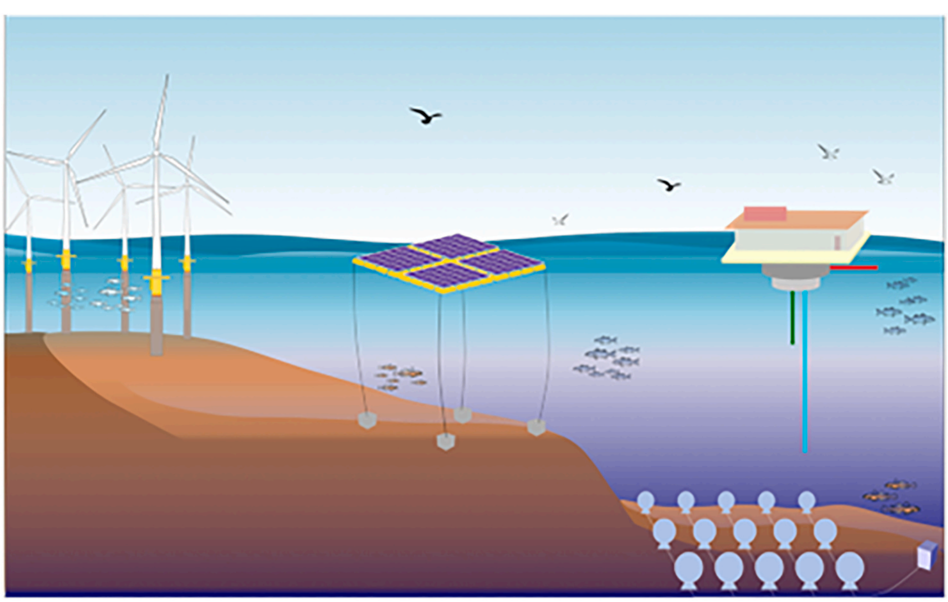

Fig. 1. Illustration of established offshore renewables (bottom based wind on left) and emerging renewables and subsea storage: floating solar (center), floating OTEC (right), and bottom based subsea storage (bottom right).

Table 2
Framework for evaluating risk from emerging renewable offshore technologies.

Emerging Technology	Stressor	Source of stress	Receptor most likely to be affected	Probability of interaction	Consequences of the interaction	Overall level risk

sounds that may range from pile driving to setting of anchors (Bellmann et al., 2020), as well as acoustic output from the additional vessel traffic needed for deployment and maintenance (Stanley et al., 2017; Lemos et al., 2022); physical risk to large cetaceans from the increase in vessel traffic (Peltier et al., 2019); providing potential pathways for invasive species to enter into the ecosystem (De Mesel et al., 2015); and emissions of electromagnetic fields from power export cables (Gill and Desender, 2020). These risks are similar to those investigated for other offshore renewables and are not the focus of this study as they are well documented elsewhere. This study focuses on risks that are unique to the emerging renewable technologies.

In addition to environmental considerations, socio-economic effects of emerging offshore renewables may occur, such as effects on commercial and recreational fishing, interference in shipping lanes and routes for commercial, recreational, and security traffic (Sahu et al., 2016). Tools such as marine spatial planning can assist with recognizing and minimizing these effects as they have for offshore wind (Schupp et al., 2019), as well as co-location of offshore renewables with other industries such as aquaculture (Zheng et al., 2020). These effects will need to be investigated but are also not the focus of this study.

3. Results

Each of the emerging renewable energy technologies – ocean thermal energy conversion, seawater air conditioning, salinity gradient power, floatovoltaics, and undersea energy storage – are addressed by the source of the energy, description of the technology, and potential environmental effects.

Many of these emerging technologies share potential environmental effects which will need to be evaluated through installation, operation, maintenance, and decommissioning stages (Gorjian et al., 2021). For example, several of the emerging technologies examined are dependent on a floating platform, tethered to the seafloor. Effects of floating offshore wind platforms may create similar effects and potential risk involving interference of movement by large marine animals. However, OTEC and SWAC platforms and floating solar systems will cover much greater areas of the sea surface, and may create shading (de Lima et al., 2021) and changes in local hydrodynamics (Karpouzoglou et al., 2020). These structures will also form larger reefs and fish aggregation devices, which may change the local ecology, and could provide a route for non-indigenous invasive species to enter into an area (Duarte et al., 2013; Adams et al., 2014).

3.1. Ocean thermal energy conversion (OTEC) and seawater air conditioning (SWAC)

3.1.1. Source of energy

The circulatory pattern of the world oceans - “ocean conveyor belt” - creates temperature gradients in tropical and subtropical waters with warm surface water and deep cold water (Lozier, 2010). The potential heat energy between these two water masses can be used to generate power through OTEC in areas where the temperature differential is at least 20°C. This distribution of warm and cold water offers opportunities to produce energy to reduce conventional energy consumption and provide products such as potable water, energy carriers, and critical minerals (Wick and Schmitt, 1977; Penney and Bharathan, 1987; Avery and Wu, 1994; Takahashi, 1999; National Research Council, 2013).

The ocean thermal resource exploitation is divided into two major categories—OTEC and cold water source cooling, also known as seawater air conditioning (SWAC). Warm surface water overlies cold deeper water in the tropical and subtropical oceans, where the temperature difference can reach more than 25°C during summer months. OTEC uses thermal heat engines that generate power using this temperature difference (D’Arsonval, 1881; Claude, 1930; Avery and Wu, 1994; Vega, 1995). SWAC uses cold ocean water, which can be located on the surface or drawn up from deeper regions to provide the cold source for air conditioning (Kempener and Neumann, 2014).

3.1.2. OTEC and SWAC technologies

OTEC plants are made up of heat exchangers, turbines, long seawater pipes and pumps with the intake (warm surface and cold deep water) and discharge pipes running to the appropriate depths in the ocean. Warm surface water is generally drawn from a few meters below the surface while the cold deep water is drawn from depths of 600–1000 m or deeper. Used (cooled) warm water is discharged near the surface while the used (warmed) deep cold water is discharged through a diffuser at a depth greater than the seasonal thermocline but shallower than the permanent thermocline.

OTEC plants can be designed for onshore with all the components on land except the intake and discharge pipes. An excellent example is the 100 kW_{net} plant at Kumejima island near Okinawa (http://www.ocean-thermal.org/kumejima-model-project/). Maintenance for onshore plants is simplified by their location and is treated as routine industrial maintenance. Offshore OTEC plants can be mounted on barges or vessels at sea, either anchored to the seafloor or freely drifting, with all components placed on the offshore platform and flexibly attached to the intake and discharge pipes to manage movement of the platform and to allow for disconnecting the platforms during severe storms. Construction of onshore plants follows that of other industrial facilities with the intake and discharge pipes laid from shore through the intertidal areas. Offshore platforms are designed usually to be moored to the seabed with a power export cable to shore. Full-scale OTEC plants require high flow rates; for example, a 1 MW_{net} plant will require a cold water flow of 2–3 m^3/s, with similar volumes of the warm water (Vega, 2017).

New offshore OTEC designs envision free floating or motorized vessels that can be used to move the plant to different locations. These platforms could be deployed far from land and, rather than connecting to shore via an export cable, would likely produce electrofuels (efuels) for export, such as ammonia and hydrogen. While maintenance of the platforms and OTEC systems should be minimal, maintenance crews would be deployed from land as the platforms are not likely to be crewed.

OTEC technologies heat a working fluid to a vapor that drives a generator (Fig. 2) (Johnson, 1992; Ascari et al., 2012). OTEC technologies exist as three major types: closed cycle, open cycle, and hybrids of the two. Closed cycle OTEC systems use a working fluid with a low boiling point, most commonly ammonia. Although other working fluids are also used, many are toxic (e.g., hydrocarbons) or of environmental concern (e.g., chlorofluorohydrocarbons). The working fluid is heated to a gas by passing warm surface seawater through a heat exchanger and is used to power a turbogenerator to produce electricity. Cold deep seawater is pumped through a second heat exchanger to condense the working fluid back to a liquid. The working fluid exists in a closed system and is reused throughout the life of the plant. Open cycle OTEC plants use seawater directly, rather than a working fluid, to generate electricity. Warm surface water is placed under low pressure, distilling the water to a freshwater vapor which can be used to drive a turbine and an electrical generator. The water vapor is condensed through heat exchangers with the cold deep ocean water, creating freshwater that is suitable for drinking and other uses. Hybrid OTEC systems combine the closed and open cycle systems, with warm seawater evaporating to steam. The steam is used to heat the working fluid (most commonly

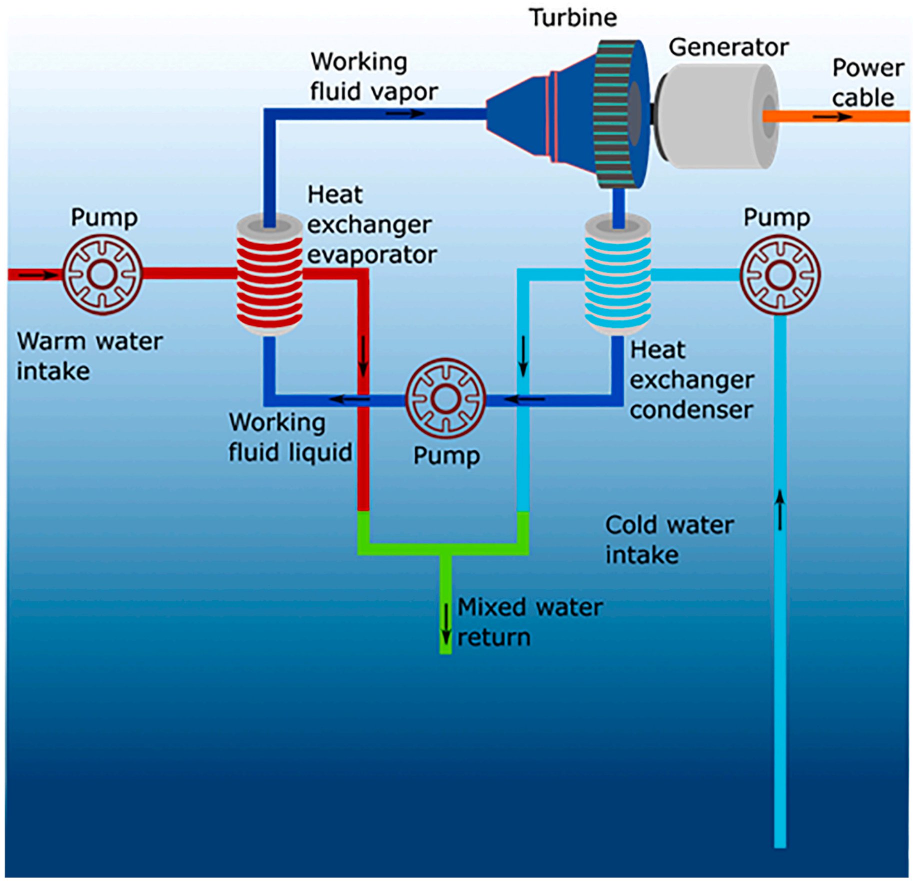

Fig. 2. Schematic that describes a typical OTEC cycle to generate power.

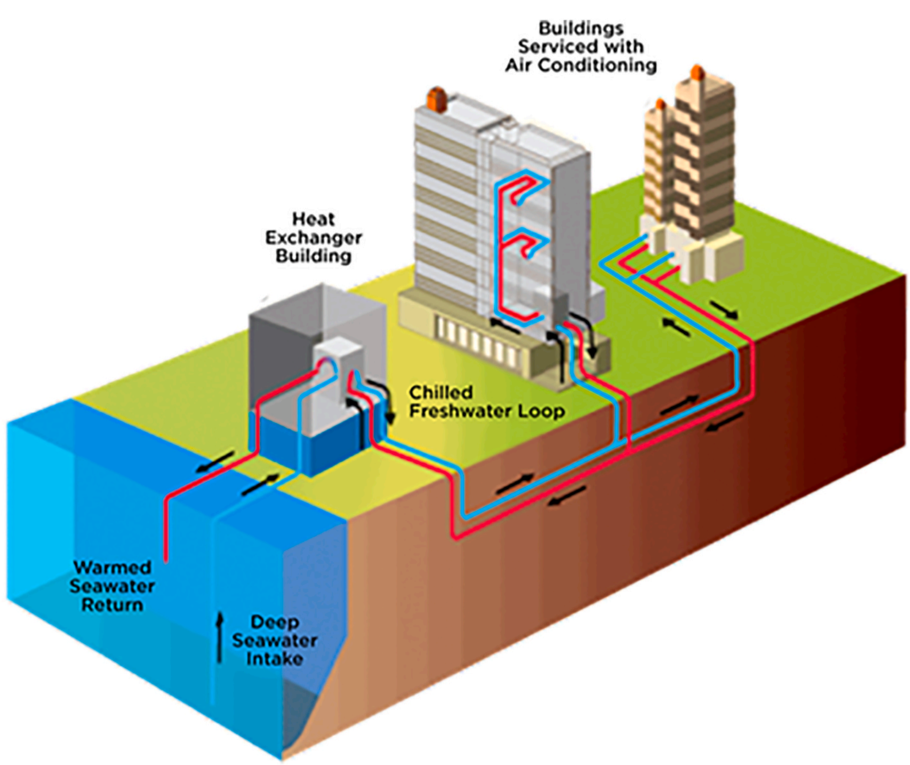

Fig. 3. Schematic of SWAC process that involves the intake of cool water, circulation through buildings, and return of warmer water to the ocean. (Source: Ocean Thermal Energy Corporation).

ammonia) in a closed loop cycle and is then cooled with the cold ocean water. This type of system can also produce freshwater.

More recently, innovative smaller-scale OTEC technologies and applications are providing interesting and increasingly affordable marine energy solutions. Waste heat recovery from commercial processes is yet another application of OTEC that can increase energy efficiency by using the temperature difference between heated water used for plant cooling and cooler local waters.

Nations with significant tropical waters have been developing small-scale coastal SWAC combined with desalination to provide cooling and desalinated water for small coastal communities and resorts.

SWAC for residential use of cold water for cooling can save significant amounts of energy used for air conditioning, both in temperate areas for industrial use (Mitchell and Spitler, 2013) and in tropical areas where the energy use can be reduced by as much as 85 to 90 percent (Makai, 2022). SWAC uses much lower volumes of cooling water than OTEC, due to the high thermal capacity of water, allowing for efficient SWAC at lower temperature differentials than OTEC (Essalhi et al., 2023; Kempener and Neumann, 2014). SWAC is also referred to as cold water cooling and has been used for pre-cooling in coastal thermal plants generating power from fossil fuels for decades (Fig. 3).

In regions with colder climates, the coastal waters and fjords may stay warmer at depth than the surface waters during winter. During winter the warmer deep water can be used for residential/district heating via heat pumps and an onshore network for warm water distribution. This is commonly termed 'thermal fjord energy'. Such plants may be run in reverse during summer, to provide residential air conditioning (Fig. 4).

3.1.3. *Potential environmental effects of OTEC and SWAC*

There are three potentially important environmental effects of OTEC, as well as some speculative additional other effects (Coastal Response Research Center, 2010a, 2010b). Potential effects of SWAC are similar to those of OTEC but are less severe as lower volumes of seawater are entrained with smaller thermal differentials. The three effects of OTEC that need particular scrutiny are: effects of the cold water return; entrainment of marine life in cold water pipes; and chemical discharges. Other potential effects from OTEC include reefing, effects on habitats and migratory routes, entanglement, and pathways for invasive species.

The cold deep ocean water brought to the surface for heat exchange in the OTEC process could be up to 20°C colder than ambient surface water, creating a thermal shock to organisms if discharged in the surface or shallow subsurface waters, and potentially destabilizing the stratification of ocean water locally that maintains warm water at the surface (Giraud et al., 2019). To mitigate these effects, the used cold water must be discharged at an intermediate depth (which can be determined by numerical modeling) in such a manner that it is diluted to match ambient water temperatures and the denser water sinks to the appropriate depth. Discharges of this type are used for wastewater and industrial discharges into the ocean and are regulated under water quality regulations in most nations. The cold deep water will also contain higher levels of dissolved nutrients, carbon dioxide, and lower levels of dissolved oxygen, which will also reach background levels at the appropriate depths in the subsurface ocean if the discharge is managed correctly.

The cold water pipe that pumps deep ocean water in most OTEC operations has the potential to entrain fish or other marine organisms, bringing them up to the surface where they are unlikely to survive the change in pressure. The presence of marine life in the deep sea is sparse, as there is little food at these depths to sustain a complex food web. Evidence from the operational OTEC plant in Okinawa province in Japan over 8 years indicates that this event is very rare—less than one fish is seen a year (pers. comm. B. Martin). Similarly, evidence from the Natural Energy Laboratory of Hawaii Authority (NELHA) plant in Hawaii indicates that this event is so rare it is never recorded. Special consideration would be given to threatened and endangered species that might come into contact with an OTEC platform or pipes, although inventories and monitoring of deep sea life are rare and effects would be difficult to discern.

OTEC platforms, particularly large plants at sea, will have some harmful chemicals on board, notably petroleum products for lubricating turbines (although biobased oils may be substituted). Closed OTEC systems use ammonia or other chemicals as the heat exchange medium. Leakage of these chemicals in gaseous form could be harmful to human

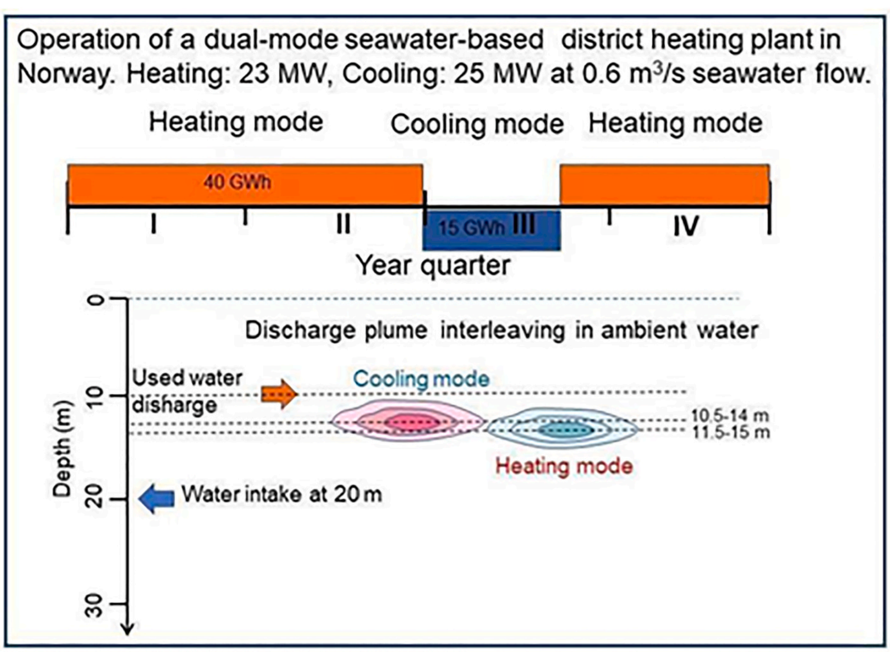

Fig. 4. Two operational modes of a plant extracting thermal energy from mid-depth in a fjord: warming during winter, and cooling during summer. The water intake in this example is at 20 m depth, and the discharge at 10 m depth. In both modes, the discharge plume tends to sink below the discharge depth and interleave somewhat deeper during winter than during summer.

and marine life. Assessments and mitigation plans for hazardous materials can be helpful in mitigating this threat and should also address shoreline and nearshore effects from losses of portions of the platform, moorings, pipes, and other hardware that might occur during a storm. The electricity cable will set up an EMF at the seabed that potentially can affect marine organisms.

For onshore OTEC plants there may be effects on subtidal and intertidal habitats from the cold and warm water pipes crossing coral reefs and other valuable habitats. Fish and other organisms may reef or congregate around an offshore floating OTEC plant and/or the intake pipes. However, it is difficult to define a pathway for harm to the organisms or the environment. Similarly, biofouling organisms will grow in heat exchangers, pipes and on all submerged parts of an OTEC plant. This becomes a maintenance issue to ensure that the growth does not impede operations but does not affect the surrounding environment. If floating offshore OTEC plants were to increase in size and number in the area of key migratory pathways for marine organisms, there is the potential for the presence of the platforms to interfere with migratory routes of marine mammals, sea turtles, and large fish to be displaced from their preferred routes, potentially causing the animals to suffer from bioenergetic losses, increased predation or competition for food, or other potentially deleterious effects. It has been postulated that mooring lines and electrical cables draped in the water column from floating platforms for offshore wind, and presumably OTEC, could pose an entanglement risk to large marine animals swimming nearby, however, to date there has been no evidence of this risk.

SWAC plants will have similar impacts in the nearshore from discharging the used water, as for OTEC. The deep water will usually contain higher concentrations of nutrients than the surface water, and thus can cause some local marine growth and eutrophication. There will also be a plume with anomalously cool water, compared to the ambient. The same applies to thermal fjord energy (Fig. 4), where discharges usually go out nearshore or in a river mouth, with potential thermal stress and nutrient stress to the surrounding aquatic environment.

3.2. Salinity gradients

3.2.1. Source of energy

Seawater salinity varies with depth, input of freshwater, and evaporation, with surface ocean waters most commonly of lower salinity than deeper waters. Areas near coastlines, particularly those with large or plentiful river mouths, tend to be less saline than open ocean water. In hot arid low latitudes, evaporation at the sea surface may result in more saline water overlaying lower salinity waters. The ocean maintains a permanent thermocline at depth while shallower waters gradually decrease in salinity towards a seasonal pycnocline with increased salinity, depending on the latitude (Tomczak, 2001).

Salinity gradient (osmotic pressure) technology can only be effectively implemented in specific locations which are limited by the steepness and stability of the gradient in a river mouth or estuary. Strong stratification or the interface between the river and seawater creates a high salinity differential over a short distance which is needed to make power generation viable (Sánchez-Santillán et al., 2012). There is interest in the use of renewable energy in several sectors in addition to generating power such as desalination and wastewater treatments (Panagopoulos and Giannika, 2022).

Producing power from salinity gradients generates negligible CO_2 emissions during operation and there is no fuel cost associated with this energy (Cipollina et al., 2018).

3.2.2. Salinity gradient technology

Harvesting energy from salinity gradients takes place by exploiting the difference in salt concentration between two fluids, across a polymer membrane (IRENA, 2014). It can be classified as a chemical to electrical, or chemical to mechanical energy system (Jung et al., 2022). Salinity gradient energy can be generated using two primary methods - pressure-retarded osmosis (PRO) and reverse electrodialysis (RED). Salinity gradients worldwide are thought to have the potential to produce about 625 TWh (Marin-Coria et al., 2021).

PRO converts the osmotic pressure difference between fresh and saline water to electrical energy by creating hydraulic pressure to rotate a turbine (Jung et al., 2022). A higher power output is produced when there is a higher osmotic pressure difference between the two solutions. Due to this potential, mixing brine (from desalination) and treated wastewater would produce more power than mixing seawater and freshwater (Al Mashrafi et al., 2022). This would allow future salinity gradient plants to be integrated with desalination plant infrastructure to utilize water with high salt concentrations (Helfer and Lemckert, 2015). RED relies on the differential salt concentrations between salt and freshwater to generate a voltage as the fluids are passed over cation and anion exchange membranes (similar to a battery) (Gill et al., 2021).

3.2.3. Potential environmental effects of salinity gradients

Generating power from salinity gradients creates outputs of water with increased salinity that must be returned to the ocean or disposed of elsewhere. Releasing high salinity plumes at river mouths or in estuaries could affect salinity patterns in the surrounding area, leading to ecosystem changes that may affect the marine food web, including fish abundance and diversity (Gallardo-Torres et al., 2012; Marin-Coria et al., 2021). The increased salinity brine produced from salinity gradient plants poses a contamination risk, as discharged brackish water is likely to contain chemical residues of antifoulants, cleaning products, and others from operation of the power plant (Seyfried et al., 2019). Industrial discharges are known to increase the frequency of harmful algal blooms around pipes, creating a health risk for humans and marine organisms (Chen et al., 2019).

3.3. Floating solar photovoltaic (PV)

3.3.1. Source of energy

Direct sunlight provides the thermal energy that enables energy production from photovoltaic (PV) panels. Offshore floating PV panels operate just as they do on land but alleviate the need for land use and other terrestrial infrastructure.

3.3.2. Floating PV technology

Photovoltaic panels are mounted to a buoyant structure and tethered to the floor or shore of the water body in which they float. Floatovoltaics can be a valuable investment for countries with minimal land available and abundant sunlight, such as small island states. The technology has been previously implemented on inland water bodies where there is less risk of damage from weather. Marine floatovoltaics have mainly been deployed in sheltered coastal areas and tidal flats, for example with a 180 MW project off the west coast of Taiwan (chenya-energy.com). Recently, several demonstration and commercial projects have been deployed in offshore seas in The Netherlands (https://oceansofenergy.blue) and China (https://oceansun.no). Fig. 5 illustrates one type of plant.

The basic individual components required to establish a floating PV system include a floating pontoon which is necessary to support the panels and their electronic parts. The buoyant structures are usually composed of hollow plastic laid out in various designs depending on the specific needs and environmental conditions of each location (The World Bank, 2019). A mooring system that may include a permanent cable connected to anchors that can be fixed to the seafloor or shore, depending on location, bathymetry, sediment type, etc. (Lee et al., 2020). The PV modules are generally constructed of poly- or mono-crystalline thin film solar panels, as are used on land. However, future developments are likely to focus on creating solar panels that are more resistant to salt, water, corrosion, and extreme wind (Sahu et al., 2016). Cables and connectors are needed to transfer the electricity generated from floatovoltaics directly to a grid connection or stored in batteries,

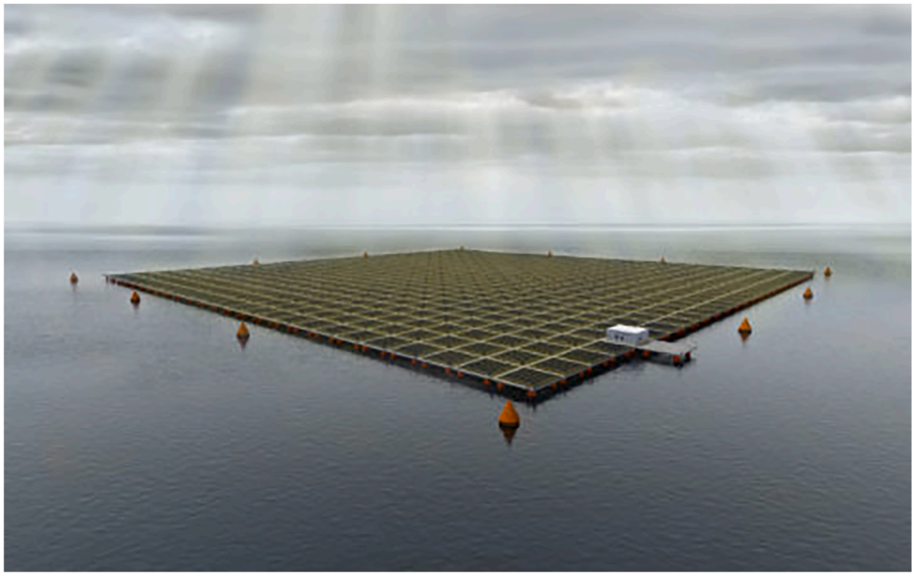

Fig. 5. A floating PV-plant. Photo: Moss Maritime.

depending on the location of the panels and ease of access for maintenance.

The cooling effect of water on PV cells at sea has been calculated to create up to 10% more electricity per unit solar energy than on land. Offshore PV technology has the potential to be combined with other activities such as aquaculture (Pringle et al., 2017; López et al., 2022), which could increase the efficiency of offshore industries such as aquaculture and wind turbines by sharing existing electrical infrastructure (Acharya and Devraj, 2019),

Floatovoltaics are at risk of damage from weather and waves. Further research is needed to establish floating system designs that can withstand harsh ocean conditions such as waves, ocean currents, harsh salinity and temperature conditions and variability, and extreme weather events including storms and rogue waves (Sahu et al., 2016), lowering the risk of disintegration at sea, spreading debris in the marine environment.

Maintenance is likely to be high for floating PV structures, due to fouling of components of the platforms including floats and cables (Nall et al., 2017; Hooper et al., 2021). Heavy biofouling loads may affect the hydrodynamics of the structure, enhance rates of corrosion, and lead to reduced efficiency, and increased maintenance costs. Similarly, salt deposition (or bird droppings) directly on the PV cells will require a means of washing the plates that has yet to be developed. Salt deposition is not a problem for floatovoltaics based in freshwater bodies (Karpouzoglou et al., 2020).

3.3.3. *Potential environmental effects of floatovoltaics*

Effects from floating PV are likely to be similar to those of other offshore structures such floating offshore wind platforms. Floating solar requires many more mooring lines to hold the platforms in place than floating offshore wind platforms (Yu et al., 2021). The three to four mooring lines that anchor floating offshore wind platforms, with spacing of 500–1000m or more between platforms, are unlikely to cause major harm to marine animals (Copping and Grear, 2018; Garavelli, 2020), the number and density of mooring lines needed to hold floatovoltaics in place may cause an increased risk. In particular, the presence of multiple catenary or tension leg mooring lines underneath and at the perimeter of a floatovoltaic installation could present a risk to large marine mammals that might become disoriented and entangled in the lines while traversing an array. Smaller marine mammals and fish are likely to navigate the lines, but large cetaceans may be at risk.

Also of environmental concern for offshore photovoltaics is the reduced light penetration, or shading effect, on the primary productivity of marine ecosystems (Karpouzoglou et al., 2020). The shading could alter the temperature and reduce the quantity of light reaching photoautotrophs, consequently limiting dissolved oxygen production and disrupting the planktonic food web and community structure (de Lima et al., 2021). The shading could also alter the thermal dynamics of the water body and subsequently modify biogeochemical processes (Exley et al., 2021). Furthermore, offshore platforms could affect local hydrodynamics, where changes in current and wave actions are expected to happen from the platform shading, shielding the sea surface from wind and the friction induced by currents at the edges of the platforms. However, these impacts are highly dependent on the characteristics of the location (e.g. mixing and stratification) and coverage percentage of offshore photovoltaic platforms (Karpouzoglou et al., 2020).

There is the potential leaching of substances/additives used in floating solar designs and maintenance into marine waters such as heavy metals, plastics, and cleaning agents, contaminating water and affecting the functioning of ecosystems (Mathijssen et al., 2020). Conversely, a study of flotovoltaics in freshwater bodies has found an increase in water quality by reducing nuisance algal blooms due to decreased light penetration into the water (Jones and Armstrong, 2018). Similarly, Karpouzoglou and colleagues suggested a reduction in turbidity in marine arrays, which is beneficial for light penetration in the waters under the floating structure (Karpouzoglou et al., 2020). To date, most information has come from numerical modeling with a very limited number of field studies. There is a need for extensive environmental assessments and testing of floatovoltaic arrays to obtain empirical data and validate the existing predictive models.

3.4. *Production of e-fuels at sea*

Power generated at sea that cannot readily be transmitted to shore due to the excessive distances for cable runs, or when the power cannot be used immediately onshore, can be transformed into compressed gasses, notably compressed air, ammonia, and hydrogen. These so-called electrofuels or e-fuels are produced from renewable energy sources, water, and CO_2. The use of these compressed gasses for energy storage is explored in the next section Energy Storage at Sea. These gasses are currently produced with the aid of industrial processes used primarily with fossil fuels, which can be adapted for using the mechanical or electrical energy from renewables (Bicer and Dincer, 2018; Kim et al., 2019; Cha et al., 2021; Sun et al., 2022).

3.4.1. Efuels technology

E-fuels can be produced by virtually any of the offshore renewable energy technologies. While such plants are not yet in use, it is assumed that installations of sufficient size would be needed to support the underlying energy harvesting technology, for the additional conversion plant that would use mechanical or electrical energy to generate e-fuels, as well as docking or lightering facilities to offload and transport the e-fuels to locations where they might be used.

As an example, emerging offshore OTEC designs envision free floating or motorized vessels that can be used to move the plant to different locations. These platforms could be deployed far from land and, rather than connecting to shore via an export cable, would likely produce e-fuels for export, such as ammonia or hydrogen. While maintenance of the platforms and OTEC systems should be minimal, maintenance crews would be deployed from land as the platforms are not likely to be crewed.

3.4.2. Potential environmental effects of e-fuels

The additional industrial processes added to offshore renewables brings increased risk from chemical spills particularly lubricants and process chemicals (Kim et al., 2019). In addition, if the efuel consists of a toxic gas such as ammonia, releases of the compressed gas itself poses a risk to marine life as well as birds and bats (Kim et al., 2019). Additional information is contained in the next section.

3.5. Energy storage at sea

While some of the energy harvested at sea may be used locally for aquaculture operations or ocean observations, most will be used on land which will require transport or transmission of the power to shore. Undersea power cables have been located in the ocean for over a century and many more are being laid for offshore wind and other more established offshore renewable sources. As power generated at sea is located at ever increasing distances from shore, there is a need to store and transform that power in new ways. Undersea energy storage is a new area of research and only a few prototypes have been tested in the ocean, while others are at the conceptual stage. The main types of storage include mechanical, electrochemical, thermal, electrical, and magnetic.

Selecting the best-suited energy storage system for power generated offshore is highly dependent on the use to which that power will be put (Olabi and Abdelkareem, 2021). Examining the availability and inherent intermittency, energy capacity, and seasonality of the renewable energy source will help to decide the optimum type and size of energy storage system, as will the type of application including industrial, domestic, or transportation-related uses.

3.5.1. Different types of energy storage

Based on early experiments and growing use in the marine environment, it is likely that energy storage at sea will take one of two forms: solid storage in the form of battery banks or similar media, or compressed gasses in impermeable containers on the sea surface and at depth. Other potential solutions have been proposed such as the use of pressurized seawater and air used through a hydropneumatic accumulator in a subsurface container or beneath the seabed (Slocum et al., 2013; Buhagiar et al., 2019); the development of supercapacitor cells (Cheng et al., 2021); deep ocean gravitational storage with either cavities of water buried at great depths in the ocean (Cazzaniga et al., 2017; Wang et al., 2019; Hunt et al., 2021) or solid masses moved up and down from deep depths (Botha and Kamper, 2019). Another concept offering promise is the sub-sea 'StEnSea' concrete sphere, sitting on the sea bottom at deep depths (Fig. 6). This form operates by sequentially evacuating the sphere (charging) and filling the sphere with ambient water (discharging), with capacity of 20 MWh per sphere (Puchta et al., 2017).

Batteries, either mounted on floating platforms or on the seabed are likely to play a significant role in energy storage for the emerging offshore renewable energy technologies. Batteries at sea will consist of one or more cells connected in series or in parallel, as needed to provide the desired output voltage and capacity. As with all electrical batteries, each battery cell will have two electrodes and an electrolyte solution to transfer electrons. The most common batteries used for storage include lead acid batteries, nickel-based batteries, lithium-ion batteries, sodium-sulphur batteries, or flow batteries, although increasingly the use of lithium and other heavy metal batteries are under scrutiny at sea for safety reasons (Romana, 2021).

Compressed gasses can be stored at sea on the surface, at depth, or attached to the seafloor in bags (Pimm et al., 2014), within offshore energy infrastructures (Li et al., 2011), or solid shaped containers (Slocum et al., 2013), with some potential for storage within seafloor sediments (Fiaschi et al., 2012). Excess energy that cannot be used immediately from each of the emerging offshore renewable technologies described here could be stored as compressed gasses, including compressed air, ammonia, hydrogen, carbon dioxide, and presumably other compounds. These gasses include compressed air that can be stored at high pressure then released through a turbine or other device that drives a generator (Pimm et al., 2014). Ammonia and hydrogen produced at sea would currently be considered as efuels that could be transported for use on land, although perhaps future processes could use these gasses at sea for powering applications. Vessels for storing compressed gasses at sea may include cable-reinforced fabric bags anchored to the seabed, known as Energy Bags (Pimm et al., 2014); concrete or metal spheres or differently shaped objects (Lim et al., 2012); as well as repurposed offshore pipelines or other offshore infrastructure (Dehghani-Sanij et al., 2019).

3.5.2. Potential environmental effects of energy storage at sea

With few large energy storage installations at sea, assessment of the risks must be considered somewhat speculative. The presence of significant electrical energy storage at sea, whether on or near the sea surface or on the seabed should be regarded as a concentrated form of electromagnetic fields that might be emitted from a power export cable. The effects on electo- and magneto-sensitive species such as certain

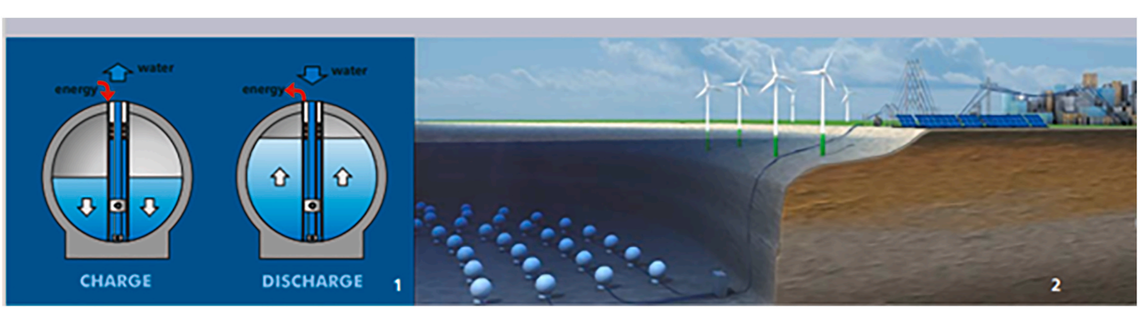

Fig. 6. Sub-sea energy storage by 'StEnSea' concrete spheres utilizing the hydrostatic pressure. Each plant will have capacity on the order of 20 MWh/4 MW. Source: Fraunhofer IEE.

elasmobranchs and crustaceans, and perhaps sea turtles and some species of fish, have been examined (Gill and Desender, 2020). It is anticipated that electrical storage at sea, unless buried deeply, will generate sizable amounts of EMFs.

Compressed gas storage at sea is likely to create few effects if the integrity of the storage chamber (bags, concrete spheres, other hollow objects) is maintained (Bouman et al., 2016). If leaks were to occur, the effects would depend on the gas used for storage, as well as the pressure under which the gas is stored. Releases of compressed air at the surface are unlikely to cause harm while the release of compressed air or any compressed gas from depth could affect water column stratification if the release were large. If the stored gas were ammonia, releases from the surface or from depth is likely to be toxic to many marine organisms in close proximity. Releases of hydrogen are likely to behave similarly to that of compressed air. There is not published research on how releases of carbon dioxide at depth might act, but it might be considered that sufficient releases could change the pH locally and or make some changes in the deep water column.

If abandoned pipelines were used for energy storage of gasses or water under pressure, any effects could be spread over longer distances but unless a toxic gas were used, the effects from pipeline leaks is likely to be small.

4. Discussion

The emerging offshore renewable energy technologies that are the subject of this paper represent existing technologies but all have had limited deployments and are not considered to be at the commercial scale that will allow end users to procure and deploy them at this time.

OTEC and SWAC are technologies that have been tested, and in the case of SWAC, used in limited circumstances for several decades. These technologies are made up of well-known subsystems that are unlikely to present difficult technical challenges to their wide spread deployment. The major environmental concern for OTEC and SWAC is the return of cold deep water to the appropriate intermediate depth to avoid thermal and chemical shocks to ambient organisms and the stability of the water column. The major impediments to large scale OTEC and wider use of SWAC is the large capital costs associated with manufacture and deployment.

Salinity gradient technologies have also not been widely in use, although the membrane technologies and water pumping do not present large technical barriers. Progress in membrane technologies will continue to improve the efficiency of systems, bringing down capital and maintenance costs. The major environmental effect of salinity gradient energy production will be the need to dispose of the brine generated on one side of the membrane; existing markets and technologies are likely to be able to take up this challenge.

Floating solar (floatovoltaics) have been deployed in sheltered freshwater lakes, ponds, and lagoons, and appear to be efficient and scalable. The major challenges facing floatovoltaic deployment in marine waters are the need to provide stable platforms that are likely to survive harsh conditions and the need to clean the plates on a frequent basis. The environmental effects associated with this technology focuses around the coverage of significant areas of the sea surface that may cause interruptions of important biological functions and changes in hydrodynamics.

Production of ammonia and/or hydrogen at sea is very much in the developmental stage and it is not clear if or when large capacity production will become economically or technically feasible. Potential environmental effects of this production will be associated with potential spills of precursor chemicals or finished products that could harm sea life.

Energy storage at sea will become more and more important as more established and emerging offshore renewables come online. Conventional battery storage in the form of metal ions and other media could pose a threat to the marine environment from the enhanced electromagnetic fields emitted, from potential spills of liquid components, and from inappropriate disposal at sea. Containers of compressed gasses used as energy storage are an option for energy storage at sea that is of great interest. If compressed air is used as the storage medium, it is unlikely to cause a risk to the marine environment. Other compressed gasses such as ammonia may cause harm to organisms, while the effect of inappropriately released hydrogen is unknown.

4.1. Risk from emerging offshore renewables

With so few commercial developments of the emerging offshore energy technologies, it is difficult to assess the potential effects of large scale development, as well as assessing which of these technologies might cause the greatest concern for marine organisms, habitats, and ecosystem processes. Based on the limited small deployments of each of the emerging technologies, some level of relative risk could be made (Table 3).

4.2. Scale and location of emerging offshore renewables

Meeting climate goals and providing electricity to the grids of developed and developing countries will require large scale deployment and operation of renewable energy sources. While solar and wind energy can be expected to take up to 80% of the renewable energy needs worldwide (Ember, 2023), the remaining 20% of current global loads will have to come from other sources, most particularly those deployed offshore. OTEC, salinity gradients, and floating solar will need to be deployed in large arrays offshore, covering significant areas of the ocean surface in many coastal areas. In addition, if removal of carbon dioxide at sea (mCDR) is to be viable at a significant scale, large offshore platforms with power generation will be needed far from shore (Cotter et al., 2021). While risks from small emerging offshore renewable installations are important avenues for research and understanding, the large commercial farms are likely to manifest the potential risks discussed in this paper. In addition, the ocean is a busy place with many other anthropogenic activities that lead to cumulative effects; adding these emerging offshore renewables will have to be examined in the context of these multiple stressors and potential synergistic or additive effects (Fulton et al., 2022). Similarly, emerging offshore industries such as large floating fish farms or multi-trophic aquaculture installations might be co-located with emerging renewable energy sources.

The emerging renewables (OTEC, SWAC, salinity gradients, floatovoltaics, e-fuel production, and undersea energy storage) will not be evenly distributed across the world. OTEC, and to a lesser degree, SWAC are dependent on warm surface waters in contrast to deep cold ocean water, limiting their use to the tropics or subtropics (although SWAC may have a wider distribution). Salinity gradient energy harvest will likely be limited to the mouths of the larger rivers on each continent. Floatovoltaics will be financially viable from the equator through temperate latitudes. E-fuel production and undersea energy storage are likely to be widespread, sited where production is located.

4.3. Research and monitoring needs for emerging offshore renewable energy effects

With few devices or commercial farms deployed, the effects of each of the emerging offshore renewables will require extensive research to determine mechanisms of potential harm to marine species, habitats, and ecosystem processes. Numerical modeling studies can assist with understanding the scale, scope, and potential severity of effects of each of the stressors from Table 3. Monitoring of small installations prior to widespread commercial development will provide essential data for validating models, while studies of animal behavior in the vicinity of early deployments will provide clues as to the potential effects of commercial scale development. Specifics of the preferred models and the field studies planned will be driven by the likely interactions of each

Table 3
Relative risk of emerging offshore energy technologies on the marine environment. Currently no data exist that will provide specific interaction outcomes between these emerging technologies and marine animals. The analysis is based on what is known about analogous offshore renewables and platforms.

Emerging Technology	Stressor	Source of stress	Receptor most likely to be affected	Probability of interaction	Consequences of the interaction	Overall risk
OTEC and SWAC	Thermal stress, changes in oceanographic conditions	Deep cold water return	Most pelagic tropical species including plankton and other micro-organisms, fish, sea turtles	Very high unless mitigated with discharge at depth	Very high unless mitigated with discharge at depth	High, but effective mitigations are available
OTEC and SWAC	Loss of deep sea organisms	Uptake in cold water pipe, brought to surface with subsequent pressure shock	Deep sea pelagic organisms, largely fish	Low as deep sea organisms are few in number	Very high if fish are brought to the surface	Low. Mitigation measures like screens on cold water pipe can lower risk further
OTEC and SWAC	Chemical releases	Ammonia or other heat exchange medium could leak into the air or marine environment	Most pelagic and benthic organisms in vicinity of spill	Low as closed-cycle OTEC systems are extensively monitored for leaks	High. A significant ammonia spill could be deadly to many organisms	Low. Monitoring of OTEC systems should provide warning of leaks and allow for mitigation and plant shutdown
OTEC and SWAC	Loss of pelagic habitat, interference with migratory corridors	Presence of many large plants at sea	Migratory cetaceans and sea turtles	Medium at high density of commercial plants in open ocean	Low-medium	Low as most migratory species have discretion in their movement. Very high sea cover by plants could cause additional risk.
Salinity gradients	Changes in oceanographic conditions, altering salinity regimes	Disposal of brine in nearshore areas	Small pelagic and benthic organisms including plankton and micro-organisms	High if brine is disposed of in area with limited circulation	Medium as most nearshore organisms are euryhaline	Medium risk that can be mitigated with careful dispersal and discharge of brine or disposal on land
Floatovoltaics	Entanglement	Multiple mooring lines	Large marine mammals, basking sharks	High if sited in migratory route of large cetaceans	High	Low if careful siting and mitigation that prevent large animals from entering array are taken
Floatovoltaics	Changes in oceanographic conditions	Shading from platforms	Planktonic primary producers, and hence marine food web	Very high as platforms will be anchored in place	High for limited areas of ocean	Low-medium as ocean waters move past the platforms
Floatovoltaics	Toxic waste and chemical discharges	Spills and use of plastics and other materials for operations and maintenance	Most pelagic and benthic organisms in vicinity	Medium	Medium for limited area of ocean	Low-medium. Hazardous waste management plans are used to minimize waste disposal and spills.
efuel production at sea	Toxic chemical discharge	Spill from production or transport of efuels at sea surface or at depth	Most pelagic and benthic organisms in vicinity of spill	Low. Ammonia and hydrogen production and transport is known technology that is tightly controlled	High. A significant ammonia spill could be deadly to many organisms.	Low-medium. Hazardous waste production, transport, and management plans are well tuned to avoid spills.
Energy storage	Electromagnetic fields	Emissions from battery banks, substations, power export cables	Marine organisms that are sensitive to EMFs	Medium, depending on the architecture of the substations and proximity to EMF-sensitive organisms	Low. To date, laboratory and field studies do not show adverse effects on EMF-sensitive organisms from emissions	Low. Substations can be separated from sensitive species through burial and shielding.
Energy storage	Changes in oceanographic conditions	Unintended releases of compressed gasses	Small pelagic organisms and perhaps fish with swim bladders	Medium.	Low. Releases of compressed air or hydrogen are unlikely to affect the chemistry or biology of the ocean. The effects of carbon dioxide releases are unknown.	Low, with proper management of energy storage containers.

technology, with opportunities to use similar models and study methodology among emerging technologies when there are stressors in common. For example, OTEC, SWAC, and salinity gradient energy harvesting are most likely to affect oceanographic processes and primary/secondary production. Hydrodynamic models that account for physical factors and planktonic organisms, coupled with standard oceanographic sampling for temperature, salinity, density, plankton biomass, primary production, and certain chemical constituents could be used across these technologies. This commonality would allow for assessments of relative risk provided by each of the emerging technologies. Similarly, the stresses of floatovoltaics, e-fuel spills, and energy storage on higher levels of the marine food web could be examined together, although the scale and placement of these emerging technologies might also require additional separate assessments. Ultimately, a life cycle assessment for each of the technologies that accounts for the carbon (and potentially toxic chemical) contributions from production through deployment, operation, maintenance, and decommissioning, will be needed to assess the real value to carbon reduction and providing clean energy.

5. Summary/Conclusion

The emerging offshore renewable technologies that are under consideration in many parts of the world include OTEC, SWAC, salinity gradient power, floating PVs, e-fuels, and energy storage. Each has its own optimal areas where siting and operation are likely to be most effective. In addition, each of these technologies will pose novel environmental challenges for management, policy, and research approaches.

OTEC, SWAC, and salinity gradient power are most likely to create pressures on oceanographic processes as the technologies scale up, with the discharge of water of different temperatures or salinities meet ambient seawater. Each of these technologies will require specialized modeling and design of discharge pipes and diffusers to ensure that the process water does not harm local environments or disrupt the stability of the water column. Additional concerns for these technologies will include potential spills from process chemicals and by products, and perhaps entanglement and displacement risks as open ocean plants are developed at scale. The very deep OTEC cold water pipe also has the potential to entrain deep sea organisms.

Floating PV systems will cover large areas of the ocean surface at scale, shading and limiting primary production in those regions, which in turn could reduce productivity throughout the marine food web. Careful siting and areas between PV platfoms may help to ameliorate some of this risk. Entanglement and displacement risks, as well as hazardous chemical spills could also result from large scale development.

E-fuels will create some risk for hazardous spills at sea or releases into the air and will require handling to that which monitors other chemicals at sea. Energy storage risks could include EMF emissions affecting sensitive species and changes in oceanographic conditions from releases of compressed gasses; these will depend on the type and location of the installation, but most could be sited and operated safely with careful planning.

As these emerging offshore technologies become more widespread, with development applications for deployments of pilot, demonstration, and commercial projects in many nations, it is essential that each project be used to learn more about potential risks to the marine environment at small and large scales. Governments and funding entities have the power to require that research and monitoring activities are carried out each time a device or platform goes in the water. The process of biodesign – the use of living organisms and systems in the design of products and services (Myers and Antonelli, 2012) – allows for technologies to be created that minimize harm and may provide benefits to living systems. Biodesign has been used effectively in other industries. For example, biodesign in conventional hydropower has led to the design of fish-friendly turbines that cause significantly less damage to fish traversing hydroelectric dams (Hou et al., 2018), while biodesign of marine anchors with crevices and holes have provided additional habitat for mobile benthic organisms such as crustaceans (Steins et al., 2021).

This paper seeks to provide insight into the available information on these new emerging offshore technologies. There are few research studies and fewer empirical data available to test the likely risk of each of the technologies examined here; as the technologies develop, it is expected that the area of study will flourish.

By ensuring that information is collected around each emerging offshore renewable, the time to fully understand the risks through accelerated learning will help these industries reach their goals of clean energy faster than older industries at sea and on land, avoiding expensive retrofitting and public outcry. This knowledge will inform the design of each of these technologies and subsystems to become increasingly more environmentally friendly over time, to improve the siting of commercial installations, and help deliver on the promise of offshore renewable energy.

CRediT authorship contribution statement

Andrea Copping: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Daniel Wood:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Bob Rumes:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ee Zin Ong:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Lars Golmen:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Rachel Mulholland:** Writing – original draft, Methodology, Formal analysis. **Olivia Harrod:** Writing – original draft, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors serve on an ICES workgroup, which originated the topic area of the paper.

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No data was used for the research described in the article.

References

Acharya, M., Devraj, S., 2019. Floating solar photovoltaic (FSPV): a Third Pillar to solar PV sector? TERI Discussion Paper: Output of the ETC India Project. The Energy and Resources Institute, New Delhi, p. 68. https://www.teriin.org/sites/default/files/2020-02/FloatingSolarPhotovoltaic%28FSPV%29AThirdPillartoSolarPVSector.pdf.

Adams, T.P., Miller, R.G., Aleynik, D., Burrows, M.T., 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. J. Appl. Ecol. 51, 330–338. https://doi.org/10.1111/1365-2664.12207. (Accessed 12 May 2016).

Al Mashrafi, S., Diaz-Elsayed, N., Benjamin, J., Arias, M.E., Zhang, Q., 2022. An environmental and economic sustainability assessment of a pressure retarded osmosis system. Desalination 537, 115869. https://linkinghub.elsevier.com/retrieve/pii/S0011916422003241.

Ascari, M.B., Hanson, H.P., Rauchenstein, L., Van Zwieten, J., Bharathan, D., Heimiller, D., Langle, N., et al., 2012. Ocean Thermal Extractable Energy Visualization – Final Technical Report on Award DE-EE0002664. U.S. Department of Energy (Office of Scientific and Technical Information), Washington, D.C.

Avery, W.H., Wu, C., 1994. Renewable Energy from the Ocean: A Guide to OTEC. Oxford University Press, New York, p. 418.

Bellmann, M., May, A., Wendt, T., Gerlach, S., Remmers, P., Brinkmann, J., 2020. Underwater Noise during Percussive Pile Driving: Influencing Factors on Pile-Driving Noise and Technical Possibilities to Comply with Noise Mitigation Values. Report by Institute of Technical and Applied Physics (itap) GmbH. Report for German Ministry for.

Bicer, Y., Dincer, I., 2018. Clean fuel options with hydrogen for sea transportation: a life cycle approach. In: International Journal of Hydrogen Energy, vol. 43. Elsevier Ltd, pp. 1179–1193. https://doi.org/10.1016/j.ijhydene.2017.10.157.

Botha, C.D., Kamper, M.J., 2019. Capability study of dry gravity energy storage. In: Journal of Energy Storage, vol. 23. Elsevier BV, pp. 159–174. https://doi.org/10.1016/j.est.2019.03.015.

Bouman, E.A., Øberg, M.M., Hertwich, E.G., 2016. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). In: Energy, vol. 95. Elsevier BV, pp. 91–98. https://doi.org/10.1016/j.energy.2015.11.041.

Buhagiar, D., Sant, T., Farrugia, R.N., Aquilina, L., Farrugia, D., Strati, F.M., 2019. Small-scale experimental testing of a novel marine floating platform with integrated Hydro-pneumatic energy storage. In: Journal of Energy Storage, vol. 24. Elsevier BV, 100774. https://doi.org/10.1016/j.est.2019.100774.

Cazzaniga, R., Cicu, M., Marrana, T., Rosa-Clot, M., Rosa-Clot, P., Tina, G.M., 2017. DOGES: deep ocean gravitational energy storage. In: Journal of Energy Storage, vol. 14. Elsevier BV, pp. 264–270. https://doi.org/10.1016/j.est.2017.06.008.

Cha, J., Park, Y., Brigljević, B., Lee, B., Lim, D., Lee, T., Jeong, H., et al., 2021. An efficient process for sustainable and scalable hydrogen production from green ammonia. Renew. Sustain. Energy Rev. 152.

Chen, Q., Yuan, H., Chen, P., 2019. Short-term effects of artificial reef construction on the taxonomic diversity and eco-exergy of the macrobenthic faunal community in the Pearl River Estuary, China. In: Ecological Indicators, vol. 98. Elsevier BV, pp. 772–782. https://doi.org/10.1016/j.ecolind.2018.12.001.

Cheng, S., Dai, Z., Fu, J., Cui, P., Wei, K., Zhang, Y., Wu, Y., et al., 2021. Towards large-scale electrochemical energy storage in the marine environment with a highly-extensible "paper-like" seawater supercapacitor device. In: Journal of Materials

Chemistry A, vol. 9. Royal Society of Chemistry (RSC), pp. 622–631. https://doi.org/10.1039/d0ta09643a.

Cipollina, A., Di Silvestre, M.L., Giacalone, F., Micale, G.M., Riva Sanseverino, E., Sangiorgio, R., Tran, Q.T., et al., 2018. A methodology for assessing the impact of salinity gradient power generation in urban contexts. Sustain. Cities Soc. 38, 158–173. https://linkinghub.elsevier.com/retrieve/pii/S2210670717311411.

Claude, G., 1930. Power from the tropical seas. Mechanical Engineering 52, 1039–1044.

Coastal Response Research Center, 2010a. Technical Readiness of Ocean Thermal Energy Conversion (OTEC). University of New Hampshire, Durham, New Hampshire, p. 27.

Coastal Response Research Center, 2010b. Ocean Thermal Energy Conversion: Assessing Potential Physical, Chemical and Biological Impacts and Risks. University of New Hampshire, Durham, New Hampshire, p. 39.

Copping, A., LiVecchi, A., Spence, H., Gorton, A., Jenne, S., Preus, R., Gill, G., et al., 2018. Maritime renewable energy markets: power from the sea. Mar. Technol. Soc. J. 52, 99–109. https://www.ingentaconnect.com/content/10.4031/MTSJ.52.5.3.

Copping, A., Grear, M., 2018. Humpback whale encounter with offshore wind mooring lines and Inter-Array cables (Report No. PNNL-27988). Report by Pacific Northwest National Laboratory (PNNL). Report for Bureau of Ocean Energy Management (BOEM).

Cotter, E., Cavagnaro, R., Copping, A., Geerlofs, S., 2021. Powering Negative-emissions technologies with marine renewable energy. In: OCEANS 2021: San Diego – Porto. IEEE, pp. 1–8. https://ieeexplore.ieee.org/document/9705807/.

D'Arsonval, A., 1881. Utilisation des forces naturelles. Avenir de l'electricite. Revolutionary Science 17, 370–372.

de Lima, R.L.P., Paxinou, K., Boogaard, F.C., Akkerman, O., Lin, F.-Y., 2021. In-situ water quality observations under a large-scale floating solar farm using Sensors and underwater Drones. Sustainability 13, 6421. https://www.mdpi.com/2071-1050/13/11/6421.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., Degraer, S., 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756, 37–50.

Dehghani-Sanij, A.R., Tharumalingam, E., Dusseault, M.B., Fraser, R., 2019. Study of energy storage systems and environmental challenges of batteries. In: Renewable and Sustainable Energy Reviews, vol. 104. Elsevier BV, pp. 192–208. https://doi.org/10.1016/j.rser.2019.01.023.

Duarte, C.M., Pitt, K.A., Lucas, C.H., Purcell, J.E., Uye, S., Robinson, K., Brotz, L., et al., 2013. Is global ocean sprawl a cause of jellyfish blooms? Front. Ecol. Environ. 11, 91–97.

Ember, 2023. Global Electricity Review, p. 163. https://ember-climate.org/insights/research/global-electricity-review-2023/.

Essalhi, M., Avci, A., Lipnizki, F., Tavajohi, N., 2023. The potential of salinity gradient energy based on natural and anthropogenic resources in Sweden. Renew. Energy 215, 118984. https://doi.org/10.1016/j.renene.2023.118984.

Exley, G., Armstrong, A., Page, T., Jones, I.D., 2021. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. In: Solar Energy, vol. 219. Elsevier BV, pp. 24–33. https://doi.org/10.1016/j.solener.2021.01.076.

Fiaschi, D., Manfrida, G., Secchi, R., Tempesti, D., 2012. A versatile system for offshore energy conversion including diversified storage. In: Energy, vol. 48. Elsevier BV, pp. 566–576. https://doi.org/10.1016/j.energy.2012.10.006.

Fulton, E., Hemery, L., Copping, A., 2022. Marine renewable energy – cumulative effects: Summary of the state of play. In: Ocean Energy Systems – Environmental (Unpublished), p. 55.

Gallardo-Torres, A., Badillo-Alemán, M., Galindo-de Santiago, C., Loera-Pérez, J., Rioja-Nieto, R., Chiappa-Carrara, X., 2012. ListadoTaxonómico de los Peces de la Laguna Boca de la Carbonera, Yucatán: Un Primer paso para el Manejo y Evaluación de los RecursosCosteros del Norte de Yucatán. In: En Recursos Acuáticos Costeros del Sureste; Vol. II. Fondo Mixto—CONACYT—Gobierno delestado de Yucatán, pp. 270–288. Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

Galparsoro, I., Menchaca, I., Seeger, I., Nurmi, M., McDonald, H., Garmendia, J.M., Pouso, S., et al., 2022. Mapping potential environmental impacts of offshore renewable energy. ETC/ICM Report 2/2022: European Topic Centre on Inland, Coastal and Marine waters 123.

Garavelli, L., 2020. Encounters of marine animals with marine renewable energy device mooring systems and subsea cables. In: Copping, A.E., Hemery, L.G. (Eds.), OES-environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES), pp. 147–153. https://doi.org/10.2172/1633184.

Gill, A., Desender, M., 2020. Risk to animals from electromagnetic fields emitted by electric cables and marine renewable energy devices. In: Copping, A.E., Hemery, L.G (Eds.), OES-environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES), pp. 86–100. Richland, WA (United States). https://www.osti.gov/servlets/purl/1633088/.

Garavelli, L., Copping, A.E., Freeman, M.C. (Eds.), 2024. OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES), p. 313. https://doi.org/10.2172/2438585.

Gill, A.B., Birchenough, S.N.R., Clarke, S., Griffith, A., Harrod, O., Lonsdale, J., Moran, C., et al., 2021. Developing a systems Framework approach to assess options for offshore marine renewable energy in the Caribbean. Cefas Project Report to Commonwealth Marine Economies Programme - CME C8159H 76.

Giraud, M., Garçon, V., de la Broise, D., L'Helguen, S., Sudre, J., Boye, M., 2019. Potential effects of deep seawater discharge by an Ocean Thermal Energy Conversion plant on the marine microorganisms in oligotrophic waters. Sci. Total Environ. 693, 133491. https://linkinghub.elsevier.com/retrieve/pii/S0048969719334114.

Gorjian, S., Sharon, H., Ebadi, H., Kant, K., Scavo, F.B., Tina, G.M., 2021. Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems. J. Clean. Prod. 278, 123285.

Green, R., Copping, A., Cavagnaro, R.J., Rose, D., Overhus, D., Jenne, D., 2019. Enabling power at sea: opportunities for expanded ocean observations through marine renewable energy integration. In: OCEANS 2019. MTS/IEEE SEATTLE, pp. 1–7. IEEE. https://ieeexplore.ieee.org/document/8962706/.

Helfer, F., Lemckert, C., 2015. The power of salinity gradients: an Australian example. Renew. Sustain. Energy Rev. 50, 1–16. https://linkinghub.elsevier.com/retrieve/pii/S136403211500461X.

Hooper, T., Armstrong, A., Vlaswinkel, B., 2021. Environmental impacts and benefits of marine floating solar. In: Solar Energy, vol. 219. Elsevier BV, pp. 11–14. https://doi.org/10.1016/j.solener.2020.10.010.

Hou, H., Deng, Z., Martinez, J., Fu, T., Duncan, J., Johnson, G., Lu, J., et al., 2018. A Hydropower Biological Evaluation Toolset (HBET) for Characterizing Hydraulic Conditions and Impacts of Hydro-Structures on Fish. Energies, vol. 11. MDPI AG, p. 990. https://doi.org/10.3390/en11040990.

Hunt, J.D., Zakeri, B., de Barros, A.G., Filho, W.L., Marques, A.D., Barbosa, P.S.F., Schneider, P.S., et al., 2021. Buoyancy Energy Storage Technology: an energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression. In: Journal of Energy Storage, vol. 40. Elsevier BV, 102746. https://doi.org/10.1016/j.est.2021.102746.

IRENA, 2014. Salinity Gradient Energy - Technology Brief, p. 28.

Johnson, F.A., 1992. Closed-cycle Ocean Thermal energy conversion. In: Ocean Energy Recovery-State of the Art, pp. 70–96. Chapter 5.

Jones, I., Armstrong, A., 2018. Investigating the impacts of floating solar on the water environment. PV Tech Power 15, 60–63.

Jung, H., Subban, C.V., McTigue, J.D., Martinez, J.J., Copping, A.E., Osorio, J., Liu, J., et al., 2022. Extracting energy from ocean thermal and salinity gradients to power unmanned underwater vehicles: State of the art, current limitations, and future outlook. Renew. Sustain. Energy Rev. 160, 112283. https://linkinghub.elsevier.com/retrieve/pii/S1364032122002027.

Karpouzoglou, T., Vlaswinkel, B., van der Molen, J., 2020. Effects of large-scale floating (solar photovoltaic) platforms on hydrodynamics and primary production in a coastal sea from a water column model. Ocean Sci. 16, 195–208.

Kempener, R., Neumann, R., 2014. Sea Water Air Conditioning Technology Brief. International Renewable Energy Agency (IRENA), p. 24.

Kim, Y.-R., Lee, M., Jung, J.-Y., Kim, T.-W., Kim, D., 2019. Initial environmental risk assessment of hazardous and noxious substances (HNS) spill accidents to mitigate its damages. In: Marine Pollution Bulletin, vol. 139. Elsevier BV, pp. 205–213. https://doi.org/10.1016/j.marpolbul.2018.12.044.

Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., Cox, S., 2020. Hybrid floating solar photovoltaics-hydropower systems: benefits and global assessment of technical potential. Renew. Energy 162, 1415–1427. https://linkinghub.elsevier.com/retrieve/pii/S0960148120313252.

Lemos, L.S., Haxel, J.H., Olsen, A., Burnett, J.D., Smith, A., Chandler, T.E., Nieukirk, S.L., et al., 2022. Effects of vessel traffic and ocean noise on gray whale stress hormones. Sci. Rep. 12, 18580. https://www.nature.com/articles/s41598-022-14510-5.

Li, P., Loth, E., Simon, T., Ven, J. Van de, Crane, S., 2011. Compressed air energy storage for offshore wind turbines. In: International Fluid Power Exhibition (IFPE). Las Vegas. US.

Lim, S.D., Mazzoleni, A.P., Park, J., Ro, P.I., Quinlan, B., 2012. Conceptual design of ocean compressed air energy storage system. IEEE. https://doi.org/10.1109/oceans.2012.6404909.

López, M., Soto, F., Hernández, Z.A., 2022. Assessment of the potential of floating solar photovoltaic panels in bodies of water in mainland Spain. J. Clean. Prod. 340, 130752. https://linkinghub.elsevier.com/retrieve/pii/S0959652622003912.

Lozier, M.S., 2010. Deconstructing the conveyor belt. Science 328, 1507–1511. https://www.science.org/doi/10.1126/science.1189250.

Makai, 2022. Sea water air conditioning. https://www.makai.com/sea-water-air-conditioning/.

Marin-Coria, E., Silva, R., Enriquez, C., Martínez, M.L., Mendoza, E., 2021. Environmental assessment of the impacts and benefits of a salinity gradient energy pilot plant. Energies 14, 3252. https://www.mdpi.com/1996-1073/14/11/3252.

Martin, Benjamin, 2023. Personal Communication.

Mathijssen, D., Hofs, B., Spierenburg-Sack, E., van Asperen, R., van der Wal, B., Vreeburg, J., Ketelaars, H., 2020. Potential impact of floating solar panels on water quality in reservoirs; pathogens and leaching. Water Pract. Technol. 15, 807–811. https://iwaponline.com/wpt/article/15/3/807/75352/Potential-impact-of-floating-solar-panels-on-water.

Mitchell, M., Spitler, J., 2013. Open-loop direct surface water cooling and surface water heat pump systems—a review. HVAC R Res. 19, 125–140.

Myers, W., Antonelli, P., 2012. Bio design: nature. Science 304. Creativity.

Nall, C.R., Schläppy, M.-L., Guerin, A.J., 2017. Characterisation of the biofouling community on a floating wave energy device. Biofouling 33, 379–396. https://doi.org/10.1080/08927014.2017.1317755. Informa UK Limited.

National Research Council, 2013. An Evaluation of the U.S. Department of Energy's Marine and Hydrokinetic Resource Assessments. National Academies Press, Washington, D.C. http://www.nap.edu/catalog/18278.

Olabi, A.G., Abdelkareem, M.A., 2021. Energy storage systems towards 2050. In: Energy. Elsevier BV, 119634. https://doi.org/10.1016/j.energy.2020.119634, 219.

Panagopoulos, A., Giannika, V., 2022. Decarbonized and circular brine management/valorization for water & valuable resource recovery via minimal/zero liquid discharge (MLD/ZLD) strategies. J. Environ. Manag. 324, 116239.

Peltier, H., Beaufils, A., Cesarini, C., Dabin, W., Dars, C., Demaret, F., Dhermain, F., et al., 2019. Monitoring of marine mammal strandings along French coasts reveals the importance of ship strikes on large cetaceans: a challenge for the European marine strategy framework directive. Front. Mar. Sci. 6. https://www.frontiersin.org/article/10.3389/fmars.2019.00486/full.
Penney, T.R., Bharathan, D., 1987. Power from the sea. Sci. Am. 256, 86–92.
Pimm, A.J., Garvey, S.D., de Jong, M., 2014. Design and testing of Energy Bags for underwater compressed air energy storage. In: Energy, vol. 66. Elsevier BV, pp. 496–508. https://doi.org/10.1016/j.energy.2013.12.010.
Pringle, A.M., Handler, R.M., Pearce, J.M., 2017. Aquavoltaics: Synergies for dual use of water area for solar photovoltaic electricity generation and aquaculture. Renew. Sustain. Energy Rev. 80, 572–584. https://linkinghub.elsevier.com/retrieve/pii/S1364032117308304.
Puchta, M., Bard, J., Dick, C., Hau, D., Krautkremer, B., Thalemann, F., Hahn, H., 2017. Development and testing of a novel offshore pumped storage concept for storing energy at sea – Stensea. In: Journal of Energy Storage, vol. 14. Elsevier BV, pp. 271–275. https://doi.org/10.1016/j.est.2017.06.004.
Romana, M., 2021. Lithium Batteries as Cargo on Sea Transports. Santakunta University of Applied Sciences. https://urn.fi/URN:NBN:fi:amk-202202082213.
Sahu, A., Yadav, N., Sudhakar, K., 2016. Floating photovoltaic power plant: a review. Renew. Sustain. Energy Rev. 66, 815–824. https://linkinghub.elsevier.com/retrieve/pii/S1364032116304841.
Sánchez-Santillán, N., Lanza-Espino, G., Sánchez-Trejo, R., 2012. Analysis of the dynamic climatology of the Yucatan Peninsula, Mexico. Recursos Acuáticos Costeros del Sureste II.
Schupp, M.F., Bocci, M., Depellegrin, D., Kafas, A., Kyriazi, Z., Lukic, I., Schultz-Zehden, A., et al., 2019. Toward a common understanding of ocean multi-use. Front. Mar. Sci. 6. https://www.frontiersin.org/article/10.3389/fmars.2019.00165/full.
Seyfried, C., Palko, H., Dubbs, L., 2019. Potential local environmental impacts of salinity gradient energy: a review. Renew. Sustain. Energy Rev. 102, 111–120. https://linkinghub.elsevier.com/retrieve/pii/S1364032118307986.
Slocum, A.H., Fennell, G.E., Dündar, G., Hodder, B.G., Meredith, J.D.C., Sager, M.A., 2013. Ocean renewable energy storage (ORES) system: analysis of an undersea energy storage concept. Proc. IEEE 101, 906–924.
Soukissian, T., O'Hagan, A.M., Azzellino, A., Boero, F., Brito e Melo, A., Comiskey, P., Gao, Z., et al., 2023. European offshore renewable energy: towards a sustainable future. In: Heymans, J.J., Kellett, P., Alexander, B., Muñiz Piniella, Á., Rodriguez Perez, A., Van Elslander, J. (Eds.), Future Science Brief No. 9 of the European Marine Board, Ostend, Belgium. ISSN: 2593-5232, p. 88. www.marineboard.eu.
Stanley, J.A., Van Parijs, S.M., Hatch, L.T., 2017. Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock. Sci. Rep. 7, 14633. https://www.nature.com/articles/s41598-017-14743-9.
Steins, N.A., Veraart, J.A., Klostermann, J.E.M., Poelman, M., 2021. Combining offshore wind farms, nature conservation and seafood: Lessons from a Dutch community of practice. In: Marine Policy, vol. 126. Elsevier BV, 104371. https://doi.org/10.1016/j.marpol.2020.104371.
Sun, C., Fan, X., Li, Y., Han, H., Zhu, J., Liu, L., Geng, X., 2022. Research on the offshore adaptability of new offshore ammonia-hydrogen coupling storage and transportation technology. In: Renewable Energy, vol. 201. Elsevier Ltd, pp. 700–711. https://doi.org/10.1016/j.renene.2022.11.017.
Takahashi, M.M., 1999. Deep Ocean Water as Our Next Natural Resource. Terra Scientific Publishing Company, Tokyo Japan, p. 99.
The World Bank, 2019. Where Sun meets water: floating solar market Report, 131. https://documents1.worldbank.org/curated/en/670101560451219695/pdf/Floating-Solar-Market-Report.pdf.
Tomczak, M., 2001. Upper Ocean mean Horizontal structure. In: Encyclopedia of Ocean Sciences. Elsevier, pp. 3083–3093. https://linkinghub.elsevier.com/retrieve/pii/B012227430X001501.
Vega, L., 2017. Ocean thermal energy conversion. In: Encyclopedia of Sustainability Science and Technology. Springer, New York, New York, NY, pp. 1–35. http://link.springer.com/10.1007/978-1-4939-2493-6_695-3.
Vega, L.A., 1995. Ocean thermal energy conversion. Encyclopedia of Energy Technology and the Environment 15, 93–103.
Wang, Z., Carriveau, R., Ting, D.S.-K., Xiong, W., Wang, Z., 2019. A review of marine renewable energy storage. In: International Journal of Energy Research, vol. 43. Hindawi Limited, pp. 6108–6150. https://doi.org/10.1002/er.4444.
Wick, G.L., Schmitt, W.R., 1977. Prospects for renewable energy from the sea. Mar. Technol. Soc. J. 11, 16–21.
Yu, F., et al., 2021. Dynamic response of the mooring system int eh floating photovoltaic power station. J. Phys.: Conf. Ser. 2087, 012028.
Zheng, X., Zheng, H., Lei, Y., Li, Y., Li, W., 2020. An offshore floating wind–solar–aquaculture system: concept design and extreme response in survival conditions. Energies 13, 604. https://www.mdpi.com/1996-1073/13/3/604.