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Trends in Ecology & Evolution

CellPress REVIEWS

Review

How 'Blue' Is 'Green' Energy?

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Often perceived as environmentally benign, 'green' renewable energy technologies have ecological costs that are often overlooked, especially those occurring below the waterline. After briefly discussing the impacts of hydropower on freshwater and marine organisms, we focus this review on the impacts of marine renewable energy devices (MREDs) on underwater marine organisms, particularly offshore wind farms and marine energy converters (e.g., tidal turbines). We consider both cumulative impacts and synergistic interactions with other anthropogenic pressures, using offshore wind farms and the Taiwanese white dolphin (*Sousa chinensis taiwanensis*) as an example. While MREDs undoubtedly can help mitigate climate change, variability in the sensitivity of different species and ecosystems means that rigorous case-by-case assessments are needed to fully comprehend the consequences of MRED use.

Growing Marine Impacts of Climate-Friendly Energy Technologies

Climate change is causing extensive and uncertain changes in the oceans, which bring new and sometimes severe challenges to marine life (see Box 1). Many nations view **renewable energy** (see Glossary) installations as part of their strategy to reduce carbon emissions and curb climate change [4]. Despite this, the environmental impacts of such installations should not be overlooked in the rush to meet political and economic targets. A previous review explored some of the impacts of **wind power**; **hydropower**; and, to a lesser extent, **solar photovoltaic** power on terrestrial environments [5]. Here we consider potential impacts below the waterline and explore how environmentally benign, or 'blue', these 'green' energy technologies really are in marine ecosystems, using the available literature.

For example, hydropower in freshwater systems alters water flow, affecting aspects of marine circulation, ice cover, size of freshwater plumes, and nutrient flux (e.g., [6–8]). Additionally, anaerobic decomposition of flooded vegetation in deep reservoirs formed above large dams often produces biologically toxic methylated mercury (e.g., [9,10]) that can have serious consequences for fish and other wildlife both in the reservoir and downstream [11]. This process also initially generates considerable greenhouse gases, meaning that hydropower installations can take decades just to reach net impact levels similar to those of **conventional energy** production [12–14].

Several technologies that are designed specifically for installation in marine environments, referred to as **marine renewable energy devices (MREDs)**, can have more direct impacts (see [15]). These technologies include offshore **wind turbines**, **marine energy converters** and **ocean thermal energy conversion** devices (although the last of these is substantially less developed than the others and is not discussed further here). **Offshore wind farms** are currently the most prevalent, although they do not actually extract the energy from the ocean itself. However, several truly marine energy technologies are in varying stages of development.

Some MREDs are nearing economic competitiveness with conventional energy production methods (e.g., [16]), despite discriminatory tax and subsidy regimes around the world (e.g., [17]). This will likely lead to the rapid proliferation of MREDs globally (as demonstrated by offshore wind farms), with countries selecting the technologies most suited to local oceanic conditions to meet looming national renewable energy targets. Therefore, it is important to explore and understand the expanding potential for environmental impacts from such technologies.

Highlights

Global offshore wind capacity has been increasing at 15–30% annually, aided partly by the establishment of the industry in China.

There are over 90 tidal energy technology developers globally, with about half focusing on horizontal axis turbines that rotate in a plane perpendicular to the flow of the current.

Over 200 companies are pursuing wave energy converter development, most commonly point absorber devices that convert the vertical motion of floats into electricity.

Construction noise impacts are relatively well understood, but those from the operation of marine renewable energy devices remain largely unknown. Monitoring at demonstration sites and full commercial projects is needed to address this knowledge gap for future installations.

Direct and indirect effects of installations on marine life depend on relative scales and interactions with impacts from other existing industries.

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Box 1. Impacts of Climate Change on Marine Life

The oceans are undergoing various physical changes, each with the potential for impacts on marine life. These include a broad warming of the oceans; reduced subsurface oxygen concentrations; ocean acidification; changes in sea level, sea ice extent, thermal stratification, and ocean circulation; and increased variability in local temperatures, with more frequent extreme oceanographic and atmospheric events (see review by [1] and L. Nunny and M.P. Simmonds, unpublished). Beyond direct impacts on physiology and mortality, such as those caused by exceeding the physiological tolerances of biota, there are numerous indirect impacts (e.g., changes in suitable habitat) and synergistic impacts (e.g., changes in the prevalence or severity of other threats for a given species) (see reviews by [1,2]). As top predators, marine mammals may either suffer or benefit from changes in the distribution and abundance of prey species [2].

There are many indications that range shifts are already occurring in several marine mammal species in response to changes in either physical oceanography or prey abundance [2,3]. One study predicted that increases in water temperature will alter the ranges of 88% of cetacean species, with the changes expected to be detrimental for nearly half of these [3].

While many marine species may be able to adapt to the effects of climate change, some may have neither the necessary behavioural plasticity nor the ability to shift their range as required [2]. For example, in 21% of cetacean species, the predicted changes in range may place at least one geographically isolated population of the species at a high risk of extinction [3]. The most seriously affected species and populations will be those that are constrained to small geographic ranges in fragmented or isolated habitat [2,3].

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Offshore Wind Farms

European leadership in offshore wind farm development has been matched by efforts to understand and mitigate its impacts on marine life, primarily marine mammals (see [18]). With **percussive pile-driving** being used to push wind turbine foundations into the seafloor, noise during construction was identified early on as a potential threat to coastal marine mammals. Typical impacts include displacement and, at close ranges, hearing damage, such as temporary or permanent threshold shifts in hearing sensitivity [19–22]. Stress responses and **masking** (including obscuration of sounds from prey species and conspecifics) are additional concerns because marine mammals depend on sound for nearly all life functions [23]. Percussive pile-driving is intermittent and produces primarily (although not exclusively) low-frequency noise [24,25]. Therefore, masking will be more problematic for animals using lower frequencies, such as baleen whales, than for small **echolocating cetaceans** (dolphins and porpoises) that generally exploit higher frequencies. Additionally, masking may be more pervasive at larger distances from the source due to the way impulsive sound propagates and spreads out in complex environments.

Concerns over masking are also greater for concurrent piling, **vibratory pile-driving**, and noise produced during the operation of a wind farm [26]. Operational noise is at lower frequencies and much lower levels than construction-related noise, comparable to or in most cases lower than noise from most ships. It is even less problematic in European waters, where low-frequency baleen whales are now much less common than they were in the past, having been decimated by historical whaling. Elsewhere, operational noise may remain a concern because the hearing ranges of most baleen whale species are thought to peak below 1 kHz [27]. These frequencies may also be relevant for underwater communication by certain pinniped species [28]. Ongoing monitoring of sound from offshore developments along the Atlantic coast of the USA may soon offer opportunities to assess possible impacts of wind energy development on some baleen whales (e.g., [26,29]).

Finally, offshore wind farms alter the benthic habitat. This can change the scale and composition of prey aggregations with knock-on consequences (good or bad) for marine mammals (e.g., [30,31]).

Marine Energy Converters

Of the various MREDs that extract energy from the ocean, marine energy converters (tidal stream generators or tidal range energy converters and, to a lesser extent, wave energy converters) are

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the most developed and thus merit discussion here. Optimal tidal energy sites tend to coincide with complex, biologically rich coastal habitat [32,33], due in part to high transport rates of larval invertebrates and nutrients to the higher **photic** (sunlit) **zone** (e.g., [34,35]). Such habitat provides predictable foraging opportunities for marine mammals [36–39], and thus marine mammals and tidal energy developments are prone to co-occur [40].

Much has been learned from the many small evaluation marine energy converter installations in Canada, the USA, the UK, Sweden, and France. Current concerns over converter technologies focus primarily on physical interactions with marine mammals and other marine life (e.g., collision with structures or moving parts), although considerable uncertainty exists regarding the nature and scale of such interactions [32,33,41–43]. While we are not aware of any recorded instances of marine mammals colliding with turbine blades, the probability of making such observations is low, meaning that the uncertainty surrounding this risk will persist (see [44,45]).

Converters may also exclude animals from important habitat due to perceived or physical barriers [39,40]. Noise from operating turbines may also change the behaviour of marine mammals and other marine fauna, cause masking, and induce stress responses [33,39,46–48]. For example, recent playback experiments at a tidally active site in Scotland found that the tagged harbour seals (*Phoca vitulina*) avoided the area, maintaining a separation distance of up to 500 m from the sound source, even though the overall numbers of seals using the site did not change [40]. Similarly, experiments in Washington State (USA) found reductions in both sightings and acoustic detections of harbour porpoises (*Phocoena phocoena*) during some playback periods, although simulated turbine sounds had no significant effect on harbour seal presence [49]. These studies suggest that the noise from turbine operations could impact the use of core foraging areas by some marine mammals. Very few studies are available on wave energy converters, but at least some types appear to have very low noise emissions [50,51].

However, much like wind farms, construction of marine energy converter installations is likely to be the most acoustically complex and loudest phase, involving not just higher sound pressure levels (relative to operational levels) but often also impulse-type sounds [32,49]. Accordingly, temporary displacement of harbour porpoises from demonstration turbine sites during construction has been reported (e.g., [52,53]). Construction of the world's first commercial-scale converter installation in Scotland [4] may provide insight into the population-level consequences of such displacement.

The direct and indirect effects of converter installations (such as those of other MREDs) will likely depend on project scale, phase of development (construction versus operation), specific device structure, site characteristics, species present, (local) population sizes and densities, proportion of each population's total distribution that overlaps the project area, and how the animals use the area [40,48]. Accordingly, risk assessments for marine energy converters and other MREDs will need not only to incorporate both direct effects (e.g., disturbance, displacement, injury, or mortality from noise and collisions) and indirect effects (e.g., changes in prey availability), but also to consider how the particular animals present in the area will respond to the specific activities and structures associated with any given development.

Impacts of MREDs on Fish, Birds and Other Marine Life

MREDs have impacts on various non-mammalian marine species (e.g., review by [54]). The injuries and deaths suffered by fish as they approach or pass through underwater turbines are perhaps the best understood. Injury and mortality may be caused by mechanical strikes, shearing, pressure fluxes, or **cavitation** [55–57]. The larger the animal, the greater the chances of a fatal strike, and if such events occur with sufficient frequency in relation to animal numbers, they could cause abundance to decline.

During MRED construction, pile-driving noise may affect fish by damaging their hearing or causing barotrauma to swim bladders and other organs [58]. To explore acoustic impacts of operations, juvenile Chinook salmon (*Oncorhynchus tshawytscha*) were exposed to simulated tidal turbine noise, resulting in low levels of nonlethal tissue damage [59].

Glossary

Cavitation: the formation of small, vapor-filled cavities in a liquid in places where the pressure has rapidly dropped, such as might occur due to the movement of a propeller through the cavity. These cavities can generate somewhat intense shock waves when they collapse again.

Conventional energy: energy derived from the combustion of nonrenewable fossil fuel sources (oil, gas, and coal).

Echolocating cetaceans: toothed cetaceans that use biosonar to detect prey and explore their environment in a similar way to bats.

Hydroelectric power or **hydropower**: electrical power generated from the energy of falling or fast-running water.

Marine energy converters: devices that convert mechanical ocean energy into electricity. These can be tidal stream generators or tidal range energy converters, which often rely on rotating blades to spin a generator, or wave energy generators that convert the vertical motion at the surface of the ocean into electricity.

Marine renewable energy device (MRED): renewable energy devices that are installed in the ocean, including offshore wind farms, or on the coast, extracting energy from the ocean.

Masking: the obscuration, by unwanted noise, of sounds of interest to a marine mammal (or other animal) from prey and conspecifics, among others.

Ocean thermal energy conversion (OTEC): the process of energy generation relying on the temperature differential between, most commonly, deep cold ocean water and warm tropical surface water to vaporise a working fluid (i.e., a fluid moved within the device up and down between those layers) with a low boiling point (such as ammonia) and turn a turbine coupled to a generator.

Offshore wind farm: a series of wind turbines used to produce electricity (i.e., 'a wind farm') that is located in the marine environment, including (and currently most commonly) in shallow near-coastal areas.

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Many MREDs are anchored to the ocean floor. Emitted noise transferred to the seabed can be carried considerable distances and remain detectable as vibration by elasmobranchs (skates and rays) and other benthic life, which are often buried in the same substrate [60]. The effects of exposure to chronic operational noise are uncertain. However, the frequency range of the noise does overlap the audiograms of most fishes, which range from approximately 15 Hz up to 1 kHz (see [59]).

For operational wind farms, impact studies on fish have focused on the artificial reef element because this may have a secondary (attractive) influence on marine mammals (e.g., [22,30,31]). However, altering benthic substrate by installing MRED structures may also have more subtle ecosystem-scale impacts, especially when MRED density is high. For example, increasing hard substrate could reduce the quantity of phytoplankton in the water column for benthic filet feeders [61], potentially changing the entire faunal composition from one based previously on soft substrate. However, it remains unclear whether artificial reefs act to increase prey productivity or simply aggregate certain species.

Like marine mammals, the relatively high longevity and low annual reproductive rates of bats and some birds may make them particularly vulnerable to impacts from MREDs [62,63]. While the effects of land-based wind farms on these taxa are well documented during both construction and operational phases [64–70], there are comparatively few peer-reviewed studies on the impacts of offshore wind farms [71]. In summary, the impacts are thought to occur via multiple pathways, including direct impacts (collision or barotrauma), indirect impacts (e.g., disturbance, displacement, and other behavioural effects), barrier presentation, and habitat alteration [63,72–74]. The scarcity of empirical information is driven by the logistical challenges and the environmental conditions offshore [72,75,76], as well as the high mobility, wide and often unpredictable or even unknown distributions, and movement patterns of the species concerned [76,77]. However, advances in technology and methodology are opening up new possibilities for data collection that will help fill knowledge gaps in the future [72,76].

Impacts of MREDs in a Wider Context: Cumulative Impacts

MREDs never enter the marine environment in isolation. Rather, every new offshore development represents an incremental addition to the pre-existing human 'footprint' on the marine ecosystem. The greater the spatial, acoustic or ecological overlap with other activities or structures, the more likely cumulative or synergistic interactions will arise. Large wind farm projects have been installed or are being planned in the coastal waters of many nations, including in eastern Asia, where the demand for energy to support current and future industrial and manufacturing aspirations is high. Much of the early development of wind energy technology occurred in Europe, where marine ecosystems are already heavily modified and under severe pressure [78].

Given the diversity of potential 'new' stressors, it is likely some will interact with each other or with pre-existing stressors to create additional hard-to-predict and unforeseen emergent impacts. The cumulative and synergistic effects that can arise when different stressors (and not necessarily the activities themselves) are present together or are triggered sequentially, are poorly understood and difficult to measure. Full comprehension of potential impact interactions may thus require contributions from individuals typically left outside impact assessment processes. Consequently, many environmental impact assessments are severely deficient in their evaluations of these aggregated effects (e.g., [79]).

Synergy of impacts from fishing and wind farm development is thought to be common. For example, construction may displace both fishing effort and the animals that fishing affects (through entanglement or bycatch) into the same areas outside of the near-radius of the wind farms (see Box 2). Similarly, if access to the vicinity operating MRED installations is unrestricted, new artificial reefs where fish and other organisms tend to aggregate can attract both fishermen and marine mammals. In both scenarios, increased spatial overlap means an elevated risk of serious injury or death through entanglement (although this effect might be mitigated or offset if fishermen change their fishing gear and practices or target different species). Conversely, if fishing is not allowed inside the immediate

Percussive pile-driving: a means of driving a pile into a substrate by repeatedly by raising and dropping a heavy weight or using a steam hammer to hit the pile head.

Photic zone: surface layer of the ocean that receives sunlight, consisting of the euphotic zone, where there is sufficient light for photosynthesis, and the remaining disphotic zone, where photosynthesis is not possible. The euphotic zone typically extends down to approximately 80 m, with the disphotic zone generally reaching about 200 m.

Renewable energy: energy derived from renewable resources that are naturally replenished, such as wind, sunlight, and geothermal heat.

Solar photovoltaic (PV): the direct type of solar energy in which photons from solar radiation are converted to electricity.

Vibratory pile-driving: a means of driving a pile into a substrate by mounting on top a device that produces vertical vibrations that are transmitted into the pile, typically using hydraulic-powered counterrotating eccentric weights.

Wind power: the use of air current to turn wind turbines to mechanically produce electricity.

Wind turbine: a device that spins a generator to produce electricity in the presence of wind, often (but not exclusively) as a result of blades rotating in a plane perpendicular to the direction of the wind movement.

Box 2. A Case Study: Offshore Wind Farms and the Taiwanese White Dolphin

Embracing renewable energy generation to meet energy demands and protect air quality, Taiwan plans to generate 5.2 GW from 400 to 600 offshore wind turbines by 2030 [80]. The planned developments are primarily in the shallow water areas along the central west coast and overlap important habitat for Taiwan's only endemic marine mammal, the geographically-restricted Taiwanese white dolphin (*Sousa chinensis taiwanensis* [81,82]). With only $\leq$75 individuals and their number steadily declining (see [83–86]), the subspecies is listed as critically endangered on the IUCN (International Union for Conservation of Nature) Red List of Threatened Species [87].

Possible direct effects of wind farms on the dolphins include: (i) disturbance to behaviour, particularly during the construction phase; (ii) temporary or permanent displacement from important areas; (iii) additional habitat loss; (iv) increased likelihood of vessel strikes (due to installation and service craft); (v) damage to hearing; and (vi) increase in stress levels.

Possible indirect impacts include changes to local faunal composition and biomass (including prey species). For example, artificial hard structures introduced into the naturally soft substrate may aggregate fish and in turn attract both dolphins (e.g., [30]) and fishermen, and they may also snag and collect discarded fishing gear [88]. More spatial overlap between dolphins and fishing gear would further elevate the already high incidence of fishery-related injuries and deaths without associated changes in fishing gear and practices (see [89,90]).

This threatened subspecies cannot sustain further stress or injury [85,91]. To avoid inadvertently pushing it into extinction, careful planning will be needed to anticipate and prevent serious impacts (including exacerbation of existing stressors). Residual injury and disturbance should be minimised by using state-of-the-art noise reduction engineering practices (e.g., [92,93]). Regulators must work with fisheries and the wind farm industry both to limit cumulative and synergistic impacts and to enhance the dolphins' resilience to wind farm impacts by reducing the existing threat of entanglement. This could, for example, be achieved through a strictly enforced permanent ban on fisheries that use high-risk gear, such as gillnets (including trammel nets [89,91]), not only near the wind farms but also more widely. The costs of mitigation, including compensation to displaced fishermen, should be borne at least partly by the wind farm companies.

area of operating installations and animals are not deterred by the activities, the installations may serve as refuges from fishing and fishing-related damage to the seabed [94].

Relative Scale: Small Populations and Large Installations

MRED impacts are also likely to be magnified for 'sensitive' animal populations, such as those that are numerically small and occur within constrained habitats, especially if they are already declining due to other factors (e.g., [95]). For example, if operational underwater turbine noise is perceived by a given species as a barrier, this may reduce the likelihood of collisions (e.g., [40]), but, as noted above, it could also exclude animals from a portion of favourable habitat, reducing foraging opportunities and leading to population-level impacts (e.g., [40]).

Such exclusions are of particular concern if the extent of habitat lost to a species or population is large in relation to its full distribution. Perhaps nowhere is this concern more evident than along the west coast of Taiwan, where the Taiwanese white dolphin (*Sousa chinensis taiwanensis*) is struggling to survive in a narrow strip of very near-shore habitat within a densely populated and heavily industrialised region (Box 2).

Achieving a Bluer Green

The choice should not be MREDs or marine life. They can coexist. In fact, the construction of wind farms or other MREDs might ultimately prove beneficial to some wild species. For example, in addition to combatting climate change, shipping is displaced by many MREDs, meaning that a substantial source of noise and other forms of pollution could be shifted farther away from prime coastal habitat (see [29,94]). MREDs can also act as obstacles to trawling, thereby reducing benthic damage and lowering bycatch risk in the vicinity of installations. Additionally, the new structures could aggregate

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prey and improve foraging, and/or attract high-value fishery species such as lobsters or crabs that can be caught without harming marine mammals (as long as the right fishing methods are used).

However, if wildlife is to experience a net benefit from MREDs, careful planning is required, and ecosystem-based management tools may need to be applied (see [29]). Actions would almost certainly need to be site-, time-, and even project-specific, given the unique mixture of human activities, geographical features, and species present at any given development location. Accordingly, coupling a rigorous impact assessment (that is thorough, credible, and not rushed to meet what are viewed as immediate political or economic mandates) with a comprehensive mitigation plan is critical.

Such assessments and plans should have four main goals as follows:

(i) To protect sensitive species from what are expected to be the most severe anthropogenic impacts, which can be direct, indirect, cumulative or synergistic, and may occur outside of the immediate geographic footprint of the activity or activities responsible.

(ii) To reduce, or preferably eliminate, all residual injury and disturbance from noise exposure. This can be achieved by, for instance, employing state-of-the-art noise reduction engineering practices during construction and operation (see [92,96]). For example, gravity and multi-pile foundations involve lower noise levels (and possibly less noise emission overall) than conventional monopile foundations, and bore piling has much lower potential than percussive piling to cause hearing damage and displace animals. Underwater noise abatement technologies, such as cofferdams, bubble curtains and other structures with encapsulated air bubbles, can also substantially reduce emitted construction noise, at least in the nearfield (e.g., [93]). Many such noise abatement technologies for pile-driving were developed or improved in response to regulatory standards introduced in Germany (see [92]). Regulators elsewhere might wish to emulate this practice of setting standards as a way to encourage innovation.

(iii) To minimise, to the greatest extent possible, the potential for cumulative and synergistic impacts, and where they are unavoidable, minimise their scale in terms of severity and spatial scope.

(iv) To reduce, and eliminate if possible, existing threats before introducing new ones so that the affected wildlife population is more resilient to the impending new impacts (e.g., [97]).

Notably, these goals differ from current ideals by focusing on the footprint of the impacts rather than on the site of a development in isolation. They also specifically incorporate mitigation of impacts from other activities and industries into the scope of potential mitigation options.

To Build or Not to Build

A good impact assessment outlines not only the potential environmental costs arising from a given development project but also the financial costs of different measures for industry (and, in turn, consumers). Such costs may include reputational damage, which is closely tied to social licence. This would allow MRED companies to balance mitigation costs against not only the environmental costs but also potential costs (and loss of earnings) related to damage to their industry-wide reputation as an 'environmentally friendly' or 'green' technology. The importance of such public relations concerns should not be underestimated if, for example, MRED installations are likely to accelerate the demise of an endemic (and iconic) dolphin subspecies (see Box 2). Even if the main concern is not the MREDs but bycatch in fisheries, for example, the incoming MRED industry may still be blamed for further population declines. It is thus in the MRED industry's own interest to consider impact assessment as an opportunity to avoid such outcomes rather than as merely a regulatory box-checking exercise. Governments could also encourage careful MRED development through, for example, revisions to discriminatory tax policies [17] to make the additional costs of environmental stewardship less onerous.

Governments must also ultimately make decisions about the fate of planned projects based on the information available (including acknowledgement of major knowledge gaps). Financial accounting

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plays a limited part here, with societal values and needs playing a larger role. For example, decisions should consider the importance of biodiversity to a nation's competitiveness in the increasingly important world of biotechnology, as well as its national security [98].

Scientists may be able to estimate, for example, the probability that a population will decline following some action, be it a direct impact due to MRED building (e.g., [99,100]) or the less direct impacts of habitat loss due to climate change (e.g., [3]). However, scientists cannot tell managers at what specific point a injury transitions from being minor to becoming a major disability, what constitutes the onset of legally defined harm to an individual or population, or how much risk of extinction is tolerable. These are policy decisions relating to standards and thresholds that are built, often without proper definition, into national laws around the world. Nonetheless, scientists can provide decision-making tools (see [97,101]) and contribute to policy discussions as subject experts (e.g., [102]). Such tools and discussions are needed to find a balance between the expected impacts of climate change, the reduction of those impacts afforded by increased reliance on renewable energy, and the environmental damage that could arise from using MREDs and their terrestrial counterparts.

It may be useful to consider other cases where technologies initially perceived as 'green' have subsequently generated considerable environmental concern. For example, offshore seismic surveys for oil and gas were historically undertaken using dynamite as an acoustic source. This practice was phased out in favour of the airgun, which was safer and, at the time, considered to be comparatively benign towards the environment. However, airguns have since been found to have their own issues, and they are now poised to be replaced by a newer technology that is less impactful still: marine vibroseis [92,96,103]. Lessons must be learned from the past, and creative business opportunities must be embraced, if renewable energy technologies are to avoid becoming the new 'black' in comparison to yet 'greener' future technologies.

Concluding Remarks

MREDs and other renewable options are integral to any nation's climate strategy because they are undoubtedly less climate-forcing than burning fossil fuels. However, as nations tackle the problem of climate change, they must not ignore the potential for damaging wildlife populations and ecosystems in the process: It matters little to a species if the habitat loss driving them to extinction is caused by climate-related changes or MRED installations. Importantly, the responsibility for minimising such harm is shared by governments and development companies. If the MRED industry seeks to capitalise on its reputation as environmentally benign (i.e., 'green'), it must accept the responsibility of investing to ensure installations really are low impact, or even beneficial, for wildlife and ecosystems. This responsibility may even represent a public relations opportunity for boosting social licence. For example, MRED companies operating in Taiwan that contribute to dolphin protection measures might embrace the idea of being 'dolphin-friendly' as among their green credentials.

However, both national governments and the MRED industry will ultimately need to make some difficult choices, given the incomplete information about maintaining biodiversity while addressing climate change (see Outstanding Questions). While prevailing opinion may be that climate change is the ultimate environmental crisis [104,105], there almost certainly will be occasions when the local impacts of MREDs are judged to be untenable in their own right, due to concerns related to security, public relations, or simply societal values. Such judgments, however, require that the specific impacts of a given installation are explored on a case-by-case basis.

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Outstanding Questions

How often do marine mammals and other marine life collide with tidal turbines and other marine energy devices?

What is the full range of potential injuries when marine life is struck by or collides with marine renewable energy devices?

What is the full risk to marine life of near-turbine encounters? What impact does this have on populations?

What is the full extent of acoustic impacts from the construction and operation of marine renewable energy devices on marine life, especially marine mammals?

How representative are impacts observed at small-scale demonstration facilities of the likely impacts of full-scale operations?

How can the possible positive effects of marine renewable energy devices be maximised while the negative effects are minimised?

How can the additional costs of environmental stewardship be made more acceptable to the MRED industry, or can they be offset entirely?

What is the value to industry of social licence and a favourable public opinion of MREDs?

How can the typical suite of mitigation options considered when planning MRED installations be expanded to include changes to existing industries to better account for cumulative impacts?

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