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Renewable energy and biodiversity: Implications for transitioning to a Green Economy

Alexandros Gasparatos[a,*], Christopher N.H. Doll[b], Miguel Esteban[c], Abubakari Ahmed[c], Tabitha A. Olang[c]

[a] Integrated Research System for Sustainability Science (IR3S), University of Tokyo, Tokyo, Japan
[b] Institute for the Advanced Study of Sustainability (UNU-IAS), United Nations University, Tokyo, Japan
[c] Graduate Programme on Sustainability Science – Global Leadership Initiative (GPSS-GLI), University of Tokyo, Kashiwa, Japan

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ABSTRACT

This literature review identifies the impacts of different renewable energy pathways on ecosystems and biodiversity, and the implications of these impacts for transitioning to a Green Economy. While the higher penetration of renewable energy is currently the backbone of Green Economy efforts, an emerging body of literature demonstrates that the renewable energy sector can affect ecosystems and biodiversity. The current review synthesizes the existing knowledge at the interface of renewable energy and biodiversity accross the five drivers of ecosystem change and biodiversity loss of the Millennium Ecosystem Assessment (MA) framework (i.e. habitat loss/change, pollution, overexploitation, climate change and introduction of invasive species). It identifies the main impact mechanisms for different renewable energy pathways, including solar, wind, hydro, ocean, geothermal and bioenergy. Our review demonstrates that while all reviewed renewable energy pathways are associated (directly or indirectly) with each of the five MA drivers of ecosystem change and biodiversity loss, the actual impact mechanisms depend significantly between the different pathways, specific technologies and the environmental contexts within which they operate. With this review we do not question the fundamental logic of renewable energy expansion as it has been shown to have high environmental and socio-economic benefits. However, we want to make the point that some negative impacts on biodiversity do exist, and need to be considered when developing renewable energy policies. We put these findings into perspective by illustrating the major knowledge/practices gaps and policy implications at the interface of renewable energy, biodiversity conservation and the Green Economy.

1. Introduction

The concept of the Green Economy has gradually gained prominence amongst academics and policy-makers [1,2]. The Green Economy was one of the two themes of the 2012 United Nations Conference on Sustainable Development (UNCSD-2012) held in Rio de Janeiro, commonly known as Rio+20. The United Nations Environment Programme (UNEP) has been at the forefront of the Green Economy discourse in the run-up to Rio+20, which culminated in the publication of its landmark Green Economy report [2] and guidance on how to formulate green economic policies, measure progress and model the future effects of a transition to a Green Economy [3].

In this discourse the Green Economy is defined as an economic system that results in "*improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities… In a green economy, growth in income and employment are driven by public and private investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services*" [2] (page 15).

* Correspondence to: Integrated Research System for Sustainability Science (IR3S), University of Tokyo Institutes for Advanced Study (UTIAS), University of Tokyo, Administration Bureau Building 2, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan.
E-mail address: gasparatos@ir3s.u-tokyo.ac.jp (A. Gasparatos).

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Conserving biodiversity[1] and maintaining ecosystem services[2] are key pillars of the efforts to transition to a Green Economy [11].

Investing in natural capital and increasing energy/resource efficiency are the two key strategies to develop "green" economic sectors as a means of transitioning towards a Green Economy [2]. The former is a major strategy for economic sectors that depend on biological resources, such as agriculture, forestry and fisheries. The latter is key to reducing resource intensity and environmental impact to economic sectors that depend on the transformation of natural capital such as manufacturing, transport and construction.

According to UNEP [2], the large-scale penetration of renewable energy is a key intervention for greening the economy considering its[3]:

- climate change mitigation potential
- fossil energy-saving potential
- ability to generate "green jobs"

While renewable energy currently accounts for a relatively small proportion of global final energy consumption (~19.1%[4] in 2013), it has the potential to provide for all human energy needs [14]. In 2014, 164 countries had already adopted some type of renewable energy policy (up from 48 in 2004) [13], with some of the targets being quite bold. For example the EU aims to meet 20% of its total energy needs through renewable energy by 2020 [12].

However, there are some interesting and under-appreciated interplays between renewable energy generation and biodiversity conservation. For example, some renewable energy pathways can have major negative impacts on biodiversity by disrupting ecosystem processes [15], and thus can potentially take a toll on the provision of ecosystem services [16]. This has been confirmed by a number of synthesis studies for individual renewable technologies, e.g. wind [17,18], solar [19–21], hydropower [22], bioenergy [23–24] and ocean energy [25,26]; as well as by comparative studies between renewable and conventional energy technologies [27,28]

This implies that while a large-scale adoption of renewable energy could reduce GHG emissions and enhance resource efficiency (two key pillars of a Green Economy), it could also clash with biodiversity conservation and the maintenance of ecosystem services (a third pillar of the Green Economy, as explained above). Yet, with the exception of some land-intensive renewable energy pathways such as bioenergy, the potential negative impacts of renewable energy on biodiversity and ecosystems have been underappreciated within the current Green Economy discourse [2].

The aim of this review is to systematize the evidence about the mechanisms through which different renewable energy technologies can drive ecosystem change and contribute to biodiversity loss, as well as identify emerging green-economic trade-offs. The review is structured alongside the five direct drivers of ecosystem change and biodiversity loss identified in the Millennium Ecosystem Assessment (MA)[5]; namely habitat loss/change, overexploitation, introduction of invasive species, pollution and climate change. Several knowledge synthesis exercises, including follow-ups to the MA from the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), have discussed how the direct drivers of ecosystem change emerge in different parts of the world, and are linked to a multitude of human interventions [6,29,30]. A deeper exposition of the links between these direct drivers and biodiversity loss can be found elsewhere [6,7,31,32].

The present study initially identifies through an extensive literature review the main mechanisms of ecosystem change and biodiversity loss for each renewable energy pathway, and the main interventions that can mitigate negative biodiversity outcomes. The renewable energy pathways covered include solar (Section 2), wind (Section 3), hydro (Section 4), bioenergy (Section 5), ocean (Section 6) and geothermal energy (Section 7).[6] We focus on renewable energy technologies that have moved beyond the laboratory phase,[7] as it allows us identify the impact mechanisms based on empirical studies, rather than solely rely on hypotheses or simulations. Section 8.1 summarizes the current evidence across the different MA drivers of ecosystem change and biodiversity loss. Section 8.2 identifies key knowledge/practice gaps and offers suggestions on how to better capture biodiversity trade-offs during the planning of large-scale renewable energy projects. Finally, Section 8.3 discusses some of the key policy implications at the interface or renewable energy, biodiversity conservation and the Green Economy.

2. Solar energy

2.1. Background

Solar energy harnesses the power of the sun to generate electricity either directly through photovoltaic (PV) cells, or indirectly by means of concentrated solar power (CSP). CSP technologies use arrays of mirrors that track the sun and continuously reflect its rays to a point (heliostats) to heat a working liquid, which is then used to generate electricity in a conventional turbine.[8] Emerging solar energy technologies also use concentrated sunlight on higher quality PVs.[9] CSP generally requires large areas to be effective, while solar PV panels may be distributed and mounted on any surface exposed to the sun, making them ideal for integration into the urban environment or man-made structures.

Large-scale solar energy generation is usually referred to as Utility Scale Solar Energy (USSE) and has a typical lifespan of 25–40 years. Solar energy generation has increased rapidly in the past decades. By 2014 177 GW of solar PV and 4.4 GW of solar CSP have been installed globally [13].

The ecological impacts of solar energy are often assumed to be negligible [15]. However USSE can affect ecosystems in multiple ways throughout its lifecycle (i.e. construction–operation–decommission)

[1] Biodiversity is *"the variability among living organisms from all sources including … terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems"* [4]. In the present review we adopt the definition of biodiversity proposed by the Convention on Biological Diversity (CBD) as it is in common usage, has policy status and is inclusive [5].

[2] Ecosystem services are the benefits that humans derive directly and indirectly from ecosystems, which contribute manifold to human wellbeing [6]. In the early ecosystem services discourse, biodiversity was not conceptualized as an ecosystem service, but as the basis of ecosystem services [7]. However the role of biodiversity for the provision of ecosystem services, and as an extent its contribution to human wellbeing, is much more complicated [8–10].

[3] This triptych of policy objectives often features in policy frameworks that aim to catalyse the penetration of renewable energy, e.g. the EU Renewable Energy Directive [12].

[4] Of which 10.1% came from modern renewables and 9% from traditional biomass [13].

(footnote continued)
[5] These drivers of ecosystem change and biodiversity loss share significant similarities with those of subsequent initiatives such as TEEB [29] and IPBES [30].

[6] There is a large body of relevant literature for some renewable energy pathways (e.g. hydro, bioenergy) and a lack for others (e.g. ocean, geothermal). For this reason our review, rather than being exhaustive, it attempts to identify the key mechanisms through which each of these renewable energy pathways contributes to ecosystem change and biodiversity loss.

[7] For example, we do not consider some advanced renewable energy technologies such as 3rd generation biofuels (algal biofuels) that have not been deployed beyond laboratory conditions [13], even though they might have some impact on ecosystems and biodiversity.

[8] CSP can have a 'tower power' configuration where mirrors focus solar energy to a central tower, or a trough system of parabolic mirrors that reflect heat onto the focal point of the array.

[9] CPV (concentrator photovoltaic) systems use lenses and sun-trackers to concentrate sunlight onto PV cells. They are more akin to conventional PV in design but, as yet, have experienced relatively limited deployment.

[33] although currently, many of these effects are hypothesized with little peer-reviewed evidence available [27].

2.2. Drivers of ecosystem change and biodiversity loss

Most of the well-documented effects of solar energy on ecosystems and biodiversity manifest through the loss and change of habitats. This is because the development of solar energy infrastructure can take up significant amounts of land modifying and fragmenting habitats in the process.

Regarding habitat loss, solar power infrastructure, and especially USSE, increasingly occupies substantial tracts of land but its design, footprint and land-use efficiency can vary considerably [21]. Supporting infrastructure (e.g. access roads and electrical equipment) and the spacing requirement of the panels, can result in the actual space requirement of solar power installations being around 2.5 times the area of the panels themselves [20].

Regarding habitat change, USSE infrastructure and land preparation activities (e.g. vegetation clearing, removal of upper soil layers) can fragment habitats, become a barrier to the movement of species, affect hiding places, preying strategies and the availability of food [20,21,27].[10] Studies have also documented the direct mortality of birds from heliostat collisions and burning from solar rays directed to the central receiving point [35]. Mortality rates and mechanisms (e.g. mortality due to collision with the structures vs. mortality from solar fluxes) vary significantly between solar PV, CSP-tower and CSP-trough configurations [36]. The polarized light that is often found at such facilities can confuse insects into laying their eggs on the panel, affecting their chances of reproduction [37,38]. Furthermore, the bright glare from CSP plants can attract insects, which in turn attracts birds that can be killed by the solar flux or be subjected to higher-level predators, making the installation an ecological trap [36]. CSP also uses large amounts of water, having a dramatic effect in water-scarce environments as exemplified by the extended drying periods of ephemeral water bodies that host endemic and migratory species [39,40].

It should be noted that contrary to USSE that require significant tracts of undeveloped land, the diffusion of solar PVs on rooftops and building facades may reduce some of the habitat loss/change effects of solar energy. This is because the solar panels are mounted on existing structures (largely in urban settings) so they do not convert or fragment habitats. Interestingly if these solar PV installations are combined with green roofs then they can potentially provide habitat for certain plant/insect species and provide a number of ecosystem services in urban areas [501,502].

Solar energy installations have also been associated with pollution. For example, in order to keep panel access to the sun, the cleared land is often maintained with dust suppressants and herbicides (in addition to other toxins used in USSE operation) [33]. The use of dust suppressants can both increase runoff and alter key chemical properties of adjoining waterways when washed out [39].

Finally, USSE can potentially affect local microclimates. For example, soil temperature changes have been reported around a CSP plant in China (0.5–4 °C lower in spring and summer and higher by the same range in winter), compared to control sites with no collectors [41]. This insulation effect was attributed not only to physical shading but also to alteration of the air-flows around the structure [41]. However, available peer-review literature regarding such micro-climatic effects is still extremely scarce.

[10] USSE infrastructure can, sometimes, provide nesting sites [21]. However, this can become a threat if it attracts species to hazardous areas such as airports [34].

2.3. Mitigation measures

In order to reduce the impacts from the deployment of solar energy on ecosystems and biodiversity, common mitigation measures include:

(a) locating solar energy installations in areas with little biodiversity

(b) developing biodiversity-friendly operational procedures for solar energy installations

Regarding (a), a general rule of thumb is to develop USSE infrastructure in desert areas that combine high levels of solar insolation with relatively low levels of cloud cover and biodiversity[11] [19,20]. Simulation modeling suggests that there is sufficient compatible land in the desert of Californian to meet the State's solar energy targets [45].[12] Other suggestions include using degraded areas of low conservation value or even the urban environment [46]. For example, it has been estimated that 200,000 ha of shallow slope, low-conservation value land would be sufficient to achieve all of California's renewable electricity targets [40].

Regarding (b), many government agencies and other organisations provide guidelines on how to effectively plan future solar energy installations, e.g. [47]. Such guidelines have proliferated in the US, but the actual specific biodiversity guidance varies considerably across States. For instance, in North Carolina guidelines indicate that certain protected tree species may be at risk if they are removed to minimise shading for the panels [48]. Guidelines in other States go further and actively detail how biodiversity can be managed on solar energy farms through guidance on how to develop biodiversity action plans. For example, in Arizona the importance of surface water to wildlife is noted, and it is pointed out that solar installations should be developed outside of key breeding periods [49]. In the UK, where solar power installations are commonly located in grassland or pasture land, recommendations include promoting nesting areas, sowing pollen and nectar strips, using sheep for grazing around panels and returning the land to its original use during the decommissioning of the project [47]. Mitigation measures for the aquatic environment include avoiding high-conservation value and sensitive areas, creating buffer zones to limit erosion and runoff around surface waters, and reducing herbicide use [39]. Much of the advice concerns detailed site monitoring, including the monitoring of water withdrawals [47].

3. Wind power

3.1. Background

Wind power is generated from turbines powered by large rotating blades. Since their widespread introduction in the 1980s, their size (radius of blade) and above-ground height has increased markedly. The largest blades are > 100 m in diameter, rotating ~100–120 m above the ground and generating ~5 MW of power [17].

Wind power has been one of the fastest growing energy generation technologies over the last two decades [51]. In 2014, installed wind energy capacity amounted to 370 GW, with China, the US and Germany being the world leaders [13].

While wind energy generation can have a number of ecological impacts on avian and aquatic species [17,18], the affected species, mechanisms and magnitude of these ecological impacts depend to a large extent on whether it is generated onshore (Section 3.2) or

[11] It should be pointed that some desert ecosystems host highly specialized and rare species that are known to be particularly vulnerable to human activity [42–44].

[12] These simulation models are often based on the premise that solar energy development should preferentially occur on highly degraded land, so as to conserve land of higher ecological value. Some of these studies have employed a hierarchical multi-criteria framework that evaluates both the onsite degradation, as well as the off-site degradation expected to occur from linking the solar energy facility to the grid [45]. In a particular study for the deserts of California, 19 layers were used in the raster model and included degradation functions related to regeneration from farming and the impact of the prevailing fire regime [45].

offshore (Section 6.2).

3.2. Drivers of ecosystem change and biodiversity loss

Any wind energy installation will result in a small loss of habitat area, either directly through the occupation of land by the towers, or indirectly due to species avoiding the areas around wind power facilities.

Regarding habitat loss, it has been reported that different bird and bat species might avoid areas that contain wind generators [17,18] (for aquatic species refer to Section 6.2). However, several studies have found minimal effects of wind farms on the occurrence/sightings of several species, including wintering birds in farmlands [52], or birds in cropland and secondary forests in southern Mexico [53]. Environmental Impact Assessments (EIAs) and post-construction monitoring studies have found no discernable effects on the populations of black grouse [54].

Regarding habitat change, unsurprisingly, the main threat to biodiversity arises from the collision of birds (especially raptors) and bats with the wind generators, as well as from the downdraught generated by the spinning blades and barotrauma [51].[13] In general, bird species that are rare/endangered, or have long lifespans and are slow to reproduce, face the greatest risk from the deployment of wind turbines [56–58]. Larger and less agile birds (e.g. geese and swans) also face greater risks [59], as do those that tend to fly in lower light conditions (dawn or dusk), as they are less likely to detect and evade the wind turbines [60,61]. While some birds can sense and adapt to wind turbines, such landscape disruptions could still affect certain activities such as distant feeding and roosting [60].

Greater collision risks exist around heavily used flyways (including migratory routes) or in areas that are regularly used for feeding and/or roosting [17]. Similarly for birds, high collision risks do not only extend to native bat species, but also to non-native species during their migration. For example, the origin of bat species killed at German wind farms was found to be as far afield as Scandinavia, Estonia and Russia [62]. It should also be noted that relative collision risk can vary for a particular species during different times of the year. For example, the little bustard tends to fly at lower altitudes during the breeding season, but at higher altitudes, closer to power lines, during winter and post-breeding [63].

An estimated 234,000 birds are killed annually from wind turbines in the United States alone [64]. Bats suffer disproportionately more than birds [65,66], with the impact estimated to be to the order of tens of bat fatalities/turbine/year [51,499] (see Section 8.2 for further discussion). While the collision risks due to the architecture of wind turbines are relatively well documented, the actual effect of collisions on bat and bird populations is less well understood [57].

Interestingly, although wind power installations can pose a risk to bird and bat species, they can have the opposite effect for some land animals such as tortoises, as decreases in road traffic, enhanced resource availability, and declining predator populations may influence annual survival [67].

3.3. Mitigation measures

In order to reduce the impact of wind energy generation on ecosystems and biodiversity, common mitigation measures include:

(a) locating wind power installations in areas of little biodiversity
(b) developing biodiversity-friendly operational procedures for wind energy generation
(c) adopting innovative policies

Regarding (a), and in contrast to solar power (Section 2.3), the most suitable places to locate wind turbines may also be the ones that could cause the most damage to avian biodiversity [17]. For example, whilst most proposed sites for onshore wind farms in the UK are located in upland areas (conveniently away from populated areas), these remote windy locations are also areas of high conservation importance for avifauna [66]. Identifying areas of low biodiversity to locate wind energy facilities would be important to mitigate their potential negative biodiversity outcomes, but sensitivity mapping studies would require frequent updating to reflect changing patterns in species distribution and their adaptation to the presence of wind farms [51,68].

Regarding (b), depending on turbine type, bird and bat species are at risk at altitudes between 20 and 180 m above the ground. Proposed mitigation measures include the minimization of the overall development footprint (e.g. by installing transmission cables underground) and the risk of collision (e.g. by making blades more visible or grouping them in configurations aligned with the main flight pathways) [17]. Interestingly, modeling studies have suggested that increasing rotor speed does not affect collision risk with the blades, as it is at the areas closer to the hub of the turbine that collisions are more likely to occur [55]. This also suggests that increasing blade size to increase wind power generation per unit of land may only have a marginal effect on the collision risk for birds, compared to the existence of the structures. On the other hand, studies have suggested that reducing rotor speed could reduce mortality for bats [500].

Other mitigation actions include halting power generation during critical migration periods [69] or times of high activity, e.g. just after sunset, during high insect activity or episodic/ad-hoc moments when threatened species are detected or predicted [27]. Modelling exercises also propoe to aggregate turbines in wind farms to lower the collision risk to raptor populations [57]. At the European level, an intersessional working group at the Agreement on the Conservation of Populations of European Bats (EUROBATS) investigates the effect of wind turbines on bats and develops guidelines for monitoring and impact assessment [70].[14]

Regarding (c), biodiversity offsetting[15] has been identified as a potential mechanism to mitigate the negative impact of wind power on biodiversity loss. Offseting schemes have been proposed for bats [51] and birds in the case of offshore installations [75]. Forest management, creation of riparian environments and other landscape features could be beneficial for the foraging, roosting and mobility of bats [51,76,77]. Other policy mechanisms include the use of subsidies to promote the avoidance and mitigation strategies discussed above [78].

4. Hydropower

4.1. Background

Hydropower is generated through the use of fresh flowing water to run turbines and generate electricity. There are different hydropower technologies that can be deployed, depending on specific geographical constraints and human demand patterns. These include:

- conventional hydropower from dams;
- run-of-river hydropower;
- pumped-storage hydropower.

When considering the amount of electricity generated, a distinction is usually made between small hydro (< 10 MW)[16] and large hydro (>

[13] Bats suffer barotrauma due to changes in air pressure, which results in severe internal organ damage [51].

[14] For more information refer to: http://www.eurobats.org/node/874

[15] Biodiversity offsetting entails compensating for biodiversity loss in one site, by generating ecological gains elsewhere [71]. Biodiversity gains can be converted into tradable 'credits' [72]. While biodiversity offsetting has been identified as a promising market-based conservation mechanism in the Green Economy discourse [2], it has been criticized for often failing to deliver the expected conservation benefits, e.g. [73,74].

10 MW). In 2012, hydropower constituted by far the largest source of renewable energy, ~16.2% of global electricity production [13]. Apart from being a renewable and dependable source of low carbon electricity, hydropower can have numerous other co-benefits such as water supply regulation, flood/drought control and agricultural irrigation [79].

Due to its longer history of deployment, hydropower is the renewable energy source for which we have the most solid information regarding its influence on biodiversity. Early hydropower developments gave little consideration to aquatic species (e.g. migratory fish) and often had a significant impact on aquatic habitats, especially through the alteration of water flows upstream and downstream of dams [80–85].

4.2. Drivers of ecosystem change and biodiversity loss

Several studies have confirmed that, overall, hydropower projects can be a major driver of habitat loss/change and fragmentation [86–88] affecting a number of species [89–92]. Regarding habitat loss, hydropower plants and dams can flood extensive upstream areas, thus fragmenting habitats (e.g. through island creation) and affecting ecosystems and the species they harbor [87,93,94]. In some cases they can even disaffect natural reserves [95]. However, in some cases hydroelectric developments can create habitats for iconic species such as the giant otter in Brazil, due to the creation of dozens of artificial islets [96].

Regarding habitat change, the most important mechanisms perhaps relate to the modification of upstream and downstream water flow regimes [85], and the obstacles that hydropower infrastructure poses to diadromous fish during their migration to upstream spawning areas [107,108]. Studies have associated water flow regime changes with negative effects on individual species [97] or species communities/assemblages, such as fish [98], insects [99,100], invertebrates [101,102] and plants [103]. However, the actual biodiversity impacts due to water flow regime changes can be different upstream and downstream of hydropower plants, as has been observed for some macro-invertebrate communities [104] and fish assemblages [105]. To complicate matters even more, intra-species diversity can be affected if unique genetic lineages are located upstream and downstream of a hydroelectric plant [106].

A decline in water quality (upstream, downstream and within the reservoir) due to changes in sediment loading and nutrient cycles can have negative environmental effects such as eutrophication [109], eventually affecting biodiversity [99,110,111]. However, there have been cases of hydropower plants (mainly small-scale) that had negligible effects on water quality [112], or whose initial negative effects were stabilized over time, eventually reaching the pre-plant water quality levels [113].

While hydropower is considered a low carbon electricity pathway [14], hydropower plants can in fact emit large amount of GHGs, mainly carbon dioxide and methane from reservoirs [114–119]. These emissions can be comparable (or even higher) to those of conventional power plants [120]. Even though the latest studies suggest lower overall GHG emissions than initially expected [121], there are hydropower plants whose carbon neutrality is contested [93,122].

The above suggests that hydropower expansion can be a potent threat to biological diversity in parts of the world that host unique and highly biodiverse ecosystems such as Amazonia [87,88,93,123], the Himalayas [124,125], China [126,127], the Mekong River delta [128] and tropical Africa [92]. In fact, there have been several cases of iconic species being negatively affected by hydropower developments, such as the panda [89], the Himalayan mahseer in the Ganges River [90], and primates in Tibet [91] and tropical Africa [92].

Future hydropower expansion could potentially have more severe biodiversity outcomes globally considering that there is (a) a higher annual hydropower growth in biodiversity hotspot countries [129], and (b) a higher probability of threat to biodiversity in areas where a large fraction of available surface water is withdrawn for hydropower [130].

4.3. Mitigation measures

In order to reduce the impact of hydropower generation on ecosystems and biodiversity, common mitigation measures include:

(a) selecting hydropower technologies that have lower impacts on ecosystems and biodiversity;
(b) using biodiversity-friendly elements in hydropower installations;
(c) adopting innovative policies.

Regarding (a), it is sometimes assumed that several smaller hydropower facilities would have a lower aggregate impact than a few larger ones considering the large-scale land conversion associated with large hydro [131]. While small hydro can indeed have a lower impact on biodiversity due to its lower space requirement, some comparative studies suggest that it can be worse if other biodiversity-related metrics are taken into account [132,133]. Specific hydropower plant technologies (e.g. run-of-river that store lower quantities of water) or design elements (e.g. bypass water with no dam), can have lower impacts on water flow regime and water quality [80], but still some ecological impact [134,135]. The above suggests that establishing optimum operational characteristics for hydropower development can be quite challenging, especially considering variable local contexts and the need to balance multiple impacts on ecosystems and human wellbeing [136,137].

Regarding (b), technological measures, both upstream (fish ladders) and downstream (fish-friendly turbines, bypass flows), could mitigate impacts on biodiversity [80,138]. However in some contexts the actual effectiveness of such measures has been scrutinized [108,139,140].

Regarding (c), regulatory measures and market-based conservation schemes could improve the environmental performance of hydropower generation. For example, issuing hydropower generation licenses for a limited term after which the operators can renew them only if they manage to comply with current environmental laws, could ensure that hydropower installations comply with the latest environmental legislation [141]. Biodiversity offsetting (Section 3.2) could also potentially mitigate some of the negative biodiversity outcomes of hydropower [71], but it is still an unproven mechanism that should be a last resort and complemented with other policies, especially in countries with poor governance and recent histories of civil conflict [92].

5. Bioenergy

5.1. Background

Bioenergy refers to the use of plant- and animal-based matter to generate renewable energy. Bioenergy sources can be as diverse as wood and residues from the forestry/arboricultural sector, crops/residues/livestock waste from the agricultural sector, waste from the manufacturing sector and food/domestic/municipal waste from the residential sector [142].

In 2014, total primary energy demand from bioenergy was ~16,250 TWh (58.5 EJ), with bioenergy's share in the total global primary energy consumption being ~10% [13]. Of these, traditional bioenergy (often associated with poor households) such as woodfuel, charcoal and dung accounted for 54–60% and was used mainly for cooking and heating [13]. Modern uses of bioenergy that are usually associated with the Green Economy include bio-heating (for the

(*footnote continued*)

[16] This can be further subdivided into mini- (10–1000kW) and micro-hydro (5–100kW).

residential and industrial sectors), bio-power and biofuels for transport [2]. Section 5.2 focuses on the ecosystem and biodiversity impacts of these modern forms of bioenergy.

The major technologies to derive modern bioenergy are broadly classified into thermochemical conversion (including combustion, gasification, pyrolysis) and biochemical conversion (including digestion and fermentation) [13,142]. Generally speaking, thermochemical conversion technologies produce bio-heat and bio-power, whilst biochemical conversion technologies produce liquid biofuel for transport, cooking and lighting (e.g. bioethanol, biodiesel).[17][18]

Popular feedstocks for bio-heat and bio-power include poplar, willow, eucalyptus, and other types of woodfuel [14]. Primary agricultural residues such as wheat straw (in EU, North Anerica), sugarcane bagasse (in Brazil), maize straw (in India, North America) and forest residues (wood pellets, wood chips) have gradually become more important for bio-heat and bio-power generation [13].

Depending on the feedstock and conversion technology used, liquid biofuels for transport can be distinguished as first-, second- and third-generation. First-generation biofuels (mainly derived from oil, sugar and starch crops) include maize ethanol in the US; sugarcane ethanol and soybean biodiesel in Brazil; rapeseed biodiesel in the EU; oilseed biodiesel and molasses ethanol in India; and, jatropha-based fuels and sugarcane ethanol in Sub-Sahara Africa [143]. Second-generation biofuels derived from the biochemical conversion of lignocellulosic material are gaining attention in the US and Europe and are slowly moving beyond the pilot scale [13]. Third-generation biofuels from algae are still at an experimental stage [13].

Considering the wide variety of bioenergy production pathways discussed above, Section 5.2.1 focuses on the impacts of biomass energy derived from lignocellulosic biomass that is combusted to produce directly heat and electricity, while Section 5.2.2 focuses on biomass convertion to liquid biofuels. In both cases the cultivation, processing and harvesting of feedstock can have some major implications for ecosystems and biodiversity. Whether these impacts are negative or positive depends on a large number of factors [23,144,145] as discussed below.

5.2. Drivers of ecosystem change and biodiversity loss

5.2.1. Biomass energy

Habitat loss and change is one of the most important drivers of ecosystem change and biodiversity loss due to biomass energy production [23]. Direct and indirect land use change effects from the expansion of biomass feedstock for energy production have resulted in habitat and biodiversity loss [144,146], especially when large-scale land conversion using mono-cultural feedstock production is adopted, e.g. [147]. Habitat change is highly context specific but mostly associated with a number of mechanisms such as tree canopy closure; rapid changing size and shape of plants; alteration of important landscape features such as riparian forests; and soil loss [144,148–154]. However, some biomass energy landscapes can provide habitat and other supporting ecosystem services compared to intensified agricultural landscapes [155–158]

Several life-cycle assessments (LCAs) have demonstrated that most biomass energy production pathways emit GHGs and atmospheric/water pollutants that can have negative effects on ecosystems and biodiversity, e.g. eutrophication, acidification and toxicity. Atmospheric emissions from biomass energy value chains can also contribute to tropospheric ozone formation, which has a negative effect on plants [174–177]. Such emissions have been confirmed for key biomass energy species such as eucalyptus [159–163], poplar [164–167] and willow [168–172], as well as short rotation coppice [173,174] and wood pellets [175,176].

However, the type and level of emissions (and thus the extent of the environmental impact) varies considerably between different biomass energy options. For example, different LCAs have demonstrated the highly variable global warming potential of different biomass energy options [14]. Important factors that affect these emissions include the feedstock, yields, conversion technologies and pollution control mechanisms [159,165,175–179]. Also, the stage of the life-cycle can be a major determinant of the type/magnitude of emissions and environmental impact, e.g. silvicultural operations are mostly associated with eutrophication due to phosphorus fertilizer use, while harvesting and transport operations are mostly linked to atmospheric emissions [165,178,179].

It should be noted that direct and indirect land use change can have important climatic effects, both due to GHG emissions [180–182] and the alteration of local micro-climates following changes in albedo and evapotranspiration [183–186], see also Section 5.2.2.

Finally, some biomass energy feedstocks (Eucalyptus species in particular) are potentially invasive [187–188]. Even though field studies across multiple continents suggest that Eucalyptus disperses more slowly than risk assessments have predicted [189], there is still evidence to suggest that it has replaced native woody species in different ecosystems [190–194].

5.2.2. Biofuels

Feedstock for liquid biofuel production has been identified as an emerging threat to biodiversity [195,196]. Habitat loss and change during feedstock cultivation (essentially an agricultural activity) is perhaps the most important mechanism of biofuel-related ecosystem change and biodiversity loss. However, the magnitude of biodiversity loss due to land use change depends on the type of land that was converted, the feedstock and the vulnerability of the affected species [197,493]. The direct conversion of natural ecosystems (e.g. grassland, forest) is more likely to result in higher levels of biodiversity loss when compared to the conversion of cultivated or idle land [196,198,493], as discussed further below. Indirect land use change can affect areas much further away from where feedstock production is concentrated [199], but its quantification is particularly challenging and often controversial [200–202]

There are several examples around the world that demonstrate the negative biodiversity outcomes of biofuel-driven habitat loss and change. For example, sugarcane production (for ethanol) has contributed to the destruction of riparian forests in the State of Sao Paulo (Brazil), and has been linked to biodiversity loss[19] [203–205]. Oil palm cultivation in Southeast Asia has mainly replaced primary/secondary tropical forests rather than agricultural land [208], potentially taking a significant toll on biodiversity [198,209,210] as oil palm plantation are less hospitable to a wide range of species [211–215]. Sugarcane (for ethanol) and jatropha (for biodiesel) production in Sub-Sahara Africa can also be detrimental to local ecosystems [216,217]. EU biofuel blending mandates could result in cropland expansion throughout the world (primarily within the EU but also in Brazil and Sub-Saharan Africa) [218], with potentially severe negative impacts on biodiversity [219]. In the US, soybean (for biodiesel) and maize/sugarcane (for ethanol) will have a consistently larger effect on future land use change than other renewable energy pathways, with most new feedstock production areas expected to be in temperate forests and grasslands [220].

[17] Sometimes the products of biochemical biomass conversion can be used for electricity generation, e.g. through the combustion of biogas from the digestion of organic waste.

[18] Bioethanol and biodiesel can be blended with conventional transport fuel in different proportions. “E5” denotes a mix of 5% bioethanol and 95% gasoline, while “B5” a mix of 5% biodiesel and 95% conventional diesel.

[19] The predicted sugarcane expansion in the Brazilian Southeast can pose an even more significant threat to biodiversity as it can affect (both directly and indirectly) highly biodiverse biomes such as the Cerrado and the Amazon [146,206,207].

On the other hand, 2nd generation biofuel feedstocks (e.g. miscanthus, switchgrass) can provide habitat to a number of species [221,222]. Often such landscapes are more accommodating to biodiversity than 1st generation feedstock landscapes (e.g. maize, soy, rapeseed) [223–231,493]. This could result in enhanced provision of ecosystem services such as pollination [232] or biocontrol [233]. However, when forests or fallow agricultural land is converted, some biodiversity loss is to be expected [231,234]. It should be noted that the future expansion of 2nd generation feedstocks in the US will take place outside the Midwest Cornbelt, meaning that more species and habitats might be affected, possibly having negative effects on biodiversity [235,236].

Comparative LCAs have confirmed that different biofuel options can have widely divergent GHG emissions depending on feedstock, agricultural production practices and production area [237–248]. While several early biofuel LCAs have disregarded the effect of land use change on GHG emissions, subsequent studies have shown that they can substantially alter carbon balances, if factored in [249]. For example, several studies have calculated high carbon debts that might take several decades to be repaid [250]. As a rule of thumb, biofuel pathways that entail the conversion of natural habitats with high carbon stocks (e.g. forests), exhibit the highest carbon debts and payback periods [251,252] (see Table 1). Indirect land use change can result in even higher carbon debts [207,253] but these effects are difficult to be quantified [200–202]. It should be noted that biofuels, apart from affecting the global climate, can also affect local microclimates due to changes in surface albedo and evapotranspiration [183,234,254–259].

Biofuels have been linked to the emission of atmospheric and aquatic pollutants [273]. However, the type and magnitude of emissions can vary significantly between different biofuel pathways and stages of the life cycle e.g. [241,247,248, 274–276]. For some pollutants and geographical contexts, biofuels can have higher emissions than conventional fossil fuels [273,274]. This is the case for particulate matter emissions from Brazilian sugarcane ethanol, as lifecycle emissions are dominated by the agricultural phase (agricultural burning in particular) [277], with most of the negative effects observed during the harvesting season when burning is used [203,278,279]. Similar air quality deterioration has been reported in areas adjacent to oil palm plantations in Southeast Asia [174,280]. Studies in Europe have modeled biofuel-related tropospheric ozone increases and their subsequent negative effects on plants [281].

It should be mentioned that emission savings can materialize through the use of agricultural waste (e.g. wheat/maize/rice straw, sugarcane bagasse) for electricity/power co-generation and 2nd generation biofuel production [241,282–285], or the development of integrated configurations, including biorefineries [286–289]

Fertilizers/agrochemical run-off and industrial effluents from biofuel production are major sources of water pollution in Brazil [203,290] and Southeast Asia [291,292]. Several studies have modeled water quality decline in the US [293–296]. For example, increased nitrogen loading should be expected along the Mississippi river (contributing to increasing levels of hypoxia in the Gulf of Mexico) if the US maize ethanol production meets the 2022 targets without changes in prevailing cultivation practices [297]. Similarly, biofuel-related eutrophication effects have been predicted for parts of Europe [298,299]. Ecotoxicity effects due to pesticide use can very between regions and feedstocks, thus posing different risks to ecosystems and biodiversity [300,301].

Finally, certain feedstocks, especially perennial grasses such as miscanthus and switchgrass, might be invasive [302–306]. Riparian habitats can be particularly susceptible [226,307–309], while there are fears that non-sterile strands of miscanthus will be difficult (or even impossible) to be contained [310]. Jatropha is the main 1st generation feedstock linked to invasive behavior and has been banned from cultivation in parts of Australia and South Africa (pre-emptively) [311]. However, the fears of jatropha's invasiveness might have been

Table 1
Carbon debt payback periods for different biofuel options.

Biofuel type	Region	Original land use	Payback period (yrs)	Source
Palm oil biodiesel	S.E. Asia	Tropical rainforest	86	[250]
	S.E. Asia	Peatland rainforest	423	[250]
	Malaysia	Lowland tropical rainforest	76	[253]
	Indonesia	Mix of lowland tropical primary/ secondary rainforest and agricultural land	58	[253]
	Indonesia	Mix of tropical peatland forest, swamp and agricultural land.	199	[253]
	Indonesia	Mainly lowland tropical primary rainforest with tropical peatland forest, swamp, and agricultural land	84	[253]
	S.E. Asia	Tropical rainforest	75–93	[212]
	S.E. Asia	Peatland rainforest	692	[212]
	S.E. Asia	Grassland	10	[212]
	Malaysia	Grassland	0–11	[260]
	Malaysia	Forest	18–38	[260]
	Cameroon	Forest	45–53	[261]
	Brazil	Forest	39	[262]
Soybean biodiesel	Brazil	Tropical rainforest	319	[250]
	Brazil	Cerrado grassland	37	[250]
	Brazil	Cerrado woodland and pasture	41	[253]
	Brazil	Degraded pasture	7	[253]
	Brazil	Mainly permanent cropland with Amazonian rainforest	16	[253]
	US	Grassland	14–96	[260]
	US	Forest	179–481	[260]
Jatropha-based fuels	Ghana	Mix of open and closed woodland, permanent cropland and fallow land	71–129	[253]
	Zambia	Mix of mature miombo woodland, permanent cropland and fallow land	20–NA	[253]
	Mozambique	Mature miombo woodland	187–966	[263]
	Africa	Miombo woodland	33	[264]
	South Africa	Converted savanna	17–36	[265]
	Zambia	Miombo woodland	32–81	[265]
	Mexico	Secondary woodland	60–101	[253]
	Mexico	Mix of secondary forest, fallow land and permanent cropland	72–183	[253]
	Mexico	Mainly agricultural land and pasture with secondary forest	7–30	[253]
	Mexico	Mix of secondary forest and low intensity pasture land	2–14	[266]
	Brazil	Caatinga woodland	10–20	[267]
Sugarcane ethanol	Brazil	Cerrado woodland	17	[250]
	Brazil	Grassland	3–10	[260]
	Brazil	Forest	15–39	[260]
	Tanzania	Forest	15–27	[268]
	Tanzania	Grassland	2–3	[268]
Cassava ethanol	Mali	Fallow land	37–81	[269]
Wheat	UK	Grassland	20–34	[260]

(continued on next page)

Table 1 *(continued)*

Biofuel type	Region	Original land use	Payback period (yrs)	Source
ethanol	UK	Forest	80–140	[260]
Maize ethanol	US	Grassland	93	[250]
	US	Abandoned cropland	48	[250]
	US	Grassland	2–25	[270]
	US	Forest	16–52	[270]
	US	Low-fertility CRP land	19–43	[271]
	US	Low-fertility CRP land	65–88	[271]
	US	Grassland	40–123	[272]
Prairie biomass ethanol	US	Abandoned cropland	1	[250]
	US	Marginal cropland	No carbon debt	[250]
	US	Grassland	No carbon debt	[272]

overstated, at least in Sub-Sahara Africa [312–314].

5.3. Mitigation measures

In order to reduce the impact of bioenergy on ecosystems and biodiversity, common mitigation measures include:

(a) adopting environmentally-friendly bioenergy production practices;
(b) locating bioenergy production in marginal, degraded and/or underutilized lands;
(c) designing multi-functional bioenergy landscapes.

Regarding (a), proposed measures include limiting the expansion of monoculture plantations, adopting wildlife-friendly production practices, installing pollution control mechanisms, and undertaking continuous landscape monitoring [24,204,315,316]. Other measures include the careful feedstock selection, as different feedstocks can have radically different environmental trade-offs [317]. For example, US studies have demonstrated that 2nd generation feedstocks grown in unfertilized land could provide benefits to biodiversity when compared to monocultural annual crops such as maize and soy that make extensive use of agrochemicals [318,319]. Adopting biodiversity-friendly practices, such as preserving understory vegetation, conserving tree patches within plantations, conserving riparian habitats and/or using buffer zones, can have positive biodiversity outcomes [152,156,204,315,320]. The above suggests that there is a need for more systematic land-use planning to achieve bioenergy production targets, while avoiding negative biodiversity trade-offs [321,322]. Such planning approaches must consider feedstock invasiveness, e.g. by developing buffer zones at plot edges to spot invasive behavior early and prevent spread [323].

Regarding (b), it is often advocated that bioenergy feedstock should be grown in marginal, degraded or underutilized lands that harbor little biodiversity [195,324–327]. Apart from minimizing impacts on biodiversity, growing feedstock on marginal land could on some occasions have ecological restoration effects [326,328]. For example, in wetlands, willow production can purify wastewater from sewage [329]. Similarly, the bioremediation potential of some bioenergy feedsctocks such as miscanthus or jatropha means that they could potentially be grown on contaminated land, restoring some ecosystem services [330–332].

Regarding (c), it has been proposed to design multifunctional bioenergy landscapes that employ a variety of biodiversity-friendly elements such as mixed-cropping for food/feed/bioenergy, crop rotation, habitat corridors, and conservation area remnants with native vegetation [158,232,333–337]. Such landscape approaches can not only preserve biodiversity, but also the services it provides (e.g. pollination), that could in turn contribute to higher bioenergy yields [232,338]. However, such landscape approaches should consider a number of planning principles if they are to be successful [339].

The mitigation options discussed above can be promoted through different types of policies, ranging from regulatory instruments to market-based mechanisms such as certification [24,146,273,340,341].

6. Ocean energy

6.1. Background

Ocean Energy encapsulates a wide range of engineering technologies to obtain energy from the ocean, including through:

- trapping the incoming tide and slowly releasing it to produce electricity, in a way similar to how conventional dams operate (tidal barrages) (Section 4.1);
- capturing the energy of ocean currents and tides through devices installed under the surface of the water to produce hydrokinetic energy;
- using the energy of surface wind waves to produce electricity through various devices installed on the sea surface (wave energy);
- using the temperature differential between cold water from the deep ocean and warm surface water (ocean thermal energy, OTEC);
- using osmotic energy, which relates to the pressure differential between salt and fresh water;
- obtaining power from offshore wind generators, similar to those discussed in Section 3.

Of these, only tidal barrages can be considered a relatively "mature" technology [342].[20] However in several countries it is not clear whether tidal barrages are economically viable, considering the massive infrastructure investments they require and their potential environmental impact [344]. For example, large-scale tidal barrages are being reappraised in the UK, though opposition from the Environment Agency and other groups makes it unlikely that any new project will ever reach construction phase [345]. Smaller schemes such as the Swansea Bay Tidal Lagoon might have more chances of being built [343].

The other ocean technologies mentioned above are typically referred to as "modern ocean energy". These technologies were expected to develop significantly in the past few years [346,347], but (with the exception of offshore wind power) rather limited developments have actually taken place[21] [13]. Interestingly, despite this lack of modern ocean energy development, the perceived environmental impacts are key obstacles to the proliferation of ocean energy projects [26,348–350]. Such perceived impacts include disturbances of coastal ecosystems at (or near) the seabed, which are known to be important habitats for many species [25,26]. The limited deployment of modern ocean energy means that there is little empirical evidence to quantify the actual effects on ecosystem change and biodiversity, with many of these effects being essentially speculative [25,26,351]. Furthermore, there is no evidence that ocean energy installations will have the same impact on biodiversity as existing (pre-commercial) isolated units, which highlights the need for further study in this area [352].

[20] La Rance in France (1966) is the earliest tidal barrage and is still operational today. This was followed by projects in Canada, China and Russia [342,481]. At present the only country that seriously undertakes efforts to construct tidal barrages is South Korea, which has recently completed a 254MW tidal barrage at Sihwa-ho Lake, and planned another one almost three times the size at Ganghwa [482,483].

[21] While the first tidal arrays might become operational in 2016 [484], there have been many setbacks in several other ocean energy companies and projects. For example, Pelamis Wave Power faced financial difficulties and was put into administration in 2014, while Aquamarine Power cut back to a skeleton staff [485]. Other big firms have either abandoned ocean energy projects or collapsed altogether [486].

6.2. Drivers of ecosystem change and biodiversity loss

Habitat change/loss is possibly the key driver of ecosystem change and biodiversity loss associated with ocean energy. Habitat loss essentially manifests due to the fact that any type of modern ocean energy unit or offshore wind pole will result in the direct loss of a small habitat area, as the section of the sea and the bottom occupied by such units will be unavailable for aquatic species. Tidal barrages can also result in habitat loss through the permanent inundation of the upstream portion of estuaries [344]. Habitat change is usually associated with the operation of ocean energy devices that can hinder the normal movement and feeding activity of bird and aquatic species, or even change the characteristics of the marine environment adjacent to the installations, including hydrodynamic processes [353,354].

When it comes to habitat loss, scour pits for the monopole foundations of offshore wind generators and ocean energy devices installed/anchored in the seabed might cause local changes in fish species composition, though the long-term effects are not yet fully understood [355]. Marine mammals often avoid areas of underwater construction (especially piling), only slowly returning after construction is finished [356,357]. However, there is great concern that some seabird species might be displaced from the immediate vicinity of offshore wind farms and within a 2–4 km buffer zone, due to the loss of feeding grounds [360]. Nevertheless, and despite some differences amongst species, for the most part seabirds seem to be relatively unhindered by the presence of offshore wind farms [355], with the overall effects on bird population being negligible [356,360,361]. Finally, a study of 3 pre-commercial tidal units showed no negative impacts on local biodiversity at any of the sites following post-installation monitoring lasting between 1–3 years [352].

It is worth noting that some evidence suggests that offshore wind farm foundation scour protection has resulted in the increase of benthic species [360,362–364] and fish, possibly due to shelter effects [360,365–367]. Similar effects have been reported for other wave [368,369]) and tidal energy [370] developments. Nevertheless, such direct impacts on seabed habitats, whether positive or negative, are likely to be limited to within 100-200 m of the array, with bedforms under the monopoles being undisturbed.

Habitat change from ocean energy installations can be a more substantial driver of ecosystem change and biodiversity loss. For example, tidal barrages could entrap species, e.g. whale entrapment at the Annapolis plant in Canada [342]. Offshore wind farms can pose similar collision risks to birds as onshore wind farms (Section 2.2), but mortality assessments are more difficult to be performed compared to conventional wind farms [18,371]. Some studies have identified that while some bird species avoided offshore wind farms, others were attracted (e.g. nocturnal migrant species attracted to illuminated obstacles), increasing the risk of collision [372,373].[22] However, the proximity of offshore wind farms to the coast can also affect migratory bird species that use the coastline for navigation. Similarly, the rotors of wave energy devices can pose collision risks to aquatic species [26,349,374,375] or affect the routes, navigation and feeding patterns of some migratory species [376], although strong evidence is lacking due to the small number of operational units (Section 6.1). Tidal turbines could interfere with some species such as diving birds or fish [358,359]. The only direct measurements of aquatic animals around tidal arrays (at the six-machine Verdant RITE project) showed that fish tended to perceive each machine as an independent object and that at least some species interacted closely with them [377]. No changes have been reported in the distribution and numbers of bird species and benthic species such as lobsters [378–380].

The alteration of hydrodynamic (i.e. wave/current patterns) and sedimentations processes can be another driver of habitat change from tidal and ocean energy devices [26,353,381,382,384]. Both types of technologies could affect depositional processes, change current and wave fields, and alter the substrates that form the habitat for benthic organisms [26,377].[23] However, benthic organisms that live in areas with high tidal or wave energy resources are likely to be relatively resistant to the low levels of disturbance caused by modern ocean energy devices [358]. OTEC plants can also induce habitat change on coastal ecosystems in tropical countries[24] as they could upwell nutrient-rich water when extracting cold water from deeper regions of the ocean [383]. OTEC plants can have effects on a number of marine species [489], including excess mortality of tropical fish due to temperature shocks from upwelled cold water[386].

There have been concerns about the pollution effects of ocean energy installations, including chemical, noise and electromagnetic pollution [26]. For example, similar to conventional hydroelectric dams (Section 4), tidal barrages can change sediment loading, salinity and water turbidity or influence the exchange between flushing of oxygenated water [377]. This can lead to instances of mass mortality of fish and other benthic species [370]. Furthermore, the installation and decommissioning of ocean energy devices could degrade temporarily habitat and water quality due to increased turbidity in the water column due to disturbances to the seabed [387]. Furthermore, noise generation during the construction and operation of some ocean energy projects or the rotary movement of tidal/offshore wind turbines, could have an effect on some (not all) aquatic species [354,355,388,389,495,496]. Increased vessel traffic and noise during these phases could also have an impact on various marine animals, fish stocks and bird populations [387,494], though these phases are relatively limited in time. Electromagnetic fields [384,387] could affect sensitive species [26], though these effects are likely to be limited to the vicinity of grid connection cables [358,387]. However, it is difficult to establish such causal effects for fish and other organisms [356,382]. Finally, there has been some speculation about the toxicity of lubricants and paints used in ocean energy facilities on marine life [26,359,374].

6.3. Mitigation measures

In order to mitigate the impacts from the deployment of ocean energy on biodiversity and ecosystems suggested measures include:

(a) selecting carefully the operational parameters of ocean energy devices
(b) locating ocean energy facilities in areas that can cause minimum disturbance to marine habitats and the sea bottom
(c) adopting biodiversity-friendly elements in the design of tidal barrages
(d) minimizing disturbances during the construction phase
(e) designating areas around ocean energy installations as no-go zones for fishing and other maritime activities

Regarding (a), carefully choosing the rotor speed of ocean energy devices can minimize species mortality due to collisions with the rotating blades. Monitoring activities in pilot and commercial projects can offer rich information towards this end. For example, the first commercial Seagen device located in Strangford Narrows, Northern Ireland, had a rotation speed of 12 rpm, and a maximum rotor blade tip velocity of around 12 m/s. It had no influence on animals that can

[22] It should be mentioned that seabird-wind farm interactions, and risks posed to bird populations, may vary over longer time-scales [487].

[23] They can also potentially affect coastal erosion [26], though these effects appear to be rather small [385].

[24] OTEC plants must be located in areas where there is a temperrature differential of ~20°C between warm surface water and the cold deep water that is no more than about 1,000 m below the surface. This typically happens between latitudes 20° North and South of the Equator [488].

hunt down fish in fast moving turbulent water and are as likely to collide with the tidal turbine rotor blades as with rocks [358,377,380,390]. Other studies at this site using Acoustic Doppler Current Profiling showed no evidence of any significant change to current flow velocities due to the installation of the turbine [380]. While fish do not entirely avoid the area occupied by the turbine, there appears to be no evidence of dead or dying fish recorded after passing through the turbines [377]. Reports from other sites such as the ORPC's TGU demonstration deployment in Cobscook Bay (USA), Verdant turbine in New York (USA), the GFE turbine in Minnesota (USA) and OpenHydro in EMEC (Scotland) report similar findings [377]. When it comes to noise reduction during the operation of ocean energy devices, mitigation strategies include acoustic shielding or damping on devices, tuning devices to operate at different frequencies, or operating at different rotational speeds [375]. In any case, given the small size of proposed ocean energy developments and the negligible impacts observed up to now, fine-tuning the operational characteristics of the slightly larger farms and arrays that are expected to become operational appears warranted at present. In any case such efforts will require baseline studies, which can prove to be be long and resource demanding processes [393].

Regarding (b), over recent years there is a trend in Europe to want to situate offshore wind farms further out and in deeper water, which will require anchoring (i.e. floating) rather than fixed structures [391]. Such new developments in offshore wind energy could reduce habitat loss from the wind turbine foundations [392], and minimize their effects on benthic environments during the construction phase (see below).

Regarding (c), to minimize habitat loss/change effects from tidal barrages it has been suggested that these structures should adopt biodiversity-friendly elements. These could include (i) intertidal areas/lagoons that can provide feeding grounds during the high water period landward of the barrage, (ii) use a dual cycle generation regime, (iii) use fish-passes similar to hydropower installations and (iv) substitute the barrage by a tidal fence [25].

Regarding (d), some of the most important ecological impacts of ocean energy facilities can manifest during the construction phase, not the least due to the high vessel traffic, noise and disturbance of the sea bottom (Section 6.2). In particular the noise generated during construction, such as pile-driving, could affect marine mammals [495]. The installation of underwater structures (e.g. wind farm foundations) can also affect migratory fish routes due the disturbance caused [35,394]. Minimising such disturbances during construction can reduce possible negative impacts on ecosystems.

Regarding (e) the installation of ocean energy units will require that their surrounding areas remain out of bound for fishing and other maritime traffic [347]. The delimitation of some sea areas around ocean energy installation as de facto marine reserves could allow the preservation of fishing stocks and other marine life [395,497], which can have significant benefits for biodiversity conservation.

7. Geothermal energy

7.1. Background

Geothermal energy is the heat derived from the earth's crust. This can include high temperature hydrothermal resources, deep aquifer systems with low and medium temperatures, and hot rock resources. Only ~6.5% of the overall global geothermal energy potential has been tapped, with the total installed capacity being in the order of 12.8 GW [13].

Geothermal power plants consist of various components such as production/reinjection boreholes, connecting/delivery pipelines, silencers, separators, turbines/generators and cooling towers. Each of these components has some environmental impact, whether temporary (e.g. during construction) or lasting (e.g. silencer noise) [396].

Geothermal resources are often located in pristine areas of high endemic biodiversity [396], and often intersect with protected areas [397]. Evidence about the biodiversity impacts of geothermal energy is scarce in the academic literature, although the process is perhaps not totally benign [396,398]. For this reason, it has been suggested to consider potential ecological effects when planning geothermal facilities and to adopt a triple-bottom line sustainability approach [399,400].

7.2. Mechanisms of ecosystem change and biodiversity loss

Geothermal energy generation has been associated with habitat change and loss, often in highly biodiverse and/or fragile ecosystems. For example, in Kenya, the Olkaria geothermal power project is situated in the Hell's Gate National Park, causing some level of habitat loss from the geothermal facilities and ancillary infrastructure [402]. Similar concerns have been raised for other parts of Kenya [403,404] and Costa Rica [405]. Activities such as site clearing, road construction, well drilling and seismic surveys [396], may cause disturbances that could affect the breeding, foraging and migration patterns of certain species [401]. Habitat change effects linked to geothermal energy development could also manifest through the increase of tourism (e.g. in New Zealand [406]).

A typical geothermal plant using hot water and steam to generate electricity emits GHGs (CO_2), air pollutants (NH_3, H_2S) and other gases (H_2, O_2, N_2) and elements (Rn, He, As, Hg, B) whose levels vary between geothermal areas [407–409]. While GHG emissions are negligible compared to conventional electricity generation [14,410], the emission of toxic pollutants such as H_2S and boric acid can have a more substantial effect on surrounding vegetation [411–414]. Geothermal activity can also be responsible for elevated arsenic concentration in water and soil, that can be subsequently absorbed by plants and fish, e.g. arsenic discharge due to geothermal development around Waikito River in New Zealand exacerbated the already high arsenic levels in the water [415]. Noise and heat pollution from geothermal facilities can also possibly have some ecological impact [408,416,417].

7.3. Mitigation measures

In order to reduce the impact of geothermal energy deployment on ecosystems and biodiversity, common mitigation measures include:

(a) adopting geothermal technologies that have low ecological impacts;

(b) promoting eco-tourism around appropriate geothermal energy facilities

Regarding (a), some geothermal energy generation technologies prevent the emission of aquatic and ambient air pollutants. For instance, binary plants that are closed-loop systems do not emit gases, while dry steam and flashed steam plants emit water vapor that contains non-condensable gases, as geothermal fluids are re-injected into the geothermal reservoir [418]. Redirecting emissions during well testing could prevent brine spray and associated defoliation in forest locations [419]. Minimizing openings and directional drilling could allow compact work areas, reducing the overall land requirement of geothermal facilities [420].

Regarding (b), natural areas could be conserved around some geothermal facilities as parts of eco-tourism sites. For example, eco-tourism can be such a conservation strategy around geothermal facilities, e.g. the Bacon-Manito Geothermal Production Field (BGPF) in Sorsogon (Philippines) [421], Rotorua (New Zealand) [422], and the Icelandic Central Highlands [423].

Table 2
MA drivers of biodiversity loss for different renewable energy pathways.

	Habitat loss/change	Pollution	Invasive-Alien Species	Over-exploitation	Climate change
Wind (Section 2.2)	✓	?*	X	X	X
Solar (Section 3.2)	✓	?	X	X	?
Hydro (Section 4.2)	✓	✓*	?	?	?
Biomass energy (Section 5.2.1)	✓	✓	✓	?	✓
Biofuels (Section 5.2.2)	✓	✓	?	?	✓
Ocean energy (Section 6.2)	✓	?*	X	X	X
Geothermal (Section 7.2)	✓	✓*	X	X	X

✓ – Strong evidence for the existence of a causal link.
X – Lack or minimal evidence for the existence of a causal link.
? – Theoretically possible causal link, but inconclusive or contextual evidence.
* – Includes non-chemical pollution such as sound, heat and light pollution.

8. Discussion

8.1. Synthesis of drivers

Sections 2–7 demonstrate that there are indeed important interplays between biodiversity and the renewable energy sector. Each of the different renewable energy pathways reviewed can be linked to at least one of the five MA drivers of ecosystem change and biodiversity loss (Table 2). However, despite the growing body of literature that confirms such causal links, strong evidence is lacking for some renewable energy pathways such as ocean energy and geothermal.

The actual mechanisms of ecosystem change and biodiversity loss can be much more diverse, depending greatly on the renewable technology, its operational characteristics[25] and the environmental context within which the renewable technology operates (Table 3).

It is worth noting that none of the renewable energy pathways reviewed is directly linked to overexploitation (Table 2). However, indirect overexploitation effects can emerge due to land use change associated with the deployment of renewables, especially in contexts where populations rely significantly on ecosystem services for their livelihoods. In such cases overexploitation effects can manifest by displacing natural resource harvesting (e.g. forest products, pasture) from the areas taken up by the renewable energy infrastructure, to ever diminishing habitats. Such points have been made for the potential future expansion of biofuels in Sub-Sahara Africa [424], hydropower in the Indian Himalayas [94] and ocean energy in Europe [425]. However, further studies are needed to understand better the true magnitude of such indirect overexploitation effects.

Finally, an interesting link between renewable energy and habitat loss/change is through the development of supporting infrastructure such as roads. Several studies have linked the construction, operation and ancillary developments alongside roads to the direct loss of habitat and the fragmentation of the wider landscape [426–430], as well as the proliferation of invasive species [431,432]. Such effects can be significant drivers of ecosystem change and potentially be highly detrimental to some species and habitats, e.g. [433–439].

8.2. Knowledge/practice gaps and recommendations

Habitat change/loss is the most prevalent driver of ecosystem change and biodiversity loss due to renewable energy expansion. In fact, all renewable energy pathways reviewed in this paper seem to have some habitat change/loss effect (Table 2) that can, however, vary across specific technologies, locations and species (Table 3). It is no wonder that a key mitigation strategy for most renewable energy pathways is the careful selection of the site where the renewable energy infrastructure will be located (Sections 2.3, 3.3, 5.3, 6.3, 7.3).

Advanced technologies such as geographic information systems (GIS) and other geospatial analysis tools can be very useful for understanding the spatial constraints (and hence suitable locations) for developing renewable energy infrastructure without compromising critical biodiversity. For example, remote sensing has been used in the assessment and monitoring of USSE installations [50]. Advanced geospatial tools have been applied to map bird sensitivities to on- and off-shore wind farms [68,440–442]. Some NGOs have produced resources such as sensitivity maps of vulnerable species and guidelines to minimize the impact of such projects [443–445]. Furthermore information of the proximate causes of bird migratory activity such as weather conditions in departure points, can be combined with surveillance and detection mechanisms as a means of reducing the negative effects of wind power farms to migratory bird species [18]. Ecological modelling could also inform the planning and operation of renewable energy facilities, e.g. to identify the occurrence and abundance of threatened plant species in the vicinity of hydropower plants [446]. Other tools can map wave energy potential and inform the selection of appropriate sites for ocean energy installations that provide maximal returns yet avoid spatial competition with other ocean uses [447]. However, such techniques can be data-intensive, hindering their adoption, especially when considering that access to appropriate biodiversity data can be challenging even when monitoring schemes are in place [448].

Furthermore, while it is relatively easy for some pathways (e.g. solar, wind, hydro, ocean, geothermal) to identify the actual location of renewable energy generation, and thus the potential biodiversity trade-offs, for others such as bioenergy this is not the case. For example, while it is relatively straightforward to estimate the amount of land that must be converted to meet bioenergy mandates, it is very difficult to identify in advance the exact location where this land conversion will take place. This is due to nemerous factors including the multifunctional nature[26] of bioenergy feedstocks, the complexity of bioenergy chains and the lack of updated datasets with sufficient spatial resolution and/or global coverage [449]. Towards this end there have been some attempts to integrate models from ecology and energy planning understand better the potential biodiversity conflicts of bioenergy expansion [197,216,450,451].

When it comes to pollutant emissions from renewable energy projects (mainly bioenergy, Table 2), the biodiversity impacts of these emissions are either considered separately in impact assessments or are not incorporated effectively into Life Cycle Assessments (LCAs). A major issue here is that the type and magnitude of these emissions differs between the different stages of the life cycle (Section 5.2). Even for pollutants for which overall life-cycle emissions savings are achieved, the actual pollutant emissions and emission savings manifest

[25] For bioenergy this includes the type of feedstock and mode of feedstock production (Section 5).

[26] A similar point has been made for large hydropower, where the reservoirs can be used for irrigation and other human uses. This multifunctionality complicates the allocation of the burden of actual energy generation on freshwater biodiversity [80].

Table 3
Mechanisms of the negative effects of different renewable energy pathways on ecosystems and biodiversity.

Pathway	Mechanism	Scale of effect	Selected sources
Solar energy (Section 2.2)	Loss and/or fragmentation of habitats from solar power installations and ancillary developments	Local/landscape	[20,21,33]
	Bird collision with solar power installations	Local	[36]
	Burns to birds from intense solar fluxes	Local	[35,36]
	Pollution of water bodies from toxic chemicals used for treating the panels and the land prior to solar power infrastructure development	Local/landscape	[39]
	Prolonged drying of ephemeral water bodies due to increasing water use (especially in water-scarce environment such as deserts)	Local/landscape	[39,40]
	Attraction and disorientation of insects and birds caused by bright and/or polarized light	Local	[36,37]
	Act as an ecological trap through cumulative attractor mechanisms	Local/landscape	[36]
	Cause changes to local micro-climate	Local	[41]
Wind energy (Section 3.2)	Bird and bat collision with wind turbines	Local	[17,18,56–59,63,64]
	Barotrauma to bats	Local	[51]
	Disrupt the migratory routes of some bird and bat species	Local/landscape Regional	[18,62]
	Alter the feeding and roosting patterns of some bird species	Local/landscape	[60]
Hydropower (Section 4.2)	Flooding of upstream areas sinks ecosystems, fragments habitats and disaffects nature reserves	Local/landscape Regional	[87,93–95]
	Alteration of water flows upstream and downstream of hydropower installations	Local/landscape Regional	[98–106]
	Disrupt the migratory routes of some diadromous fish species	Local/landscape Regional	[107,108]
	Deteriorate water quality due to changes in sediment loading, turbidity and eutrophication	Local/landscape Regional	[99–111]
	Emissions of GHGs from reservoir that contribute to anthropogenic climate change	Global	[114–121]
Bioenergy (Section 5.2)	Loss and fragmentation of habitats due to land conversion into agricultural landscapes dominated by a single crop (usually associated with large-scale monocultural modes of feedstock production)	Local/landscape	[144,146,147,195,196,198,203–205,209,210,216–220]
	Simplification and homogenization of habitats due to the extensive modification of landscape elements and ecosystem processes (usually associated with large-scale monocultural modes of feedstock production)	Local/landscape	[195,196,198,203,204,210,216]
	Pollution of soil and water from fertiliser/pesticide use that causes toxicity and eutrophication (usually associated with large-scale monocultural modes of feedstock production)	Local/landscape, Regional	[203,290–301]
	Emission of ambient air pollutants that contribute to acidification and tropospheric ozone formation	Local/landscape Regional	[159–182,203,237–248,274–276,278,279,280,281] Table 1
	Emission of GHGs during the entire life-cycle of bioenergy generation (including from direct and indirect land use change) that contributes to anthropogenic climate change	Global	
	Effects to local micro-climates due to changes in albedo and evapotranspiration	Local/landscape, Regional	[183,234,254–259]
	Invasive behavior of some feedstock species (e.g. eucalyptus, miscanthus) that compete with native vegetation	Local/landscape, Regional	[302–306,311]
Ocean energy (Section 6.2)	Fish/benthic species composition changes due to habitat loss from scour pits at the foundations of offshore wind generators and ocean energy devices installed/anchored in the seabed	Local	[355]
	Loss/change of habitat from the permanent inundation of the upstream portions of estuaries from tidal barrages.	Local/landscape	[344]
	Habitat change due to the alteration of hydrodynamic and sedimentation processes	Local/seascape	[26,353,381,382]
	Avoidance of underwater areas close to ocean energy installations by some species (especially during construction)	Local/seascape	[354,356,357]
	Species entrapment at tidal barrages	Local/landscape	[342]
	Collision of birds (with offshore wind generators) and aquatic species (with wave energy devices)	Local	[18,26,349,371,374,375]
	Interference with navigation and feeding patterns of local and migratory species	Local/seascape	[358,359,376]
	Excess mortality of tropical fish due to temperature shocks from upwelled cold water at OTEC projects	Local	[386]
	Increased turbidity at water column due to distrurbances in the seabed	Local	[387]
	Changes in salinity, water turbidity and exchange between flushing of oxygenated water in tidal barrages	Local	[370,377]
	Noise pollution during the construction and operation affects some aquatic species (particularly aquatic mammals)	Local	[355,388,389]
	Electromagnetic pollution from underwater cables can affect sensitive species	Local	[26,384,387]
	Chemical pollution from toxic lubricants and paints	Local	[26,359,374]

(continued on next page)

Table 3 *(continued)*

Pathway	Mechanism	Scale of effect	Selected sources
Geothermal (Section 7.2)	Habitat loss during the conversion of natural areas into geothermal facilities	Local/landscape	[402–405]
	Habitat change during site clearing, road construction, well drilling and seismic surveys that affects the breeding, foraging and migration patterns of certain species	Local/landscape	[401]
	Emission of toxic pollutants such as H_2S, arsenic and boric acid which can defoliate plants or be uptaken by biota	Local/landscape	[411–415]
	Noise and heat pollution from geothermal facilities	Local/landscape	[408,416,417]

at different areas, i.e. emissions savings at combustion sites (usually cities) and emissions at feedstock production and biofuel refining sites (usually rural or peri-urban areas) [275,277,452]. This means that the spatial distribution of these emissions, and thus their impact on ecosystems and biodiversity, can vary accordingly. Including a spatial element in LCAs can help identify those areas most likely to experience negative biodiversity outcomes due to these emissions. In any case further integrating advanced technological options to mitigate pollution and increase efficiency in biofuel processing plants can reduce emissions harmful to ecosystems and biodiversity [503,504].

Setting up effective metrics for communicating the biodiversity impacts of the renewable energy sector has also garnered some attention and controversy. For example, fatality estimates for wind farms have been compared to the biodiversity effects of fossil fuels and nuclear energy [453], concluding that fatalities per MWh would be a better indicator.[27] The ensuing spat over basic ecological understanding, data and interpretation, "birds and not bats" [454] vs. "megawatts are not megawatt-hours" [455], highlights the different perspectives and assumptions employed by biodiversity and energy specialists. This highlights the need to be actively aware of different disciplinary approaches at the interface of renewable energy and biodiversity conservation, in order to make sensible planning decisions.

Most current evidence about the interrelationship between renewable energy and biodiversity focuses on potential risks rather than direct information about impacts at the species-level (Sections 2–7, Table 3). However there is an emerging body of literature on species-level impacts, especially in the southwestern US; e.g. for the San Joaquin kit fox [456], desert tortoise [457] and the Mohave ground squirrel [458].

Finally, it is worth noting that despite the negative biodiversity impacts discussed throughout this literature review, some renewable energy pathways can have a lower (or even possitive, Table 4) overall biodiversity impact compared to other energy forms. For example an assessment of 12 potential impacts of solar energy on wildlife and habitats found that solar energy was more detrimental only for one impact compared to conventional electricity pathways [20].[28] Finally, despite the potentially large negative effects of some bioenergy pathways on ecosystems and biodiversity (Section 5), it has been argued that the overall biodiversity impacts of future bioenergy expansion might be lower compared to those of fossil fuel exploration and extraction [460].

Table 4
Biodiversity benefits of different renewable energy pathways.

Renewable pathway	Biodiversity benefit	Selected sources
Solar energy	Solar energy installations can provide cover/habitat and feeding areas (e.g. grazing) for certain animals. This includes both USSE and photovoltaic panels mounted on rooftops and building facades.	[21,47]
Wind energy	Wind power installations might provide favourable grounds for some terrestrial species due to reduced traffic, greater availability of food and lack of predators	[66]
Hydropower	Hydroelectric facilities can create new habitats for some iconic species	[96]
Bioenergy	Some bioenergy landscapes (e.g. miscanthus, switchgrass) can provide habitat, food and other supporting ecosystem services compared to other agricultural practices (especially intensified monocultures)	[155–158] [221–233]
Ocean/Offshore wind energy	Ocean/offshore wind energy facilities can make marine areas inaccessible to fishing and maritime activities, protecting fish stocks and acting as de facto marine reserves	[395,497]
Ocean/Offshore wind energy	Benthic and fish species increases around offshore wind farms and wave/tidal infrastructure possibly due to shelter effects.	[360,362–364, 360,365–370]

8.3. Policy implications

When exploring policy implications at the interface of renewable energy and biodiversity it is important to keep in mind that different countries have pursued renewable energy (and often different renewable energy pathways) for different reasons. The most common drivers of renewable energy expansion have been energy security, economic development (through the often termed "green jobs") and climate change mitigation [13], e.g. see the EU Renewable Energy Directive (2009/28/EC) [12]. The influence of these drivers differs among countries, as is obvious for some renewable energy pathways such as biofuels. For example, most countries promoted biofuels to meet energy security and economic development objectives, rather than to promote environmental sustainability [273,461,490].[29]

This suggests that the environment is not always a consideration when adopting renewable energy policies. It also seems that when the environment was a strong driver for adopting renewable energy policies, such concerns were equated to climate change mitigation, treating climate as synonymous with the entire range of environmental issues. In this respect the negative local biodiversity outcomes might have been overshadowed by the deep optimism that renewable energy could overall pose a lower risk to ecosystems than fossil fuels [462,480].

Whatever the case, the fact remains that trade-offs do exist between renewable energy and biodiversity, as discussed throughout this re-

[27] Similar comparative studies have been conducted for large/small hydro and wind energy, also reaching interesting results [132].

[28] In fact, three quarters of the other impacts were found to be beneficial to biodiversity, including lower pollutant/GHG emissions, even when factoring in that solar installations would have necessitated the removal of forests [20].

[29] Furthermore, several countries adopted biofuel mandates to regulate demand, not necessarily complementing them with policies to improve the environmental performance of biofuels [14,461].

view. In the authors' opinion these trade-offs must be considered in policies that promote renewable energy, if economic growth is to be achieved in a socially inclusive manner within environmental limits (i.e. the professed targets of the Green Economy, Section 1). This reflects that biodiversity conservation is (and should be) as much a legitimate goal of the Green Economy as curbing GHG emissions (Section 1), and that green economic policies that promote renewable energy should take into account the potential biodiversity trade-offs.

Considering the (a) different drivers of renewable energy adoption (see above), (b) very diverse (and often highly contextual) biodiversity outcomes of renewable energy (Sections 2–7) and (c) numerous policy instruments at the interface of renewable energy and biodiversity [80,491], it is not straightforward to make concrete policy recommendations within the confines of this review.

In our opinion, four factors that need to be seriously considered during the development of green economic policies at the interface of renewable energy and biodiversity conservation. These are:

- the scale mismatches between the policy objectives of renewable energy and biodiversity conservation;
- the growing importance of the private sector in the Green Economy discourse;
- the appropriate definition(s) of degraded lands for locating renewable energy activities;
- the potential clashes between renewable energy expansion and market-based biodiversity conservation instruments.

There is a clear mismatch between the scale that the negative biodiversity outcomes of renewable energy manifest (local/landscape, Table 3), and its intended benefits such as climate change mitigation, energy security and green growth (mainly national, regional and global), e.g. [462]. This scale mismatch can lead to implementation conflicts between site/local-specific conservation goals and national energy policy/climate change mitigation priorities [480]. Mechanisms for addressing such scale mismatches do exist in some regions (e.g. EU) considering the current attempts to mainstream biodiversity across different policy domains [11,491]. However in several other countries (particularly developing countries) such capacity is simply lacking [463]. While different initiatives such as energy efficiency indicators, certification schemes and market-based conservation instruments, are currently being developed for various renewable energy pathways, most still await adoption and implementation, as renewable energy production and biodiversity conservation are largely not approached in an integrated way [273]. Yet, there are numerous international biodiversity agreements (e.g. CBD, Ramsar Convention on Wetlands) with agreed international biodiversity targets (e.g. CBD Aichi Targets) that require implementation at the national-level. Although often separately considered, these policy instruments can offer a space to align national-level renewable energy and biodiversity policies. Towards this end identifying potential synergies between multi-lateral environmental agreements such as the UNFCCC and the CBD [492] could be a first step towards appropriately overcoming such scale mismatches.

Within the current Green Economy discourse private enterprises are a key player for catalyzing green economic transitions, including transitions in the renewable energy sector [2]. In fact, the private sector is seen as a key investor in renewable energy technologies, a source of the intellectual property necessary for technological innovation, and even a supplier of raw material (e.g. bioenergy feedstock) for renewable energy generation [2]. Regarding the latter, a major policy challenge falls within the purview of managing biodiversity conservation in lands privately owned by individuals or companies [464]. Some scholars argue that with the appropriate incentives and policies (e.g. zoning), biodiversity conservation in privately-owned bioenergy landscapes could improve [465–467]. However, the lack of clear land tenure and land acquisition laws for bioenergy production has been a major policy challenge for the conservation of biodiversity, especially in developing countries [468,469]. This suggests there is a fine line between attracting green investments for renewable energy from the private sector, whilst at the same time, regulating and incentivizing the private enterprises to conserve biodiversity in privately-owned lands used for renewable energy purposes.

Relevant to the above, is the issue of expanding renewable energy generation in degraded lands [45,326], (Sections 2.2 and 5.2). In the US for example, abandoned cropland of approximately 683,000 km² could allow for the production of 14,000 GW of solar/wind power and bioenergy [473]. However, there are wide differences between definitions (and policies) of what constitutes a degraded land [470–472]. In the context of renewable energy the terms 'degraded' and 'marginal' land have been used synonymously and interchangeably with unused, idle, abandoned, undeveloped, fallow and low biomass land [472]. What is more important though is that marginal lands suitable for renewable energy generation can still have high biodiversity value or provide multiple ecosystem services [216,498]. The loss of access to ecosystem services provided by degraded lands used for bioenergy generation can have important ramifications for human livelihoods [472–474].

Finally, the renewable energy sector can have interesting interplays with market-based conservation instruments that have gained popularity within the current Green Economy discourse, such as Payment for Ecosystem Services (PES) schemes, biodiversity offsetting and product certification [2–144]. For example, hydropower can affect negatively some PES schemes [475–476]. Other studies have suggested the positive synergies between hydropower and forest conservation PES schemes that reward the long-term cooperation of local communities in conserving and protecting restored forest ecosystems [477]. Apart from PES schemes, certification standards for bioenergy and feedstock production have proliferated in the past decade [146]. While these standards often promote environmentally-sensitive production practices, their actual biodiversity outcomes are yet to be ascertained. This is not the least due to the indicators chosen, which aim to achieve compliance with existing legislation rather than ensure environmental sustainability [478]. Finally, biodiversity offsetting has also been perceived as a potential way to minimize the negative ecological impacts of hydropower and wind energy, with mixed, however, results [71–92]. These examples suggest that whilst there are some interesting synergies between renewable energy and market-based biodiversity conservation, their interplay can be quite complicated.

9. Conclusions

Renewable energy pathways are often implicitly considered as environmentally benign because of their crucial role in combating climate change. In truth there are no renewable energy pathways that have zero environmental impact presently, especially if they are to be deployed at the large-scale needed to enable a transition towards a Green Economy [2].

Our review demonstrates that current renewable energy pathways are associated (directly or indirectly) with all five MA drivers of ecosystem change and biodiversity loss (Table 2). The actual mechanisms, however, vary significantly between the different pathways and environmental contexts within which they operate. While the current evidence base is stronger for some pathways (e.g. bioenergy, hydropower) than others (e.g. solar, wind, ocean, geothermal), the fact remains that the large-scale deployment of renewable energy can have some biodiversity tradeoffs.

Given that the renewable energy sector is key for the transition towards a Green Economy, this means that there is a possibility for green-economic tradeoffs with economic sectors that directly depend on biological resources such as agriculture, forestry and fisheries [11]. Similarly, broader human wellbeing trade-offs that go beyond simple economic losses may emerge due to the loss of biodiversity-derived regulating and cultural ecosystem services [11]. Such examples include, among several others, the decline of cultural ecosystem services (e.g. recreation) following the large-scale deployment of some renewables [479,480].

Considering that the biodiversity impacts of renewable energy may vary between technologies, locations and species; adopting the avoid-minimize-restore-compensate mitigation hierarchy [2] would seem appropriate on a case-by-case basis. The model of displacement, diffusion and intensification that has been used to understand policy impacts on fish stocks [459] could also be used to classify renewable energy impacts and mitigation actions.

When it comes to the biodiversity impacts of renewable energy, it is also important to recognize the chain of information flow. Often raw site evidence coming from the biological sciences is aggregated and interpreted by ecologists, and then passed on to planners to regulate and implement; with energy policy coming in as a top-down, governmental process. It is therefore entirely likely that renewable energy goals are conceived without fully considering their potential impacts on biodiversity.

While biodiversity assessments can be useful tools to identify and minimize biodiversity conflicts from renewable energy expansion, these assessments should not exclusively focus on the negative impacts as this runs the risk of ignoring any potential benefits that may accrue from sensible planning. In fact, our review has highlighted some of the direct and indirect benefits of renewable energy on biodiversity (Table 4). In any case, to bridge the gap from site suitability analysis to broader biodiversity planning it will require the adoption of wider disciplinary perspectives.

We must note that with this review we do not question the fundamental logic of promoting renewable energy, as it has been shown to have high environmental and socio-economic benefits. However, we want to make the point that some negative impacts on biodiversity do exist, and need to be considered when developing renewable energy policies. This is particularly important given that non-linear effects can emerge during scaling up and that seemingly low impacts could become considerable when renewable energy technologies are deployed at a scale commensurate to achieve a transition towards a Green Economy.

To sum up, determining the hidden "green-economic" trade-offs of renewable energy expansion is crucial for understanding better both the role of biodiversity within a Green Economy, as well as the economic costs and benefits that its conservation may yield [11]. While some knowledge exists about the nature of these trade-offs, developing a stronger evidence base and appropriate assessment/planning tools will be necessary to guide the transition towards a Green Economy while avoiding negative biodiversity outcomes.

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