Trends in Ecology & Evolution

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Review

How Green is 'Green' Energy?

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Renewable energy is an important piece of the puzzle in meeting growing energy demands and mitigating climate change, but the potentially adverse effects of such technologies are often overlooked. Given that climate and ecology are inextricably linked, assessing the effects of energy technologies requires one to consider their full suite of global environmental concerns. We review here the ecological impacts of three major types of renewable energy – hydro, solar, and wind energy – and highlight some strategies for mitigating their negative effects. All three types can have significant environmental consequences in certain contexts. Wind power has the fewest and most easily mitigated impacts; solar energy is comparably benign if designed and managed carefully. Hydropower clearly has the greatest risks, particularly in certain ecological and geographical settings. More research is needed to assess the environmental impacts of these 'green' energy technologies, given that all are rapidly expanding globally.

Trends

Renewable energy is expanding rapidly. Growth is greatest in China, which now constitutes 28%, 26%, and 35% of the global capacity of hydro, solar, and wind power, respectively.

Hydropower has the largest environmental impacts, mostly because of habitat loss and fragmentation caused by impoundment reservoirs and roads needed for dam construction and maintenance. Dams block animal migration and disrupt river flows, creating homogenized conditions favoring non-native species. Hydropower also generates greenhouse gases, especially methane, particularly in the tropics.

Wind power kills 100 000 s of birds and bats every year. Wind farms can affect bird migrations and trigger population declines. Wind turbines increase ambient temperature and noise, harming some native species.

Solar energy is the fastest growing renewable, but its impacts are poorly known. More research is needed in this area.

The Rise of Renewables

Growing human populations and rising levels of consumption have elevated energy demands, placing increasing burdens on the environment – particularly on the global climate. In a transition to clean sources of energy, much energy growth will come from **renewable energy** (see Glossary) sources and, as of 2016, 176 nations have set targets to obtain certain proportions from so-called 'green' energy sources [1]. While these efforts are commendable, much of the development of green energy is having large impacts on the environment and biodiversity, particularly in the hyperdiverse tropics where human populations and economies are expanding most rapidly [2].

Global attention has largely focused on the environmental impacts of **conventional energy** sources, particularly fossil fuels [3,4]. However, some recent reviews have compared the impacts among different renewable energy sources [5–8]. While renewable energy sources generally have low carbon emissions, they are often more land-use intensive than conventional energy sources [6], thereby creating potential conflicts with the conservation of terrestrial biodiversity and ecological services [7]. In a theoretical comparison of **wind turbines**, **solar photovoltaic** (PV) **panels**, and **bioenergy** from the perennial grass *Miscanthus*, bioenergy posed the highest threat to biodiversity – largely because of a high degree of overlap between potential *Miscanthus* production lands and habitats sustaining high biodiversity [7]. In another study accounting for electricity price, greenhouse gas emissions, energy conversion efficiency, land and water requirements, and social impacts, **wind power** was found to be the most sustainable form of renewable energy, followed by **hydropower** [5]. However, to date there has been no comprehensive review of the different sources of green energy and their impacts on biodiversity.

We provide here a general overview of three of the most important renewable energy sources – hydropower, **solar energy**, and wind power – and assess their potential impacts on

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biodiversity and key ecosystem services. Our review does not cover **geothermal energy**, with a power capacity an order of magnitude lower than that of the other three types above; nor bioenergy, which is presently based mostly on the production of agricultural crops [9], and differs markedly from the types of infrastructure developments associated with hydro, solar, and wind energy. We describe recent and projected growth in these three energy types, key sites for each energy source, and their consequences for biodiversity and ecological health.

Overall Trends in Renewable Energy

In 2016 the installed **electricity generation capacity** of hydropower was 1096 GW [1] (Figure 1). Actual **electricity generation**, however, was estimated at only 4.1 PWh, much lower than the potential global annual generation of 52.0 PWh [10]. This could be due to droughts that caused downturns in power production in some regions, including the Americas and Southeast Asia [1]. This global capacity is not distributed evenly around the world because there are important regional differences in potential hydropower capacity based on river flows and elevation [10]; China has the highest potential generation (7.17 TWh/year) and installed hydropower capacity (305 GW), followed by Brazil (3.63 TWh/year, 97 GW) [1] (Figure 1).

Solar PV capacity grew by 33% from 2015 to 2016, a remarkably rapid rate of expansion, from 228 to 303 GW globally [1] (Figure 2). Global capacity has increased 65-fold in the past decade. China remained the country with largest capacity (77.4 GW), comprising more than a quarter of the global capacity [1] (Figure 2). Although **concentrating solar power** (CSP) capacity grew to 4.8 GW, it provides only 1.6% of solar PV capacity [1].

Wind power also expanded substantially in 2016, with a 54 GW addition increasing global capacity to 487 GW [1] (Figure 3). In 2015 wind was the largest source of new energy capacity in Europe and the USA, and the second highest in China [1]. China has the highest capacity (168.7 GW), comprising an astounding one third of current global capacity [1] (Figure 3). Globally, 12 GW comes from offshore **wind farms**, representing a 3.4 GW increase since 2014 [1].

Global investment in renewable energy reached an all-time high in 2015 of US$312.2 billion [excluding large (> 50 MW) hydropower projects] [1]. For the first time, developing countries (including the 'BRICS' nations of Brazil, Russia, India, China, and South Africa) exceeded developed countries in investment, with China alone accounting for 32% of total global investment in renewable energy [1]. Globally, 2015 was the first year in which renewables comprised the majority (53.6%) of newly created energy capacity (excluding large hydropower) [11].

In China, the largest energy consumer worldwide, energy use is expected to increase by 60% between 2015 and 2030 [12]. Between 2020 and 2050 hydropower generation in China is expected to rise from 11.4 to 15.5 TWh (while declining from 13.1% to 11.1% as a proportion of total energy generation), whereas wind is projected to increase from 3.2 to 10.4 TWh (from 3.7% to 7.5%), and solar from 0.3 to 4.8 TWh (from 0.4% to 3.4%) [12]. Based on these projections, hydropower will continue to provide the largest share of renewable energy generation, both globally and within China, followed by wind and then solar.

Hydropower: The Largest Renewable Energy Source

Carbon Emissions

As of March 2014 some 3700 sizable (>1 MW) **hydroelectric dams** were either planned (83%) or under construction (17%) worldwide, with about nine-tenths of these being in developing nations [13]. Despite being touted as a clean energy source, hydropower causes substantial emissions of greenhouse gases such as CO_2, methane (CH_4), and nitrous oxide

Glossary

Bioenergy: energy from materials derived from biological products (e.g., wood, algae) which are often burned to generate electricity.
Concentrating solar power (CSP): the indirect type of solar energy which uses mirrors or lenses to concentrate sunlight onto a small area, generating heat which produces electricity (often via a steam turbine).
Conventional energy: energy derived from non-renewable fossil fuel sources (oil, gas, and coal).
Electricity generation: the amount of electricity produced over a specified period of time, measured in watt-hours (Wh). For example, a wind turbine with a capacity of 1 MW operating at full capacity for one hour will produce 1 MWh. 1 PWh = 10^3 TWh = 10^6 GWh = 10^9 MWh = 10^{12} KWh = 10^{15} Wh.
Electricity generation capacity: the maximum possible electricity output at any given time, measured in watts (W). 1 GW = 10^3 MW = 10^6 KW = 10^9 W.
Geothermal energy: heat energy generated and stored in the Earth; often converted to electricity.
Hydroelectric dam: a barrier that stops or restricts the flow of water; used to create energy in the water flow that can be captured by a turbine to generate electricity.
Hydroelectric reservoir: the body of water formed upstream by the creation of a hydroelectric dam.
Hydropower: power derived from the energy of falling water or fast-running water to generate electricity.
Impoundment reservoir: a body of water confined within an enclosure, for example behind a dam.
Renewable energy: energy derived from renewable resources which are naturally replenished, for example wind, sunlight, and geothermal heat.
Solar energy: radiant light and heat from the sun harnessed and converted to electricity by different methods [see solar PV and concentrating solar power (CSP)].
Solar photovoltaic (PV): the direct type of solar energy in which photons from solar radiation are converted to electricity.
Solar PV panel: an arrangement of PV materials that absorbs and converts sunlight into electricity.
Transmission lines: power lines used to move electricity from a

generating site (e.g., a power plant) to an electrical substation, which often transforms the voltage from high to low before reaching consumers.
Wind farm: a group of wind turbines used to produce electricity.
Wind power: the use of air flow through wind turbines to mechanically produce electricity.
Wind turbine: a device with two or three propeller-like blades which in the presence of wind turn around a rotor, spinning a generator to produce electricity.

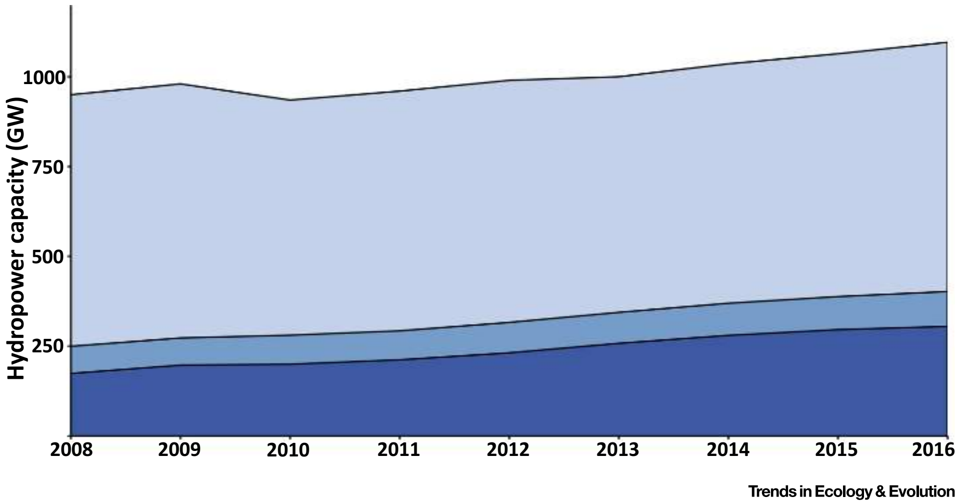

Figure 1. Hydropower Installed Capacity (GW) 2008–2016 for China (Dark Blue), Brazil (Intermediate Blue), and the Rest of the World (Light Blue). Data from [1].

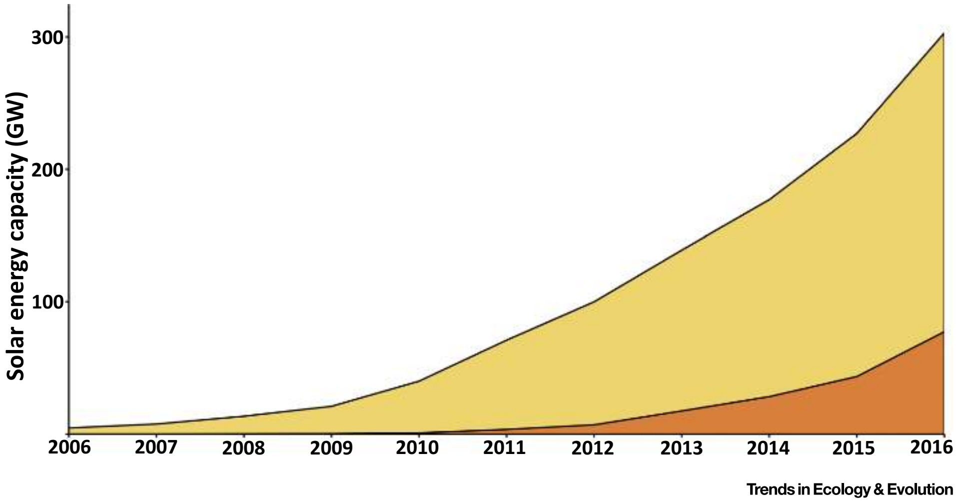

Figure 2. Solar Photovoltaic Energy Installed Capacity (GW) 2006–2016 for China (Orange) and the Rest of the World (Yellow). Data from [1].

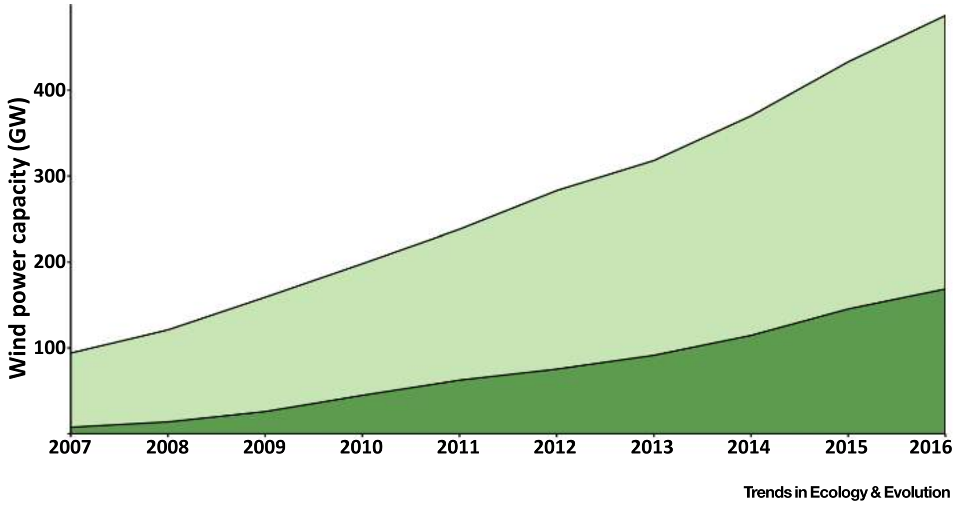

Figure 3. Wind Power Installed Capacity (GW) 2007–2016 for China (Dark Green) and the Rest of the World (Light Green). Data from [1].

(N_2O) [14]. Decomposition of vegetation in anaerobic conditions at the bottom of **hydroelectric reservoirs** produces substantial quantities of CH_4, and water passed through turbines and spillways also releases CH_4 dissolved in the water; upstream emissions are proportional to reservoir surface area, whereas downstream emissions are proportional to flow rate [15]. Further, many new hydropower dams require networks of roads for dam construction and maintenance that in turn increase deforestation and forest colonization (Box 1).

The largest greenhouse gas emissions are typically emitted from hydropower reservoirs in tropical regions [16]. Hydroelectric reservoirs in the tropics are often created in areas with large stocks of above- and below-ground carbon, especially in humid regions that support dense rainforests. Because these forest habitats are flooded by reservoirs, the large carbon stocks produce heavy CH_4 and CO_2 emissions. In addition, falling water levels during the dry season, combined with rapid plant growth, result in an annual proliferation of fast-growing plant species

Box 1. Hydropower Expansion Threatens the Amazon and the Andean Foothills

Hydroelectric dams on major river tributaries in the Amazon basin and adjoining Andean foothills – which drain into the Amazon River – are exploding in number (Figure I). Currently there are 48 dams of >2 MW capacity in the Andean foothills, with another 151 dams planned over the next 20 years, which will disrupt ecological connectivity of five of the six major Andean tributaries of the Amazon [84]. Currently, 191 dams exist in the Amazon basin itself, and another 246 are planned or are under construction [21]. The largest nation in the Amazon, Brazil – which comprises 8.6% of the global hydropower capacity, second only to China (27.9%) [1] – derives >70% of its electricity generation from hydropower [85].

The potential for new dams to promote deforestation, not only by flooding forest but also by promoting road and power line networks that greatly increase human access to forests, is often underappreciated. Of the planned and existing Andean dams, 36% would require new roads and 79% new transmission lines [84]. Deforestation and forest degradation has affected thousands of square kilometers of forest surrounding the Tucuruí Dam in Brazil, largely from a 10-fold increase in the human population and in associated logging and forest clearing [86]. Twelve large dams planned for the Tapajós River and its tributaries in the eastern Amazon are projected to increase deforestation by nearly 1 million ha by 2030, largely as a result of increased road and power line construction [87].

Although the massive Balbina Hydroelectric Reservoir in the Brazilian Amazon increased the available habitat and doubled the population size of the giant otter (*Pteronura brasiliensis*) [88], this same reservoir flooded more than 3000 km^2 of undisturbed rainforest, and 98% of the 3546 islands in the reservoir lost at least 25% of the vertebrate species originally occupying the landscape [89]. Similar consequences can be expected from the hundreds of dams that are planned or under construction in the Amazon.

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Figure I. The Tucuruí Dam in Brazil. Photo credit Museu Virtual de Tucuruí.

along the exposed margins of tropical reservoirs. These regenerating plants are then flooded and killed during the wet season, producing additional carbon emissions each year. For example, the 40 MW Curuá-Una Dam in Pará, Brazil, which spans 72 km^2 in surface area, releases 3.6-fold the amount of greenhouse gases annually than would be produced by generating the same energy from fossil fuels [17]. In the vast tropical regions such as the Amazon (Box 1) and Congo basins, very large reservoirs are necessary to generate adequate power because of the flat topography [18]; the high ratio of reservoir surface area to power generation only increases these emissions [15].

Globally, hydroelectric reservoirs emit substantial amounts of CO_2 and CH_4 into the atmosphere, ranging from 48–82 Tg of CO_2 and 3–14 Tg of CH_4 per year from their reservoir surfaces [16,19]. Further emissions are frequently caused by habitat loss and fragmentation associated with networks of roads and power lines needed for dam construction and operation (Box 1).

Impacts on Biodiversity

In many contexts, the largest impact caused by hydropower is the habitat lost to **impoundment reservoirs**. Globally, hydroelectric reservoirs cover an area of 340 000 km^2 [16], nearly the size of Germany, replacing important lowland and riverine forest and grassland habitats used by countless species. Secondary impacts caused by hydropower development, in the form of access roads and **transmission lines**, can also contribute to environmental degradation, sometimes superseding habitat losses from the reservoir itself. For example, ongoing construction of the Belo Monte Dam in Brazil will flood 440 km^2 behind the main dam, and another 6140 km^2 behind the Altamira/Babaquara Dam that will regulate riverflow [20]. However, another 4000–5000 km^2 of forest is expected to disappear after the project is completed, when construction workers join other migrants in the search for livelihoods in the region, often causing further deforestation [21].

As hydropower reservoirs are formed, the fragmented habitat within or surrounding the reservoir becomes vulnerable to biodiversity loss. Islands persisting in Lago Guri, a massive (4250 km^2) hydropower reservoir in Venezuela, experienced great losses in biodiversity and such dramatic changes in species composition that it was termed an ‘ecological meltdown’ [22]. Similarly, small (<60 ha) islands formed by Chiew Larn Reservoir in Thailand (Figure 4)

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Figure 4. Chiew Larn Reservoir in Thailand Flooded 165 km^2 of Forest Habitat, Previously Home to Tigers and Other Wildlife. Fauna on isolated hilltops in the reservoir have suffered catastrophic extinctions [23]. Photo credit Stuart Kirkland.

suffered catastrophic extinctions, with all 12 native small mammal species disappearing in only 25 years [23]. Finally, habitat loss and fragmentation from a hydroelectric dam in Portugal caused the regional distributions of the European wildcat (*Felis silvestris*) and European polecat (*Mustela putorius*) to shrink by half and two-thirds, respectively [although the water-dependent European otter (*Lutra lutra*) expanded its range] [24].

Hydroelectric dams also create barriers to downriver sediment flow and block the migration of animals upstream or downstream [21,25]. Dam construction in the Amazon has fragmented populations of two species of dolphins, the Amazon River dolphin (*Inia geoffrensis*) and the tucuxi (*Sotalia fluviatilis*). Distribution and population records, however, are poorly understood, and there has been little effort to mitigate the impacts of ongoing dam construction on these species [26]. Dams have also negatively affected river dolphin species in Asia [27]. The scores of planned Mekong dams will also endanger a critically imperiled population of freshwater dolphin (*Orcaella brevirostris*), which has fewer than 100 individuals remaining [28].

Dams and impoundment reservoirs form major barriers which disrupt the migration patterns of neotropical migratory fish [25]. Dams along the Mekong and its tributaries create barriers that disrupt upstream spawning migration and the downstream drift of fish eggs and larvae [29], and threaten fisheries that provide likelihoods and food resources for many of the 65 million people living there [30]. Dams along the Yangtze have driven large species such as the Yangtze sturgeon (*Acipenser dabryanus*), the Chinese sturgeon (*Acipenser sinensis*), and the Chinese paddlefish (*Psephurus gladius*) to be listed as 'critically endangered' by the International Union for Conservation of Nature (IUCN) [31]. Large migratory species are particularly vulnerable to dams; in the past two decades populations of the Mekong giant catfish (*Pangasianodon gigas*) declined by 80% [32].

Tonle Sap, the largest lake in Southeast Asia and an important wetland habitat for migrating birds and spawning ground for freshwater fisheries, will also suffer from hydropower. Dams on the Mekong are projected to cause a 41.6% $\pm$ 7.7% decline in sedimentation, and similar reductions in net primary productivity (NPP) – 42% among flooded grasslands, 39% among flooded shrublands, and 50% in gallery forests – which in turn are projected to decline in extent by 22% [33].

Dams regulate water flow and disrupt natural flow cycles, creating homogenized, disturbed conditions that favor the spread of non-native species that in turn threaten many native species [34]. The shift from lotic (fast-flowing) to lentic (still) waters favors generalist species which can displace range-restricted endemic species [21,35]. In natural and man-made lakes in Wisconsin and northern Michigan, non-native species were 2.4–7.8-fold more likely to be found in man-made reservoirs than in natural lakes [36].

Dams can also contribute to increased saltwater intrusion in river mouths by blocking the flow of sediment which helps to keep deltas above sea level [37]. One of the few positive effects of hydroelectric development is that the impoundment of 10 800 km^3 of water in reservoirs worldwide has reduced global sea level rise by 3 cm, slowing sea-level increases by an average of 0.55 mm $year^{-1}$ over the past half-century [38]. This also suggests that other sources of sea level rise have been underestimated.

Construction of hydroelectric reservoirs spiked from the 1950s through the 1980s, subsequently slowed, and is rebounding at present. Currently, nearly half of all freshwater ecoregions globally are obstructed by medium- and large-sized dams [39]. Hydropower impacts will only grow as more dams are constructed, particularly in the tropics. More than 450 dams are planned in the Amazon, Congo, and Mekong river basins, which collectively host one third of the freshwater fish species of the world [35,40]. Overall, the substantial greenhouse gas emissions and pronounced disruption of terrestrial and aquatic ecosystems from hydropower dams raise serious questions as to whether they should be considered 'green energy' at all [14].

Solar Energy: The Fastest Growing Renewable

Many different methods exist for converting sunlight to energy [41] but, in general, solar power plants require large land areas and high water use – particularly to cool the steam turbine and clean solar panels and reflective surfaces [42]. Other than this, little is known about the specific impacts of solar energy development on wildlife [43].

In the USA solar energy potential is highest in the southwestern deserts, which are closest to the equator and have minimal cloud cover. This area overlaps with the distribution of Agassiz desert tortoise (*Gopherus agassizii*), an ecological-engineer species that constructs burrows that are used by other animals to avoid high temperatures in the desert habitat. Solar plant development often removes vegetation and creates dust emissions, and the construction and maintenance of the facilities can cause animal burrows to collapse. The dust emissions from large solar facilities can impair the gas exchange, photosynthesis, and water usage of desert plants, whereas heat emissions could alter sex ratios in animal species whose sex is determined by incubation temperatures [43].

The Mojave Desert of California and Nevada has seen rapid expansion of solar energy facilities [44] (Box 2). Although ample space exists to develop solar facilities outside areas of high conservation value, much development has occurred in core ecological habitats, which could affect desert wildlife [45].

In the USA an estimated 38 000–138 000 birds are killed each year by utility-scale solar energy development (16 000–59 000 in southern California) [46]. To some aquatic insects, solar panels appear to be bodies of water and can attract mayflies, caddis flies, long-legged flies (Dolichopodidae), and tabanid flies to lay eggs on the panels, wasting their reproductive effort or exposing them to elevated predation risk [47]. Microclimates beneath solar panels are also typically altered; at a UK solar park temperature decreased (by up to 5.2°C) and increased dryness led to a 74% decline in plant biomass and associated declines in diversity and photosynthesis rates [48]. However, these changes could actually enhance local biodiversity, particularly in regions of the world where heat and drought are growth-limiting factors for species.

Wind Power: The Renewable with the Smallest Footprint?

As with solar energy, little is known about the potential impacts of wind energy development on biodiversity. Construction of wind farms can affect habitat quality, attract predators, and elevate the risk of fire [49]. Roads built for access to turbines and culverts built for water drainage can cause mortality to the Agassiz desert tortoise (*Gopherus agassizii*), a species listed as 'vulnerable' by the IUCN [49]. However, at the Mesa wind farm with 460 turbines near Palm Springs, California, clutch size, nest predation rates, and hatching successes of desert tortoises were similar to those in adjacent undisturbed sites in similar habitats [50]. Studies over longer time-periods will help to determine the long-term impacts of wind energy on this threatened species.

One of the greatest threats posed by wind power is turbine collision with birds and bats. Turbine siting is important, and the highest collision rates are found along forested ridgelines [51,52]. In the USA an estimated 600 000–888 000 bats [53,54] and 573 000 birds (including 83 000 raptors) [54] were killed by wind turbines in 2012. This includes 134 000–230 000 small passerine birds [55]. Although mortality caused by wind turbines is vastly lower than that caused by other anthropogenic sources (e.g., in the USA 0.57 million birds are killed annually by wind turbines versus 5.63 million killed by power line electrocution, 22.8 million by power line collisions, 199.6 million by automobile collisions, 599 million by collisions with buildings, and 2.4 billion by cats [56]), in some cases low mortality rates can trigger substantial population declines for raptors, as for the endangered Egyptian vultures (*Neophron percnopterus*) in Spain [57] and white-tailed eagles (*Haliaeetus albicilla*) in Finland [58] and Norway [59].

California, which has the most wind turbines, is believed to have nearly half (46.4%) of all bird collisions in the USA (Box 2) [60]. A review of 33 wind farms across North America concluded that rotor diameter did not affect the mortality rates of birds or bats, but greater tower height increased mortality among bats – especially when tower height exceeded 65 m [61]. Bird mortality also increases with greater turbine height [60]. At the La Venta II wind farm in Oaxaca, Mexico, nearly one-tenth (34 of 353) of the bird species found locally suffered fatal collisions with wind turbines. Species at highest risk of collisions were smaller in size, with short wing-spans and heavier wing loadings [62]. Among bats, migratory, tree-roosting species are most commonly killed by wind turbines [63].

Box 2. Wind and Solar Energy Imperil Biodiversity in California

California is a pioneer in renewable energy and has set strict targets to reduce its greenhouse gas emissions. In January 2017 the California Air Resources Board approved a plan to reduce its emissions by 2030 to levels 40% lower than those in 1990, the most ambitious target in North America [90]. This plan involves obtaining one third of its energy from renewables by 2020, and half by 2030 [91]. California has invested heavily in wind and solar energy [44], and is currently the largest producer of solar energy [92] and the fourth-largest producer of wind energy [93] in the USA.

The rapid expansion of wind and solar energy imperils some species in California. The 5400 wind turbines at Altamont Pass Wind Resource Area (Figure I) are estimated to kill some 2700 birds per year, including over 1100 raptors, of which 67 are golden eagles (*Aquila chrysaetos*) [94]. Among the golden eagles killed, at least 25% were recent immigrants (from >100 km away), suggesting this single facility has continental-scale impacts [95]. The Altamont Pass turbines also affect California ground squirrels (*Spermophilus beecheyi*); individuals living under the turbines had elevated vigilance rates owing to the high background noise [96]. If displaced by noise from this wind farm, their loss could affect predators such as golden eagles and other species that use their burrows for shelter (e.g., burrowing owls, red-legged frogs, California tiger salamanders) [96].

Figure I. Altamont Pass Wind Resource Area Is One of the Largest Wind Farms in California, but Causes the Death of an Estimated 67 Golden Eagles (*Aquila chrysaetos*) Every Year [94]. Photo credit Steve Boland.

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The endangered Mojave ground squirrel (*Xerospermophilus mohavensis*) is expected to lose up to one tenth of its habitat from expansion of wind and solar energy facilities in the Mojave Desert [97], which has four of the five largest solar thermal-power stations worldwide. The largest of these (Figure II) was built in prime habitat for the Mojave desert tortoise (*Gopherus agassizii*) (Figure III). To mitigate its impact, at least 55 tortoises were translocated short distances (<500 m) outside the facility. Compared to control populations, translocated tortoises had somewhat differing activity patterns in the first year after translocation, but there were no differences in body condition, growth, or mortality in subsequent years [98,99]. This same power plant caused an estimated 3500 bird deaths per year, most due to collisions [100].

Figure II. Ivanpah Solar Electric Generating System, Located in the Mojave Desert, Is the Largest Concentrating Solar Power Plant in the World, With a Capacity of 392 MW. Photo credit Jamey Stillings (http://jameystillingsprojects.com).

Figure III. Solar Energy Developments and Associated Transmission Lines and Access Roads Could Imperil Threatened Species Including the Mojave Desert Tortoise (*Gopherus agassizii*). Photo credit Dakota Gale.

Wind farms can also impact resident and migrating bird populations [64]. Three wind farms in North and South Dakota caused the displacement of seven breeding grassland bird species, effects that extended beyond the first year after construction [65]. In Finland, breeding success of white-tailed eagles (*Haliaeetus albicilla*) was lower in territories located closer to wind turbines [58]. By contrast, nests of scissor-tailed flycatchers (*Tyrannus forficatus*) had higher survival rates close to turbines at a Texas wind farm, possibly due to reduced activity by raptors, a key nest predator, around the wind turbines [66].

Wind farms affect both local and distant populations. Stable hydrogen isotope analysis showed that 28% of the noctule bats (*Nyctalus noctula*) killed by wind turbines in eastern Germany were migratory, originating from distant parts of northern and northeast Europe including the Baltic states, Belarus, or Russia [67]. In the Appalachian Mountains, two bat species sustained the highest levels of mortality at a wind farm; for the eastern red bat (*Lasiurus borealis*) 57% of mortalities were of non-local individuals, whereas for the hoary bat (*L. cinereus*) 99% of killed individuals were local, suggesting that ongoing mortality could imperil this species [68].

Offshore wind farms can also affect bird populations and migration patterns. The Belwind Wind Farm at Bligh Bank, 46 km off the coast of Belgium, caused an 85% decline in northern gannets (*Morus bassanus*), a 71% decline in common guillemots (*Uria aalge*), and a 64% decline in razorbills (*Alca torda*) [69]. Conversely, there was a 430% increase in lesser black-backed gulls (*Larus fuscus*) and a 850% increase in herring gulls (*Larus argentatus*) at the same wind farm site, possibly because of increased roosting or feeding opportunities [69]. Pink-footed geese (*Anser brachyrhynchus*) migrating between Greenland or Iceland and the UK altered their migration route to avoid newly constructed wind farms off the eastern coast of England [70]. Common eider (*Somateria mollissima*) and geese altered their migration routes to avoid a wind farm in the Baltic Sea off the coast of Denmark; the proportion of flocks migrating through the wind farm declined sharply from 40.4% before construction to only 8.9% after construction [71]. Altered migration patterns can also occur in response to onshore wind farms, as observed for migrating raptors at wind farms in the Isthmus of Tehuantepec in Mexico [72]. Shifting migration patterns could result in increased energy expenditure by migrating birds and associated declines in survival [73].

Noise from wind farms can also affect wildlife (Box 2). On wind farms European robins (*Erithacus rubecula*) decreased their territorial response to intruders because of turbine noise, and this could potentially reduce their ability to deter rivals and thereby reduce their breeding success [74]. Amphibians, reptiles, birds, and mammals had reduced species richness at wind farms in Portugal [75], possibly also because of cascading effects caused by wind turbines.

Wind farms can also increase local temperatures. Active wind farms in Scotland raised air temperature by 0.18°C and absolute humidity by 0.03 g m^{-3} during the night, and also increased variability in air, surface, and soil temperature [76]. Based on satellite data, four large wind farms in Texas were found to increase local temperature by up to 0.72°C per decade relative to nearby control sites [77]. The implications of this temperature increase are unknown but might have additional consequences for biodiversity.

Prescriptions for Sustainable Renewable Energy Growth

It is important to emphasize that research efforts on the three renewable energy sources examined here are uneven, with a particular gap in our understanding of solar energy and its impacts on biodiversity. However, based on this review, we found the most serious biodiversity and environmental impacts likely to arise from hydropower, followed by wind power and then solar energy. All three generate environmental disturbances, some of which have been largely ignored, but many of which can be mitigated.

Given that hydropower facilities are so large and require the most land area, it is difficult to mitigate their effects on biodiversity. That hydropower requires the construction of large reservoirs of water on previously dry land is an inescapable problem [25]. The large-scale effects on the flooded habitat and the secondary effects of associated roads and power lines on land-use change pose a serious threat to terrestrial biodiversity. Impacts on freshwater species and ecosystems are also substantial, although these are incompletely understood, and there is a growing appreciation that hydropower is often a substantial source of greenhouse gas emissions. Fortunately, the HydroCalculator, a free tool recently developed by the Conservation Strategy Fund, allows local citizens, scientists, and policymakers to calculate the projected carbon emissions produced by planned hydropower dams, and this could influence decisions about future dam construction [78].

The siting of these energy facilities is a crucial factor affecting their impacts on biodiversity. For hydropower, the landscape terrain often constrains development strategies for dams, but increasingly there is a recognized need that many decisions must be made at the river-basin scale. In the Mississippi River Basin, several of the largest tributaries of the river sustain >80% of large-river specialist fishes found in the river mainstem [79]. This suggests that large tributaries might serve as ecological surrogates for mainstems, and represent underappreciated conservation opportunities for the preservation of megafauna in major river systems [79]. Recent basin-scale assessments have been made for the Mekong River [30] and the Amazon [80], incorporating projected changes in hydrology and sediment transport that would affect ecosystem productivity, rural livelihoods, and biodiversity along the mainstem and tributaries. Such basin-scale assessments will be vital to balance the gains in energy supply versus losses in fisheries, agriculture, and biodiversity [35].

Little is known about the environmental impacts of solar energy [43]. However, based on available evidence, we know that the impacts of solar energy can be greatly reduced if new development is focused on lands that are already degraded and lack threatened species [45]. Solar installations should not be constructed in ecologically sensitive habitat. There are currently 1.1 billion ha of degraded lands globally [81], and at current capacity <0.1% of the available degraded lands would be necessary to double the current solar PV capacity – even without accounting for advances in the efficiency of solar energy [82]. More research on the specific impacts of solar energy developments are urgently needed, particularly given the rapid growth of this energy source.

The design of wind farms can be significantly improved to limit biodiversity impacts. In general, mortality rates increase with turbine height [56,60]. By building wind turbines at the lowest height feasible, mortality of birds and bats can be markedly reduced, although there may be tradeoffs between having a smaller number of large turbines versus many smaller turbines. Turbine placement is also crucial, and particular areas such as ridgelines, which are high-volume transit areas for flying wildlife, should be avoided whenever possible [56]. Wind farms should not be constructed near habitats for threatened bird or bat species, and important migratory routes for flying animals should be avoided whenever possible. Furthermore, wind technology should be improved to reduce the noise and heat generated by turbines.

Given that wind energy requires a smaller footprint than either solar or hydropower, and that its impacts are more easily addressed, wind is likely the safest form of green energy in terms of biodiversity. Clearly, however, there is scope to refine strategies to minimize the impacts of new wind projects on biodiversity and ecosystems.

Concluding Remarks

Renewable energy, a vital component of our global climate change mitigation strategy, needs to be considered within the broader context of biodiversity and ecosystem protection. Our analysis of three major types of renewables – hydro, solar, and wind energy – suggests that wind power is most likely the safest form of renewable energy in terms of its overall ecological impacts. Hydropower appears to be the most dangerous in terms of its potential impacts on terrestrial and aquatic species, native habitats, and greenhouse gas emissions. However, more research is needed on the long-term impacts of all three types of renewables and the best strategies to help to mitigate them. Recent policy changes targeting carbon emissions – including the landmark Paris Agreement – could trigger an avalanche of renewable energy projects [83], and concerted research efforts and practical planning guidelines will be necessary to help to ensure that such developments are truly as 'green' as possible.

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Outstanding Questions

How do environmental impacts of hydro, solar, and wind energy vary by latitude, elevation, temperature, and across other geographic gradients?

What conditions would minimize greenhouse gas emissions from hydropower?

What regions have the most degraded lands in proximity to energy demand that would be suitable targets for solar energy expansion?

How do solar PV and concentrating solar power differ in terms of electricity generation and environmental impacts per unit area?

How will improvements in solar PV technology reduce the land area required for electricity generation?

Can solar PV panels be innovated to eliminate the need for precious metals?

What technologies added to wind turbines can minimize mortality of birds and bats?

Can different renewable energy types be combined into the same facility, thereby reducing needed land area and minimizing environmental impacts?

How can governmental policies, particularly in countries with large growth and/or potential in renewable energy, encourage 'smart' development of renewables?

How can different countries work together to harness and share renewable energy from different sources that might have different peaks of electricity generation?

What are the net biodiversity impacts of renewable energy when reduction in fossil fuel extraction and combustion is considered?

Is it ecologically and technologically feasible to completely replace fossil fuels with renewable energy?

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