Climate meets nature

Integrating biodiversity into the energy transition

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Contents

Foreword

01 Climate meets nature: A practitioner's guide to biodiversity and the energy transition

Executive summary

02 Introduction
06 Focus on three key technologies
08 Investment implications

Solar Power

14 What are the most material natural capital impacts for solar power?
16 Habitat loss and damage caused by solar PV from mining
19 Habitat loss and wildlife impacts from installing and operating solar farms
22 End-of-life waste from solar farms
27 Engagement questions for minimizing natural capital impacts from solar power

Wind power

32 What are the most material natural capital impacts for wind power?
34 Mining-related habitat loss and damage caused by wind power
37 Wildlife impacts from installing and operating wind farms
41 End-of-life waste from wind turbine blades
43 Engagement questions for minimizing natural capital impacts from wind power

Bioenergy

51 What are the most material natural capital impacts of second generation bioenergy?
53 Land use change, habitat and biodiversity loss from second generation biofuels
56 Carbon emissions from wastes and residues
59 Ecosystem impacts from removing wastes and residues
61 Engagement questions for minimizing natural capital impacts from second generation bioenergy

Foreword

Barry Gill
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Climate meets nature: A practitioner's guide to biodiversity and the energy transition

Like many things, this report started out with a simple aim: to serve as a useful tool for anyone in the investment value chain wanting to incorporate natural capital and biodiversity considerations into their investment decisions and engagement efforts.

The findings and guidance are relevant for both public and private markets. They should help both asset owners and individual companies build metrics on these important issues. As climate and nature are inextricably linked, we knew it was critical to create a report that reflected this fact. We needed the output be practical and useful, but we also wanted it to help harmonize sustainability efforts by reducing siloed thinking and the various approaches to tackling such issues.

The nexus of climate and nature is a big topic, with lots of nuance, complexity and trade-offs. Interdependencies and unintended consequences abound. To make things manageable, we decided to focus on three essential technologies in the energy transition: solar, wind and bioenergy. And when wrestling with the trade-offs and negative consequences of these new energy sources, we were also extremely cognizant the opportunity costs; continuing to rely on fossil fuel-based solutions is not zero cost – indeed, the status quo's impacts are much more consequential.

Any equation considering the negative effects of the new world therefore needs to balance out the current realities of the old one. We call for a pragmatic response and approach which, among other things, requires better management of the upstream impacts of transition technologies and the utilization of lifecycle analysis.

With over 50% of the global economy reliant on healthily functioning ecosystems,[1] nature loss is a topic investors cannot afford to ignore. We believe understanding the two-way risks on nature and portfolios and managing them will be key to delivering value.

Barry Gill
Head of investments,
UBS Asset Management

Executive summary

Introduction

Climate and nature are so intertwined that impacts on one affect the other. This dynamic is evident worldwide. The energy transition is crucial for meeting our climate goals and protecting nature. From 2019 to 2023, deploying key clean energy technologies helped us avoid around 2.2 billion tons of emissions annually, nearly equal to the combined emissions of Japan, South Korea and Germany.[†] The anticipated growth in these technologies is critical to addressing our emissions budget challenge.

However, the scale of growth in clean technologies could negatively impact nature. This paper explains why we must remove our carbon blinkers when planning and executing for the energy transition and offers practical steps to achieve this balance.

† Technologies includes wind power, nuclear power, electric cars, and heat pumps.

Climate and nature are inextricably linked: Climate change is having dramatic effects on nature's ecosystems and biodiversity. And vice versa. Nature is an important regulator in the carbon cycle as it sequesters carbon, for example through forests and wetlands. If these land systems are degraded, they can turn from being carbon sinks to carbon sources. The Amazon is a case in point – its deforestation has been linked to such a tipping point, moving from a carbon sink to a source of carbon emissions.[2]

New energy technologies are central to the energy transition: The energy transition is replacing fossil fuel-based energy sources with technologies that can provide energy with a substantially lower carbon intensity. To do this, we need annual renewable energy use to increase at an average rate of about 13% between 2023-2030, twice as much as the average over the past five years. This massive scale-up will have co-benefits for the environmental in general; as a simple signpost, the extraction footprint – i.e., moving rocks and earth – of fuel required to power coal plants is at least 20 times the total mining footprint of onshore wind.[3]

But new energy sources also have an impact on nature: The scale of required growth in new energy sources has the potential to also impact nature. In this paper, we identify three key impacts common to the main renewables technologies — solar, wind and bioenergy:

1 Land use and site management:
The high energy density of fossil fuels means that replacing them with new energy technologies requires more land. This is true of the siting of solar and wind farms as well as the growing of feedstock for biofuels, which have impact on local nature.

2 Habitat loss and damage from the extraction of raw materials and their use:
According to the Energy Transitions Commission, between 2022–2050, the energy transition could require the production of 6.5 billion tonnes of end-use materials. 95% of these materials will be steel, copper and aluminium, along with smaller quantities of critical minerals and materials such as lithium, cobalt, graphite or rare earths. This will require us to ensure an extension in mining activities occurs in a sustainable and responsible way, will be key challenge for the transition.

3 Managing the input and output of waste:
New energy technologies represent an opportunity to use waste as an energy feedstock. However, the challenges associated with accounting for carbon emissions, where the emissions and value from so-called waste and residue feedstocks are often underestimated, can result in climate and biodiversity risks. On the flip side, we are also facing a waste management challenge once equipment from solar and wind farms comes to end of their useful life.

Mitigating impacts on nature: We set out three main approaches to mitigate these key impacts on nature.

These are:

Improving land management practices:
Biodiversity loss and damage can be limited for solar PV, wind power and bioenergy through environmental assessments and taking care to avoid siting projects in sensitive habitats, including protected areas and areas identified as high biodiversity value. There are also opportunities to actively improve biodiversity outcomes, particularly where projects are sited in areas of low biodiversity value.

Carrying out lifecycle analysis:
There is significant value and benefit from undertaking full lifecycle assessment of the natural capital impacts of energy transition technologies to identify the most impactful stages in a project's technology lifecycle. This is true for solar and wind and especially true for bioenergy, where the results of lifecycles assessments have highlighted which feedstocks should be avoided due to significant natural capital risks, including higher greenhouse gas emissions than fossil fuel equivalents in some cases.

Recycle and repair to reduce waste production:
For wind and solar energy projects, there is an emphasis on minimizing virgin material required for wind turbines and solar panels by extending the lifespan of equipment through repairs and upgrades, and by embedding circularity as a design principle (see case study on redesign of wind turbines). As older wind and solar projects come to their end of life, there is also an increasing need for companies to reduce end-of-life equipment waste through reuse and recycling.

Circularity solution to end landfill for turbine blades

Turbine blades are hard to recycle due the presence of epoxy resin, a widely used chemical substance that is challenging to break down. The market has been trying to find alternatives, but meanwhile tens of thousands of tons of wind turbines (manufactured with epoxy-based resin) are reaching the end of their lives and need to be recycled.

Danish wind manufacturer Vestas has partnered with other value chain actors on developing a novel process that can chemically break down epoxy resin into virgin-grade materials. These so-called new epoxies can be used in wind turbine blades. The company is now focussed on scaling this process commercially.

Focus on three key technologies

Focus on three key technologies: This report focuses on three foundational energy transition solutions: **solar, wind** and **bioenergy**. Solar and wind technologies consistently attract the largest share of investment. In 2020, solar photovoltaic (PV) alone attracted 43% of the total, followed by onshore and offshore wind (at 35% and 12%, respectively). In addition, second generation bioenergy is a high growth technology which needs to accelerate as indicated by the IEA Net Zero Emissions Roadmap. For each of these technologies we provide an outline of the key natural capital impacts, risks, and mitigation options across their respective lifecycles:

Solar photovoltaics (PV): Currently the fastest growing source of renewable energy globally, with solar PV generation up 26% from 2021 to 2022. The IEA forecasts solar PV capacity additions to increase to 672 gigawatts by 2028, over 65% above 2023 levels. To put that scale in context, it takes over 2.5 million solar panels to generate one gigawatt of power.

Most material natural capital impact	Mitigation methods
Land use and site management	– Site selection to minimize impacts and micro-siting infrastructure to avoid sensitive areas for wildlife within solar PV farm – Solar PV panel foundation's area can be minimized to reduce the impact on soil functioning and vegetation – Reducing water used for cleaning solar panels, particularly in arid areas where dust requires regular panel washing – Solar farm sites should be managed to improve habitats and biodiversity – Non polarising tape can be used to mark the edges of panels making them less attractive to insects
Life cycle analysis and materials	– Sourcing from metals and mining companies enforcing best practice environmental standards, such as the Initiative for Responsible – Mining Assurance, for setting up, operating and rehabilitating mines – Using recycled materials to manufacture solar panels; while this is broadly possible with aluminium, copper and glass, recycling silicon remains a key cost and technical challenge. – Repowering solar PV farms, a strategy that is already in use across many commercial operations
End-of-life waste	– Refurbishing and reusing old solar PV panels – Extracting working components (silicon cells and glass panels) for reuse in remanufactured solar modules – Extracting raw materials from old solar panels and recycling for use in solar panels or other industries – Solar PV panels can be designed for recycling

Wind power: Generation increased by a record 17% in 2022, and this trend will need to continue to meet the IEA's Net Zero Emissions Scenario trajectory, which envisages wind power reaching 21% of global energy generation by 2030. It takes 310 utility scale wind turbines to generate one gigawatt of power, and by some estimates, each 5-megawatt turbine requires around 900 metric tons of steel.

Most material natural capital impact	Mitigation methods
Land use and site management	– Site selection to minimize impacts and micro-siting infrastructure to avoid sensitive areas for wildlife within wind farm – Adapting technologies to increase visibility, installing acoustic systems to deter bats, applying automated image detection and radar to prevent bird and bat collisions, and raising wind turbine cut-in speed to minimise bat collisions
Life cycle analysis and materials	– Wind farm lifetime extension activities through upgrading existing turbine components – Using recycled materials to manufacture wind turbines – Repowering wind farms by replacing old turbines with more efficient ones – Sourcing from metals and mining companies enforcing best practice environmental standards for setting up, operating and rehabilitating mines
End-of-life waste	– Turbine blade refurbishment and reuse in wind farm lifetime extension activities – Developing novel commercially viable turbine blade material which can be recycled – Processing of materials into other useful materials or combustion in cement coprocessing

Modern bioenergy: Makes up around 6% of total primary energy supply globally. However, to accelerate modern bioenergy deployment in line with the NZE Scenario, deployment needs to increase by 8% per year between 2022 and 2030, while simultaneously ensuring that bioenergy production does not have a negative impact on natural capital.

Most material natural capital impact	Mitigation methods
Land use change	– Second generation bioenergy feedstocks can contribute directly and indirectly to land use change and associated habitat and biodiversity loss. – Use third-party sustainability certification schemes to provide third-party chain of custody certification to ensure bioenergy feedstocks are not sourced from high biodiversity or carbon value ecosystems, such as primary forests, protected areas, or threatened or endangered ecosystems – Examples include: ISCC, RSB, FSC
Underestimating carbon emissions	– The lifecycle carbon footprint of second generation bioenergy feedstocks is usually considered to be significantly lower than that of fossil fuels – however, these emissions could be underestimated with current accounting methodologies – Lifecycle assessments can provide a better understanding of the potential range of lifecycle carbon emissions from second generation bioenergy feedstocks
Ecosystem impacts from removing wastes and residues	– Nature has a purpose for everything, and our classification of forest and agricultural residues as 'waste' could have negative implications for soil health and ecosystem biodiversity – Due to the current lack of in-depth research and guidance, the main opportunities for companies aiming to mitigate ecosystem impacts from removing wastes and residues is to support more research into this area, alongside the development of best practice standards

Investment implications

Ignoring natural capital has investment risk implications for investors. The impacts and dependencies linked to nature are complex, location-specific, and are not easily substituted, even within the same company. While investors recognize the existential threat posed by natural capital degradation, they lack a roadmap for systematically factoring these risks into investment decisions. To manage natural capital risk properly (and to spot opportunities), investors require an understanding of how these risks impact the business model of companies and assets to help determine the risk premium and impact on cash flows. These risks can vary by sector, geography or even product.

The risks to nature that this report highlights represent many investment risks:

Land use and site management: Investment risk arises where land selection and site operation vary from recognised good practice. This may lead to conflict with key stakeholders such as government, regulators, and local communities. This risk is near term and affects the efficiency of design and the operational availability of the assets. It can also constrain the growth of the sector; in markets such as the US and Canada, studies have found growing opposition to wind energy projects across North America over time for reasons ranging from land use to wildlife impacts.

Growing regulatory scrutiny: Enhanced disclosure and transparency regimes, such as the CSRD and the recent EU deforestation regulation, are making companies vulnerable to regulatory and stakeholder scrutiny. Upcoming regulations like the EU Net-Zero Industry Act are backing the inclusion of non-price resilience and sustainability criteria, including supply chain management and environmental performance, when ranking public auction bids to build renewables capacity. Companies that have prioritised investments in building transparent supply chains and embedding circularity into design considerations already have an edge in expanding their market share vis-à-vis peers just starting to build their capabilities here.

Materials: Due to the projected growth of these technologies, the most immediate investment risk arises from the ability to purchase required materials and components in developing solar and wind projects, and to sourcing of inputs for second generation bioenergy. Projects that are unable to secure materials and inputs are exposed to the effect of changing economics on their overall investment returns and to growing sustainability risks. For example, meeting the IEA's forecast for global bioenergy feedstocks would require 100% of estimated used cooking oil and animal fats supplies; the tight supply in this market is already leading to fraud, for example, in the Netherlands, where investigations have found that a third of the used cooking oil feedstock could in fact be virgin oil biodiesel.

Wastes and residues: The wastes and residues that are the feedstock for second generation bioenergy represent a key operating and environmental risk, overseen by regulators, which can be mitigated by stronger use of lifecycle impact analysis and supply chain transparency. As the first generation of solar and wind assets approach the end of their lives, the risks involved in the challenges of recycling turbine blades and solar panels are becoming more prominent.

Due Diligence and Engagement are critical first steps, especially in the absence of reliable and comparable data. As capital providers and active owners, asset managers can raise awareness within investee companies and asset operators on the importance of understanding and measuring natural capital assets. Collaborative engagements such as Nature Action 100 and reporting benchmarks such as GRESB provide a platform for investors to ensure good corporate practice. The report contains suggested engagement questions at the end of each of the sections covering the three technologies of solar, wind and bioenergy.

Our objective: Maximize new energy investment and minimize impacts on nature

This report has been designed to be a practitioner's guide for improving due diligence on risks through understanding impacts on nature. Investors cannot do it alone and we invite all market participants to engage with the content of this report and assess how they can take it forward into their own spheres of influence – whether that is as a financier or investor in the energy system, or as a provider or consumer of new energies. After all, integrating natural capital into the energy transition will only be possible with the support of all key decision makers at every stage of planning, financing and implementation.

We hope this report helps investors and financiers have more meaningful discussions with companies on how they are embedding nature into their decision-making. This is only the start of the journey; the impacts and solutions we highlight in the report can lend themselves to help build metrics to better measure risks and opportunities. As we seek to build a more sustainable and resilient energy system, integrating nature into the energy transition can help to minimize any unintended negative impacts that would worsen the very climate crisis we are hoping to solve.

Solar power

Solar power

Material impact: For solar power, much of habitat loss and damage is driven by indirect land use change caused by mining for the metals and silica used to create solar power panels and associated infrastructure. Habitat is lost and damaged in clearing land for mine sites and extracting materials, as well clearing land for supporting infrastructure.

Best practice: It is important for developers to assess the risk of habitat loss and damage in their supply chains, prioritize solar panel lifetime extension activities and manufacture panels and components from recycled materials to reduce demand for virgin materials.

Material impact: Solar farms can have ongoing wildlife impacts through the day-to-day operation of the facility. In addition, preparing the site for a solar farm can include clearance of vegetation and soil which may be removed to level the ground. These activities can fragment habitats, disrupting species movement and migration as well as affecting wildlife hiding places, preying strategies and food availability

Best practice: Companies should continually assess their ongoing wildlife impacts during operation of their facilities and manage them with a view to minimizing negative impacts and promoting biodiversity, and commit to restoration of sites at the end of life.

Material impact: There is a growing wave of solar waste expected over the next few decades, yet recycling capacity remains small and underdeveloped due to low volumes of waste and the low value of recycled raw materials produced compared to the cost of recycling. Increasing the circularity of the solar industry is a key step in reducing the natural capital risk from the expected wave of old infrastructure.

Best practice: Increasing the circularity of the solar industry is a key step in reducing the natural capital risk from the expected wave of old infrastructure. Companies should recycle panels at the end of life either themselves, or via a credible partner, and support efforts to develop and scale solar waste recycling facilities and procure panels which incorporate recycled material.

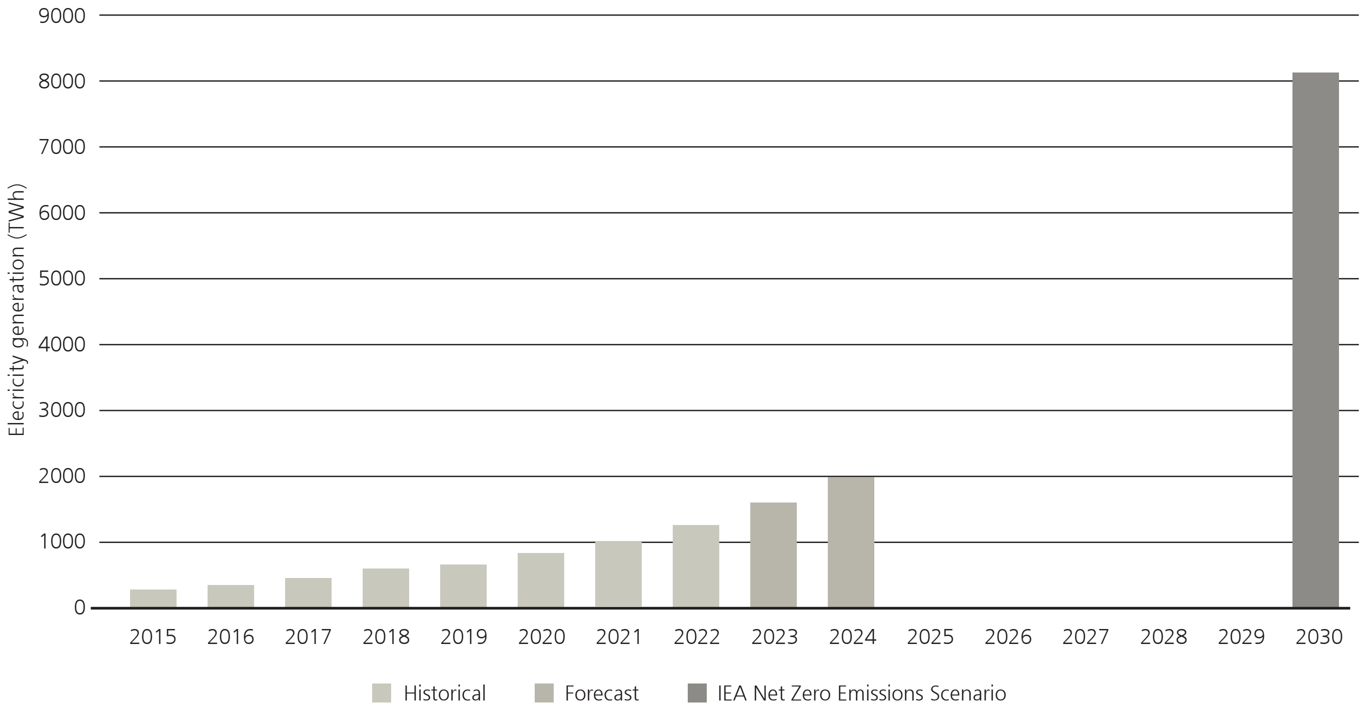
State of play and future demand

Solar photovoltaics (PV) is currently the fastest growing source of renewable energy globally, with solar PV generation up 26% from 2021 to 2022.[4] In 2022, solar PV made 4.5% (nearly 1,300 TWh) of the world's electricity up from 1.1% in 2015,[5] and utility-scale solar PV has also become the cheapest source of electricity in history.[6] Under the latest IPCC scenarios, solar PV is projected to triple by 2030, making up 23% of global electricity production[7] in line with the IEA Net Zero Emissions Scenario.[8]

This will require solar PV generation to increase by 25% each year to 2030.[9] Such extraordinary growth rates are likely to be made possible by the fact that the technology is easily mass produced, creating economies of scale, while at the same time the technology is also modular and can be deployed flexibly in very small quantities. This means applications can range from small residential roof-top systems to utility-scale power generation facilities. Indeed, IEA data for 2023 noted that spot prices for solar PV modules declined by almost 50% year on year, with manufacturing capacity reaching three times 2021 levels.[10]

Future growth in solar PV is projected to be on track to meet the climate targets and commitments outlined above.[11] This is largely due to the continued economic attractiveness of the technology, massive supply chain development (China doubled its solar PV manufacturing capacity in 2021[12]) and increasing policy support, particularly in China, the United States, the European Union and India.

Figure 1: Solar PV generation deployment needs to continue to grow



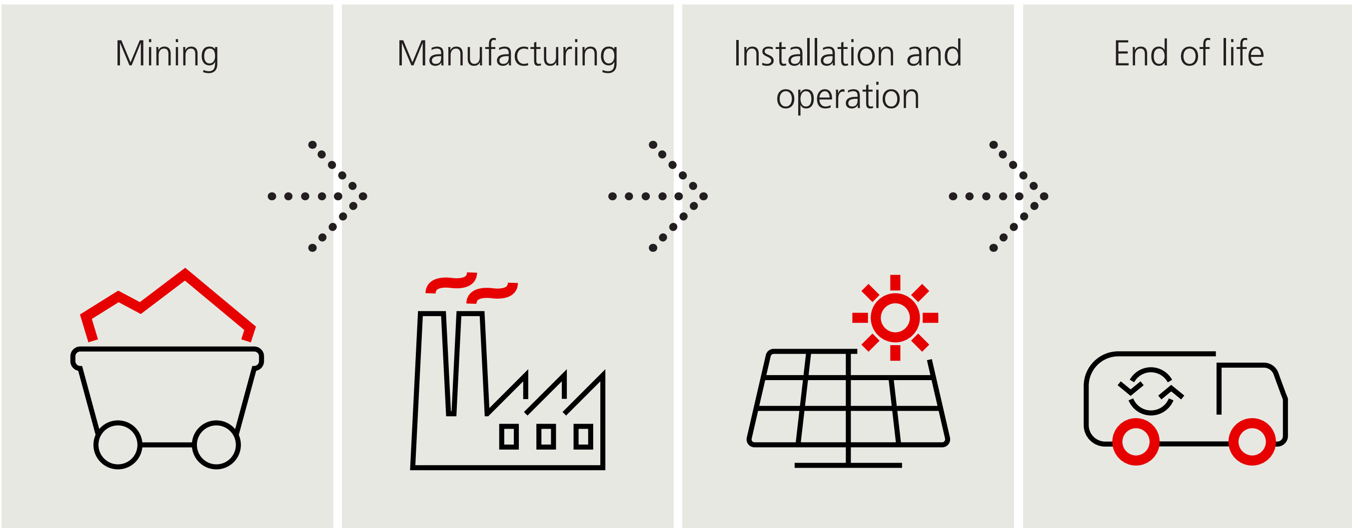
Source: IEA

What are the most material natural capital impacts for solar power?

Global solar PV capacity additions are expected to reach almost 672 GW in 2028 (accelerated case). To put that scale in context, the US Department of Energy notes that it takes 2.5 million solar panels to generate 1 gigawatt of power. Our analysis has found that estimates for environmental impacts of solar power vary depending on a variety of factors, including: the electricity mix during the manufacture phase, the type of cell used, the amount of solar irradiation the plant receives (which impacts efficiency), the assumed lifetime of a project and project size.[13] In this report we focus on the impact of large commercial solar PV farms (also known as utility scale solar PV) rather than distributed roof top solar projects.

What is clear is that across the full lifecycle of a solar power facility, manufacturing the panels and associated equipment, including mining and production of materials, creates the most significant natural capital impacts at more than 80% of the total impact (including greenhouse gas emissions).[14]

Figure 2: Solar PV lifecycle



Source: Planet Tracker (2024).

Greenhouse gas emissions of solar power across its lifecycle are driven primarily by the manufacturing and installation phase, notably the electricity intensive production of the panels.[15] The degree of emissions is influenced by the panel type (thin-film technologies are lower emission than silicon-based) and the location of manufacturing due to carbon intensity of the country's prevalent energy mix.[16] However, lifecycle CO_2 emissions from solar power are minimal compared to fossil fuel-based energy production.[17] A solar panel will typically have a carbon payback period of around 1.6 years, and a review of 40 years of photovoltaics development found that for poly- and monocrystalline based photovoltaic systems, "every doubling of installed photovoltaic capacity decreases energy use by 13% and 12% and greenhouse gas footprints by 17% and 24%, respectively."[18] In effect, greenhouse gas emissions during the production process are not material vis-à-vis other natural capital impacts.

Indeed, our analysis shows that the most material natural capital impacts of solar power are habitat loss and damage from the extraction of raw materials (for instance silica mining), habitat loss and damage from the creation of the solar farm site; wildlife impacts from the operation of the solar farm, and, end-of-life waste in the form of the degraded panels which include silicon, glass and metals.

We also found other likely impacts from solar farms. For instance, the installation of perimeter security fences could create a potential barrier to migration of larger animals. Scientific evidence on the size of this impact seems to be limited, but it has been shown to potentially impact species movement and range size.[19 20 21]

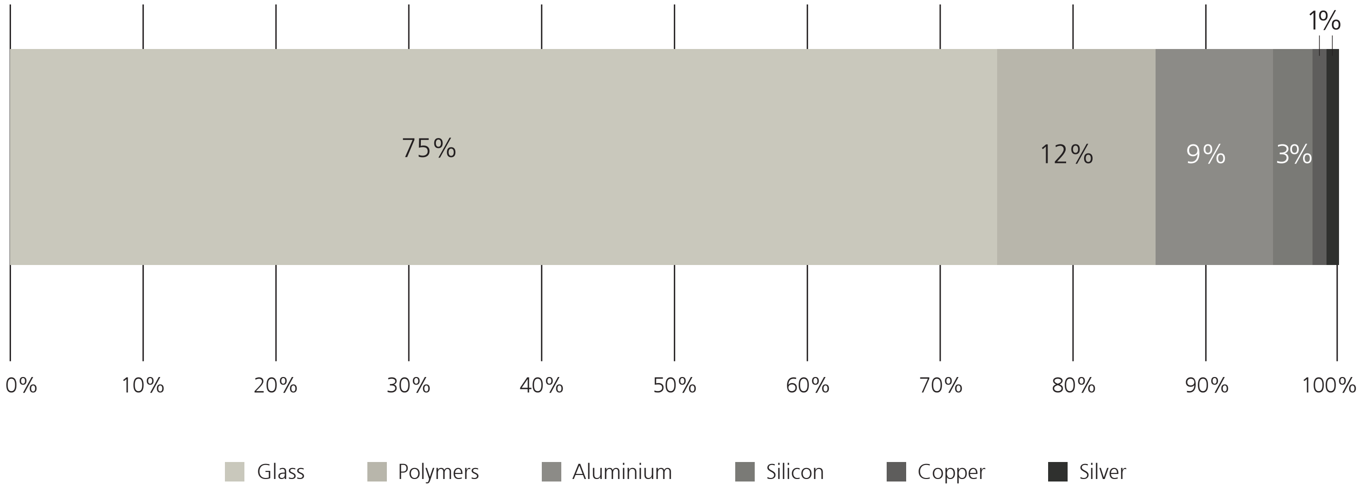
Many of these natural capital impacts create real risks to business, including legal and regulatory risks that may pause or halt solar power projects, and supply chain risks where natural capital impacts are embedded in solar farm component production. As solar power expands, these risks will evolve, particularly in jurisdictions where environmental regulation for the solar power and mining sectors is in its infancy but is likely to mature over the coming years.

Habitat loss and damage caused by solar PV from mining

A study from the University of California found that aluminium (bauxite) mining causes the most significant negative impact on biodiversity-rich habitats in Australia, Brazil, Suriname and Venezuela.[22] This study highlighted that while Venezuela and Suriname make up less than 1% of global aluminium mining, the two countries account for more than 20% of total aluminium-mining related biodiversity loss, highlighting that total metal production and mined area are often not directly correlated with biodiversity loss.[23]

In addition, mining for copper in Chile also has significant impact on biodiversity-rich habitats (mainly tropical forests), followed by Peru and Indonesia, posing risks to businesses in the solar power value chain.

Figure 3: Materials in a typical silicon solar PV cell by weight



Source: Peplow, M. Solar Panels Face Recycling Challenge. ACS Central Science 2022, 8, 299–302.

While this report focuses on the energy generation technologies (solar PV, wind power and bioenergy) it is worth noting that energy storage options will be associated with mining-related habitat loss and damage. Pumped-storage hydropower currently makes up over 90% of global electricity storage to balance variations in renewable electricity output,[24] but increasing use of grid-scale batteries has been projected to increase as costs decrease and more efficient technologies emerge.[25]

Historically, grid-scale batteries have been dominated by lithium-ion nickel manganese cobalt (NMC) chemistries, requiring nickel and cobalt which pose a particular risk to habitat loss and damage from mining in biodiversity rich rainforest ecosystems: 29% of nickel is mined in tropical forests in Indonesia, 14% in the Philippines and 8% in New Caledonia; while 75% of cobalt supply is from biodiversity rich forests in the Democratic Republic of Congo (almost exclusively as a by-product of copper).[26 27 28] While lithium mining often takes place in relatively low-biodiversity arid environments, it could have an increasingly significant impact on habitat and biodiversity loss and damage with the expansion of brine-based lithium extraction in China, Australia, Chile and Argentina, due to the development of evaporation pans/pools with a significant land footprint.[29]

However, battery chemistries are evolving rapidly, in many cases reducing or eliminating reliance on cobalt and nickel and reducing the associated risk of habitat and biodiversity loss.[30 31] This includes the rapid rise in the use of nickel and cobalt-free lithium iron phosphate (LFP) batteries which have overtaken NMC batteries as a cheaper option,[32 33 34] using iron and phosphate which pose a relatively lower risk to habitat and biodiversity loss from mining.[35] The use of sodium-ion batteries is also set to increase in use for grid scale batteries out to 2030,[36] mainly using chemistries that eliminate the need for cobalt and lithium and use either no, or relatively little, nickel[37] and present a lower risk to biodiversity loss from mining.[38]

It is worth noting that grid-scale batteries today do not make a significant contribution to overall demand for lithium-ion batteries (and mining for their metals): over 90% of demand is driven by the transport sector, a trend which is projected to continue up to 2030.[39] Other energy storage options are also being developed for grid-scale energy storage beyond batteries, including green hydrogen[40] and thermal energy storage.[41]

Demand for critical minerals, including concerns about supply security, geographical concentration and long mining project lead times, has opened up debates about mining the deep sea, which has been proposed as an alternative to conventional land-based mining for cobalt, copper and ferromanganese in particular (copper is the only metal directly significant to solar PV production). However, research by organisations including Planet Tracker,[42] the UN Environmental Program[43] and Flora and Fauna International[44] has noted the risks of significant permanent damage to deep sea ecosystems from deep sea mining. The deep-sea mining industry argues that there are options to mitigate these environmental harms by applying a mitigation hierarchy.

Deep sea mining is not currently taking place and has been attracting significant attention. The interests have accelerated as the International Seabed Agency is expecting to adopt regulations in 2025 and has already granted over 30 licenses for the right to mine, although none of them have started yet. We expect more guidance on environmental due diligence and impact assessment to ensure that operators, financiers and other potential investors understand the risks and opportunities that deep sea mining present.

Risks to business caused by habitat loss and damage from mining

There are a range of risks for businesses throughout the solar power value chain posed by mining-related habitat loss and damage. Downstream companies, such as project developers, may be exposed to supply chain risks where environmental permitting causes delays in bringing new mines into operation or stops mining projects from going ahead.

Companies may face reputational risks from sourcing from mines in sensitive (protected, biodiverse or wild) areas, which could become legal risks if local communities or NGOs take legal action against such projects. For example, the Wagina people of the Solomon Islands won a legal battle against a proposed bauxite (aluminium) mine development that they alleged would have taken 60% of their island home, clearing 2,000 hectares of virgin forest and causing significant impacts on the local habitats and the wildlife they contain.[45] The legal case highlighted the impact that this environmental damage would have on resident's livelihoods, with many people reliant on the land and sea for food, income, timber and other natural resources essential to their cultural heritage. A Lithium mine in the US state of Nevada has also faced challenges from conservation groups due to the risk it posed to an endangered wildflower (Tiehm's buckwheat),[46] with significant state financing depending on whether the mining company compled the environmental review process.[47]

Mitigation opportunities for habitat loss and damage from mining

A range of mature and emerging solutions exist to mitigate the impact of habitat damage and loss within solar power value chains. Solutions that aim to reduce the need to mine virgin materials in the first place can have the most significant impact on reducing mining-related ecosystem loss and damage. These include solar farm lifetime extension activities (solar panels have a lifecycle of 25-30 years)[48] and manufacturing panels from recycled materials. Where mining is still required, mitigation options focus on minimizing habitat loss and damage caused by mining, for instance supporting best practice environmental standards for mining operations.

Extending the life of solar farms can also mitigate habitat loss and damage caused by the construction of the farm by reducing demand for new sites. This can be achieved by repowering the site, with older panels which have reached the end of life replaced by new panels, extending the life of the solar farm.

Where new sites are constructed, full environmental impact assessment should be undertaken to determine how to minimize habitat impacts and sites should be chosen based on their relative lower impact.

Figure 4: Key mitigation options for reducing mining-related habitat loss and damage from solar farms

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Using recycled materials to manufacture solar panels. Particularly aluminium, copper and glass. For minimum impact, recycled metals can be manufactured using renewable energy.	■■■■■■■■■■■■■ **High:** Reduces the need for mining virgin materials to make solar PV panels. Impact can be even greater where recycled materials are sourced from old solar PV panels to reduce natural capital impact of panels entering landfill.	**Varied:** recycled aluminium, copper and glass is well readily available in most markets, but commercial scale silicon recycling technologies remain at the early stages of development.[49]	**Varied:** Cost of frequently recycled materials like aluminium, copper and glass is economically viable in many markets, but recycled silicon is significantly higher cost than virgin silicon while recycling technologies are developed.	Limited supply and high cost of recycled silicon as recycling technology is currently at the early stages of commercialisation. Recycled silicon can have lower performance in solar panels than virgin silicon.[50]
Repowering solar PV farms involves replacing or upgrading equipment including solar PV panels and inverters with the latest technology.	■■■■■■■□□□□□□ **Medium:** Repowering can reduce demand for new sites and increase the amount of electricity produced from the same area of land. However, significant expected growth in overall solar demand means more sites will be constructed even if all old ones are repowered. Repowering should be combined with old equipment recycling to reduce overall natural capital impacts further.[51]	**Already used in commercial operations.** There are a range of companies offering repowering services, e.g., BayWa r.e.[52]	■■□□□□□□□□□□□ **Low:** costs of new solar panels and other ancillary equipment such as inverters are much lower than older models, and today's PV technology is more cost-efficient, generating long-term savings.[53]	In some jurisdictions, getting permits for repowering can be resource intensive and time consuming, although some regulators (e.g., the EU) are actively trying to reduce permitting timelines for repowering.[54]
Sourcing from metals and mining companies enforcing **best practice environmental standards for setting up, operating and rehabilitating mines.**	■■□□□□□□□□□□□ **Low:** Sourcing materials from companies that comply with environmental legal standards and requirement for mining, or third-party sustainability initiatives such as The Initiative for Responsible Mining Assurance.[55] These aim to minimize some environmental impacts of mining, but operations will still cause significant ecosystem loss and damage.	**Varied:** There are significant gaps in monitoring or enforcement of environmental legal standards globally and low uptake of sustainable mining initiatives. Most mine rehabilitation is a process of trial-and-error, due to the lack knowledge of how ecosystems function.[56]	■■■■■■■■■■■■■ **High:** Limited data available on the cost to companies of implementing environmental standards. The cost to the Australian government of rehabilitating 50,000 abandoned mines[57] is estimated to be over AUD 1 billion.[58]	Environmental regulations for mining are often ignored by companies. E.g. over 50,000 abandoned mines in Australia[59], over 161,000 abandoned mines in the US[60] and over 10,000 abandoned mines in Canada.[61] All these jurisdictions have world-leading environmental regulations for mining.[62]

Source: Planet Tracker.

Habitat loss and wildlife impacts from installing and operating solar farms

Installing and operating solar farms take up significant amounts of land, which changes and fragments habitats.[63] Supporting infrastructure including electrical equipment and access roads, as well as the spacing requirements of solar panels can mean solar installations take up around 2.5 times the area of the panels alone.[64]

Preparing the site for a solar farm can include clearance of vegetation and soil which may be removed to level the ground. These activities can fragment habitats, disrupting species movement and migration as well as affecting wildlife hiding places, preying strategies and food availability.[65] Habitat fragmentation can lead to the decline of genetic diversity and thus resilience of species.[66] [67]

Particularly in arid regions, solar farms can also consume a significant proportion of available water to clean the panels, this can negatively impact wildlife due to changes in hydrology and water availability.[68] Finally, the operation of the solar farm can involve the use of herbicides and dust suppressants to help ensure the panels maintain full access to the sun. These can pollute local water sources and soils and reduce biodiversity directly.[69]

There has been academic work on collision risks associated with solar farms, where it is suggested that the way solar panels reflect and/or polarize light could confuse birds and bats. There have been suggestions that large PV arrays can confuse water birds which mistake them for lakes and collide with them, causing injury.[70] However, we note that there remains a lack of scientific evidence for bird and bat collision with solar PV, and further research into these ecological impacts of solar PV arrays is needed.[71] [72] [73]

Research has shown that insects (particularly aquatic insects) can be attracted to solar panels,[74] and have been seen to display egg laying behaviour on panels, suggesting they mistake them for open water bodies.[75] [76] The link to aquatic insects suggests this may be a particular issue where solar farms are located near water bodies. A concentration of insects over solar panels could attract predators in the form of birds or bats, raising the risk of collision with the panels,[77] but research to understand this issue remains scarce.

Risks to business caused by negative wildlife impacts from installing and operating solar farms

In more mature jurisdictions, such as the EU or UK, environmental impact assessments are recommended before construction begins.[78] [79] Businesses may face risks as regulation and policy aimed at minimizing or managing solar farm wildlife impacts changes, or, develops, in jurisdictions which are starting to deploy solar PV power. Mitigation measures might be required to reduce impacts on wildlife, and this may add costs to developments where more specific studies are required to better understand potential impacts.

Requirements to assess intended solar farm sites for potential habitat loss impacts could become more stringent over time, adding cost and time to the permitting and other regulatory approval processes. Policies to require development to display a net positive nature impact might be introduced and require developers to create wildlife habitats to offset those impacted by the solar farm construction. For example, in the Netherlands, the government has placed a high priority on nature protection and landscape-integration for solar PV projects, including a focus on dual-land use on solar farms such as introducing sheep grazing, food crop production and use of degraded land.[80]

Fines or litigation related to damage caused during the construction of solar farms is also a potential risk, with a few solar farms in the US penalized in recent years. For example, four solar farms located in Illinois, Alabama and Idaho faced issues related to the mismanagement of stormwater controls and construction permits, leading to sediment runoff into nearby waterways, and therefore were in breach of the Clean Water Act.[81] The fines were a result of failures to install and maintain proper stormwater controls, conduct site inspections, use qualified personnel for inspections, accurately report and address stormwater issues, and unauthorized discharge of sediment into waterways.[82] In 2024, the company involved in constructing these solar farms in Alabama, Idaho and Illinois[83] agreed to pay a USD 2.3 million penalty to resolve allegations of violating the Clean Water Act and related state laws. Additionally, the company will have to undertake mitigation actions to restore the Portneuf River in Idaho and restore habitats in the watershed surrounding the Alabama site.

Mitigation opportunities for wildlife impacts from installing and operating solar farms

The siting of solar farms is a major mitigation method to minimize wildlife impacts. Sites should be chosen which harbour lower biodiversity, have minimal impact on wildlife migration patterns and minimize the chance of degrading surrounding waterways and land (avoiding sites next to areas of high biodiversity).

During operation, the site should be monitored and managed with a view to maximizing biodiversity. For instance, control of vegetation should be done naturally where possible and with seasonal risks (such as bird nesting or insect foraging needs) borne in mind. Water withdrawals should be monitored and minimised, particularly during periods of drought.

Figure 5: Key mitigation options for reducing wildlife impacts during solar farm installation and operation

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Site selection to minimize impacts and **micro-siting** infrastructure to avoid sensitive areas for wildlife within a solar PV farm can help reduce negative habitat impacts. Developers should assess sites using environmental impact assessments (required by law in some jurisdictions) or adopt policies that adhere to best practice were legal requirements are weak or nonexistent	■■■■■■■■■■■■■ **High**: Being careful with selection of sites as solar farms can minimise their negative impacts. For instance, use of already degraded areas, avoiding areas of high biodiversity or floating solar farms. Micro-siting involves designing the farm to avoid placing infrastructure in areas sensitive for wildlife feeding, nesting, mating and migration within a solar farm site. Best practice includes maintaining vegetation as much as possible during solar farm construction and creating wildlife corridors for migration within sites.	**Varied:** Many jurisdictions have regulations around impact assessment for potential solar farm sites, e.g., France, Germany, Portugal, the Netherlands.[84]	■■□□□□□□□□□□□ **Low:** Assessment prior to construction has a relatively low cost.	Legal requirements for environmental impact assessments prior to construction vary by jurisdiction which can add costs and time to project development. A widely agreed upon tool for conducting environmental assessments on solar PV sites is lacking, even within some jurisdictions which require such assessments by regulation.[85]
Solar PV panel foundations area can be minimized to reduce the impact on soil functioning and vegetation. This is done by using posts on smaller pile driven or screw foundations which can leave more soil and vegetation intact than large concrete bases which remove large amounts of soil.	■■■■■■■□□□□□□ **Medium:** Smaller solar PV foundation minimise negative effects on natural soil functioning, such as its filtering and buffering characteristics, while maintaining habitats for both below and above-ground biodiversity.[86]	**Already used at commercial scale:** The use of posts with smaller pile driven or screw foundations is well understood and widely available.	■■□□□□□□□□□□□ **Low:** Lower impact solar PV foundations are widespread and cost effective.	Some smaller lower impact solar PV foundation options may not be suitable for certain locations – for instance some soil types and slopes may not providing a stable enough foundationor the panels.

Source: Planet Tracker.

Figure 5 (continued): Key mitigation options for reducing wildlife impacts during solar farm installation and operation

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Reducing water used for cleaning solar panels, particularly in arid areas where dust requires regular panel washing. Panels can be cleaned without water (e.g., with a dry brush) and revegetation under panels and around solar farms reduce dust, reducing cleaning requirements.	**Varied:** Revegetating areas under panels and around solar farms with native plant varieties can increase biodiversity and outcomes for wildlife, however there is little research into the effectiveness of this measure for dust suppression in different climates.[87] The "Mohammed bin Rashid Al Maktoum Solar Park" in the UAE uses robots with a dry brush to clean the PV without water.[88]	**Already used at commercial scale:** Revegetation and dry brush cleaning are already being deployed in commercial solar PV farms.	**Varied:** High tech solutions such as the use of dry brush robot cleaners have relatively high set up and maintenance costs. Revegetation is relatively low cost to implement and maintain, in environments where there is enough rainfall to maintain plant life.	Revegetation may be technically challenging in some more arid environments, e.g. desserts, where vegetation is naturally scarce. Some dry brush cleaning systems may be prohibitively costly, e.g., where the cleaning is carried out by robots.
Solar farm sites should be managed to improve habitats and biodiversity. This includes planting diverse vegetation with solar farms to attract pollinators and create foraging areas; creating green corridors for wildlife migration and nesting areas; switching from herbicide and pesticide use to animal grazing.	■■■■■■■■■■■■■ **High:** Solar PV farms can have higher biodiversity than surrounding agricultural or brownfield land when biodiversity focused revegetation is employed alongside creating green corridors for wildlife and replacing pesticide and herbicide use with animal grazing or manual trimming or hand pulling as has been demonstrated in the UK.[89]	**Already used at commercial scale:** Measures to promote biodiversity are well understood and applied on solar farms.[90] Some measures may be promoted by policy or regulation.[91]	**Varied:** The cost of interventions will vary by site (e.g. local climate, availability of information on local vegetation). Some interventions may be more costly than herbicide use – for instance seasonal hand management of vegetation levels.	Understanding exactly how to maximise biodiversity requires site-by-site assessment, and there is no one-size fits all solution.
Non-polarising tape can be used to mark the edges of panels making them less attractive to insects.	■■■■■■■□□□□□□ **Medium:** An experiment in Hungary showed adding tape could deter mayflies, stoneflies, long-legged flies and tabanid flies.[92]	■■□□□□□□□□□□□ **Not widely tested:** Although a low technology intervention, it has not yet been widely tested in the field.[93]	■■□□□□□□□□□□□ **Low:** Adding tape to panels is unlikely to be a highly expensive intervention.	N/A

Source: Planet Tracker.

End-of-life waste from solar farms

Nature positive opportunities for solar power: habitat creation and restoration

While habitat loss and damage may occur over the lifecycle of solar power facilities, there are also opportunities to restore and even create new habitats. Placement of solar farms on previously degraded or low quality land (such as contaminated land, or brownfield sites formerly used for industrial purposes) can offer the opportunity to improve the health of soils and local biodiversity if the site of the solar farm is appropriately managed.[94]

Through biodiversity positive management including revegetating land with a variety of local species and scheduling vegetation clearance/management to avoid breeding seasons, a solar farm can, in some cases, display greater biodiversity than the previous usage of the site.[95] [96] For instance, in an analysis of 11 solar farms in the UK, the authors suggested that solar farms have a greater diversity of vegetation, invertebrates and birds than surrounding agricultural or other brownfield land partly as a result of reseeding of solar farms and other land management practices.[97]

When a solar farm reaches the end-of-life (and assuming it is not slated for repowering) then the site can be decommissioned and wild habitats in the area restored. This can be positive, particularly if the original site chosen was significantly degraded prior to the construction of the solar farm.

We expect the issue of how to deal with end-of-life waste from solar farms will grow over the medium term as more farms reach the end of their productive lifespan. Much of the current installed capacity is expected to reach end-of-life by 2050.[98] At this point, some estimates suggest that solar PV waste as a percentage of new installations will reach 80%.[99]

The landfilling of solar panels can have significant negative natural capital impacts – it could require additional space for landfill sites (potentially leading to habitat destruction) and cause soil and/or watercourse contamination due to leaching of toxic substances such as cadmium, lead and silicon.[100] [101]

Risks to business caused by end-of-life waste from solar farms

With the significant growth in solar waste expected in the coming decades, solar farms are likely to come under increased scrutiny for the management of this waste. Moves to incentivize or mandate recycling as part of extended producer responsibility schemes could add costs to decommissioning sites.

Regulation on solar PV waste management varies by jurisdiction. For example, currently in the US there is no federal regulation requiring the recycling of solar panels. The lack of regulation means the US National Renewable Energy Laboratory (NREL) estimates only 10% of panels are recycled at the end-of-life.[102] The NREL estimate that currently the cost of recycling a solar panel is USD 15-USD 45 vs. only USD 1-USD 5 to send it to landfill.

In Europe, a drive towards responsible end-of-life management for solar PV modules has taken form in the Directive on Waste Electrical and Electronic Equipment (WEEE; Directive 2012/19/UE of the European Parliament and the Council),[103] according to which decommissioned PV panels are included as domestic and professional types of WEEE. This directive aims to promote the use of recycled materials in order to foster more efficient use of natural resources associated with PV production. Solar PV panel manufacturers are required to recover at least 80% of the panel mass at end of life,[104] and in countries like Germany, France and Italy companies are obliged to deal with panel waste, including reuse and recycling, at no cost to customers.[105] The UK[106] and the US state of Washington[107] have similar policies emphasizing manufacturer responsibility for solar panel end-of-life waste recycling.

Regulation incentivizing sustainable solutions and circularity

The European Parliament has backed the inclusion of non-price resilience and sustainability criteria when ranking public auction bids to build renewables capacity in the EU Net-Zero Industry Act. This further incentivizes companies to accelerate investment and progress in recycling and helps to connect strategy and financial materiality to impact. The criteria cover supply chain management, environmental performance, such as carbon footprint and energy efficiency, recyclability and circularity by design, as well as human rights and labour management quality.[108]

As solar PV expands and old sites come to their end of life, regulation encouraging the recycling of solar PV components is likely to develop, exposing businesses to regulatory risks. Risks from legal cases related to landfill leachate contaminating water or soil are possible, but likely low probability given the difficulty of proving causality and responsibility given the likely mixed waste stream involved in most landfills.

Mitigation opportunities for end-of-life waste from solar farms

Circular economy strategies are key for reducing the volume of end-of-life waste from solar farms. It is expected that 8 million tons of solar infrastructure will reach end of life by 2030 and 80 million tons by 2050.[109] The global average recycling rate of PV modules was around 14% in 2019 with the potential to reach 35% by 2030 and 70% by 2050, assuming a scenario with significant increases in recycling capacity.[110]

Several strategies have emerged to make solar PV panel recycling economically viable and keep materials in use for longer. Refurbishing and reusing old solar PV panels is one of the most impactful solutions, keeping panels in use for longer at a relatively low financial and environmental cost. Many decommissioned solar panels are still working but at around 80% of their original efficiency.[111] These panels are cleaned, inspected, refurbished, tested and resold in secondary markets (mainly in developing economies) at around 50% of the cost of new solar PV panels.[112]

Where solar PV panels are too damaged or inefficient to be reused, the next best option is to extract working components for use in remanufactured panels. However, due to the wide variations in solar cell structure and efficiency and solar module structure (e.g., glass panes are different sizes) scaling old component reuse can be challenging. For example, recycling companies would have to sell different varieties of components to different manufacturers as producing dozens of different types of solar modules in small quantities would not be profitable.[113]

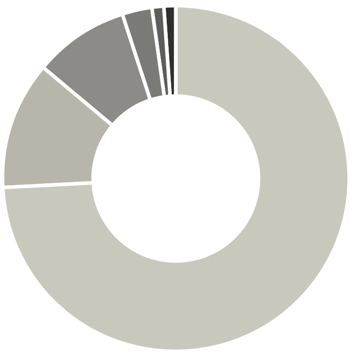
Another solution here, in theory, is the development of circular solar PV panels. An EU Horizon funded project PILATUS[114] has brought together 19 companies and research institutions to develop a pilot production line for circular solar PV panels, which are designed to be disassembled and the components reused and recycled. However, the lack of standardization of solar PV modules could make this challenging.

Where the components of a solar module are too damaged or inefficient to be reused, raw materials from solar panels can be extracted and recycled. Recycling can be done physically, thermally or chemically, and processes can use all three methods.[115] Physical recycling involves dismantling the aluminium frames, cables and junction boxes and crushing the solar panel. Thermal treatments, are used to recover glass by heating crushed panels in furnaces, while less commercially used chemical treatments use different solvents and chemical solutions to recover different elements of solar panels (e.g., silicon, silver and copper).[116]

Most commercial solar PV recycling companies currently only recover glass, aluminium and copper from solar panels that can easily be stripped from modules by mechanical methods.[117]

Figure 6: Materials in a typical silicon photovoltaic cell solar panel

Distribution of materials by mass



	% of total
Glass	75%
Polymers	12%
Aluminium	9%
Silicon	3%
Copper	1%
Silver	1%

Distribution of materials by value

	% of total
Glass	8%
Aluminium	26%
Silicon	11%
Copper	8%
Silver	47%

Source: Peplow, M. Solar Panels Face Recycling Challenge. ACS Central Science 2022, 8, 299–302

Recycled glass, aluminium and copper generates around USD 3 of revenue for a 60-cell silicon PV module,[118] which the International Renewable Energy Agency projects could create USD 15 billion in cumulative revenue by 2050.[119] However, it costs far more than USD 3 per module to collect and process waste solar PV panels and companies will require government subsidies or fees from solar module owners to be profitable.[120]

To improve the economic viability of solar PV panel recycling, various environmentally friendly methods for extracting other valuable materials such as silver are being developed. For example, the University of New South Wales is developing a stainless-steel ball-aided sieving technology to extract metals such as silver from crushed solar panels.[121] Researchers at the University of Virginia are also exploring the use of laser ablation to convert the silver electrical contact material into nanoparticles which can be used in new silicon solar modules without the need for further refining.[122]

As well as the need to recycle old panels, old inverters are also a source of potential recycling value. Inverters include metals such as copper and steel along with circuit boards. It is estimated that metals represent 60% of the weight of the inverter, and 90% of these metals are recyclable. Printed circuit boards make up the other 40% of the weight of the inverter, and it is suggested 65% of printed circuit boards are recyclable.[123]

A significant challenge to scaling the extraction and recycling of raw materials from solar PV panels is not only that it is more expensive than landfilling, but that there are not large enough volumes of waste panels at the moment to make it an economically viable business at scale. And the unpredictability of solar PV panel waste streams poses a challenge even in more mature recycling markets.[124] As the volume of PV waste increases, scaling recycling will become more viable. Estimates indicate that commercially viable volumes of solar PV waste will be generated before 2030 in developed markets such as Japan, Italy, the US and France.[125] This should help make solar PV recycling a more attractive business opportunity, along with greater regulatory support for solar PV recycling.

Figure 7: Key mitigation options for improving the circularity of solar farm infrastructure

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Refurbishing and reusing old solar PV panel. Many decommissioned solar modules still function but at around 80% of the original efficiency. They can be refurbished and reused in secondary markets at around 50% of the price of a new module.[126]	■■■■■■■■■■■■■■ **High:** Significantly reduces the need for mining virgin materials, by keeping old panels in use for longer with minimal new components. The process of refurbishing panels is also relatively low- environmental impact: panes are cleaned, visually inspected, repaired and tested.	**Already in operation at commercial scale.** Commercial solar panel reuse and refurbishment is established in many markets around the world, but remains neither systematized or standardized, and carried out by private companies without support from the original manufacturers.[127]	■■□□□□□□□□□□□□ **Low:** Requires the fewest and cheapest processing steps of all recycling options (cleaning, inspection, repair and testing). Higher costs for decommissioning, packaging and shipping to prevent damage to panels but this can be offset as refurbished solar panels can be sold in secondary markets at around 50% of the price of a new module.[128]	Not all old solar panels are suitable for refurbishment and recycling, especially where panels have been damaged. There may not be a big enough market for reused solar panels, as the cost of new modules is so low.[129] Reused solar panels are lower efficiency, have a shorter lifetime and can have more quality and safety issues compared to new panels. Reused modules will eventually stop working and will need to be recycled, requiring other strategies highlighted in this table.
Extracting working components (silicon cells and glass panels) from old solar PV panels for reuse in remanufactured solar modules. Old modules are cleaned and visually inspected before the junction box, its copper wiring and the aluminium frame are removed. The silicon cells are then separated from glass pane and polymers and working silicon cells and undamaged glass panes are recovered for reuse.	■■■■■■■□□□□□□□ **Medium:** Extracting working components is currently limited mainly to glass panes (if they are extracted intact and clean) and silicon cells (if they are extracted with good efficiency and can still be soldered to other components). Other components may end up in landfill, potentially causing environmental damage due to leakage of toxic chemicals if not managed properly.	**Already in operation at commercial scale.** Old components are already extracted and reused around the world, but this is limited by the cheap cost of new components.	■■■■■■■□□□□□□□ **Medium:** Higher costs for decommissioning, packaging and shipping to prevent damage to panels but this can be offset as components are relatively high value, at around 50% of the price of new components.[130]	Only solar glass panes and silicone cells can currently be extracted for reuse in new panels. Other components (e.g., aluminium frame and junction box case) often cannot be removed from solar modules without being damaged and are unfit for reuse. Old components can only be reused if their performance is comparable with newly produced components, and many of the oldest solar cells are too inefficient to be reused. Wide variations in solar cell structure and efficiency and solar module structure (e.g., glass panes are different sizes) pose a challenge to scaling old component reuse.

Source: Planet Tracker.

Figure 7 (continued): Key mitigation options for improving the circularity of solar farm infrastructure

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Extracting raw materials from old solar PV panels and recycling for use in solar panels or other industries. Solar modules are cleaned and visually inspected before the junction box and aluminium frame is removed. Ideally the silicon cells and copper ribbons are then separated from the glass and polymers and metals are extracted from the cells. Raw materials can then be used in other industries, or if they are high enough quality can be used in solar PV manufacturing.	■■■■■■■□□□□□□ **Medium:** Recovery of glass, aluminium and copper from solar PV panels is already possible and in commercial use using low-environmental impact mechanical methods and reduces the need to mine these virgin materials.[131] However, technologies are still under development for separating silicon cells and copper ribbons from glass and extracting metals from non-silicon panel layers and these materials are often sent to landfill or incineration. Established chemical and thermal extraction methods for these materials can be both expensive and environmentally harmful due to the use or release of toxic chemicals and high energy requirements.[132] If high levels of recycling can be achieved, this would mitigate much of the coming "wave" of PV waste expected over the next decades.[133] Mechanical methods are being explored, e.g., University of New South Wales are developing a stainless steel ball-aided sieving technology to extract other metals such as silver from solar panels.[134]	**Varied:** Recovery of glass, aluminium and copper is already in operation at a commercial scale, e.g., US company First Solar has been recovering and recycling over 90% of solar module materials at a commercial scale since 2005, and now has international operations.[135] [136] However, technologies for separating silicon cells and copper ribbons from glass and extracting metals from non-silicon panel layers are yet to be commercialised at scale.	**Varied:** Mechanical separation and recovery of glass, aluminium and copper are relatively low-cost processes, but technologies for chemically and thermally extracting other materials (e.g., silicon and silver) are more expensive and are yet to be made commercially viable at scale. Lower cost mechanical extraction of silver is being explored by University of New South Wales.[137]	Recovery currently focuses on glass, aluminium and copper, due to being technically easier and cheaper to extract. Developing economically and environmentally viable methods to extract other materials is challenging. There are not yet large enough volumes of solar PV panel waste to make recycling economically viable at scale in most markets and the unpredictability of solar PV panel waste streams poses a challenge even in more mature recycling markets.[138] Landfilling is a cheaper option than recycling solar PV panels, due to the relatively high cost of collecting and processing old panels to extract raw materials.[139] Regulatory and policy support is currently needed to make recycling economically viable. Raw materials extracted from solar panels can be relatively low[140] and low quality, e.g., if recycled glass is contaminated with metals, it is not high enough quality to be reused in solar PV panel manufacturing.[141]
Solar PV panels can be designed for recycling. However, with the long lifecycle of panels, changes made today will only impact in a few decades.	■■■■■■■■■■■■■ **High:** Current panels are difficult and costly to disassemble in their entirety despite the value of some of the components, i.e., silver, copper, silicon. Panels which are easy to disassemble would be attractive to allow these valuable inputs to be reclaimed.	**At research and development stage:** Ideas for how to design for recycling are yet to reach pilot phase testing. Horizon funded project PILATUS is developing a pilot production line for circular solar PV panels, which are designed to be disassembled and the components reused and recycled.[142]	■■■■■■■■■■■■■ **High:** Significant research is needed to find appropriate technologies that provide high functionality but ease of disassembly.	The science of how to do this is still in its infancy. Long life cycles mean changes now only benefit in a few decades making economics difficult. Lack of standardisation of solar PV modules could make this difficult to scale.

Source: Planet Tracker.

Engagement questions for minimizing natural capital impacts from solar power

Figure 8: Minimizing natural capital impacts from solar power

Recommended questions

1

What actions are being taken to engage with metals and mining companies to assess and minimize habitat loss in relation to sourcing solar panel materials and components?

To what extent are solar farm lifetime extension activities being planned to reduce reliance on virgin materials?

How much recycled material is currently being used in new infrastructure and what investment is planned to increase this?

2

What actions have been taken to assess the potential impact on biodiversity in the design and installation of the solar facility? What designs steps have been taken to reduce the impact?

What actions have been taken to reduce the impact on biodiversity in the installation of the solar facility, including prioritizing the use of degraded land?

What actions have been taken to promote biodiversity during operation of the solar facility? Are pesticides or dust suppressants used in solar facility operations? If yes, are there plans to phase these out?

Has the project committed to monitoring its ongoing impacts and rewilding of the site at the end of life?

3

What measures are being taken to ensure that the solar farm infrastructure will be recycled at the end of life?

What research and development is being conducted for solar waste recycling?

Wind power

Wind power

Material impact: Wind power is estimated to have the lowest natural capital impact compared to fossil fuels, solar PV and other renewable energy technologies. For wind power, most of the habitat loss and damage is driven by indirect land use change caused by mining for the iron ore (for steel) used to create wind turbine towers and copper for turbine generators. Habitat is lost and damaged in clearing land for mine sites and extracting materials, as well clearing land for supporting infrastructure.

Best practice: Companies should assess the risk of habitat loss and damage in iron ore/steel and copper supply chains. Companies should also prioritise wind farm lifetime extension activities and manufacture turbines from recycled materials to reduce demand for virgin materials. Other measures to mitigate mining-related habitat loss and damage may include repowering wind farms which replaces old turbines with fewer new ones and supporting best practice environmental standards for mining operations.

Material impact: The issue of bird and bat collisions with wind turbines attracts considerable attention in policy, regulation and in the media, and companies face legal risks from failing to tackle this issue. Impacts on other species require more research.

Best practice: Companies demonstrate that they are including bird and bat collision risk as part of environmental impact assessment (EIA) before setting up wind farms. At the project design phase, companies provide evidence of locating windfarms or turbines and other infrastructure away from sensitive areas for wildlife and altering wind farm layouts to minimize barriers to movement with the overall aim of decreasing risk of mortality and injury for wildlife. Where significant bird and bat collision risks remain, companies demonstrate that they have implemented measures to minimize impacts where possible, including modifying wind farm infrastructure or temporarily shutting down turbines to minimize impacts on wildlife. All of the above may be legally required.

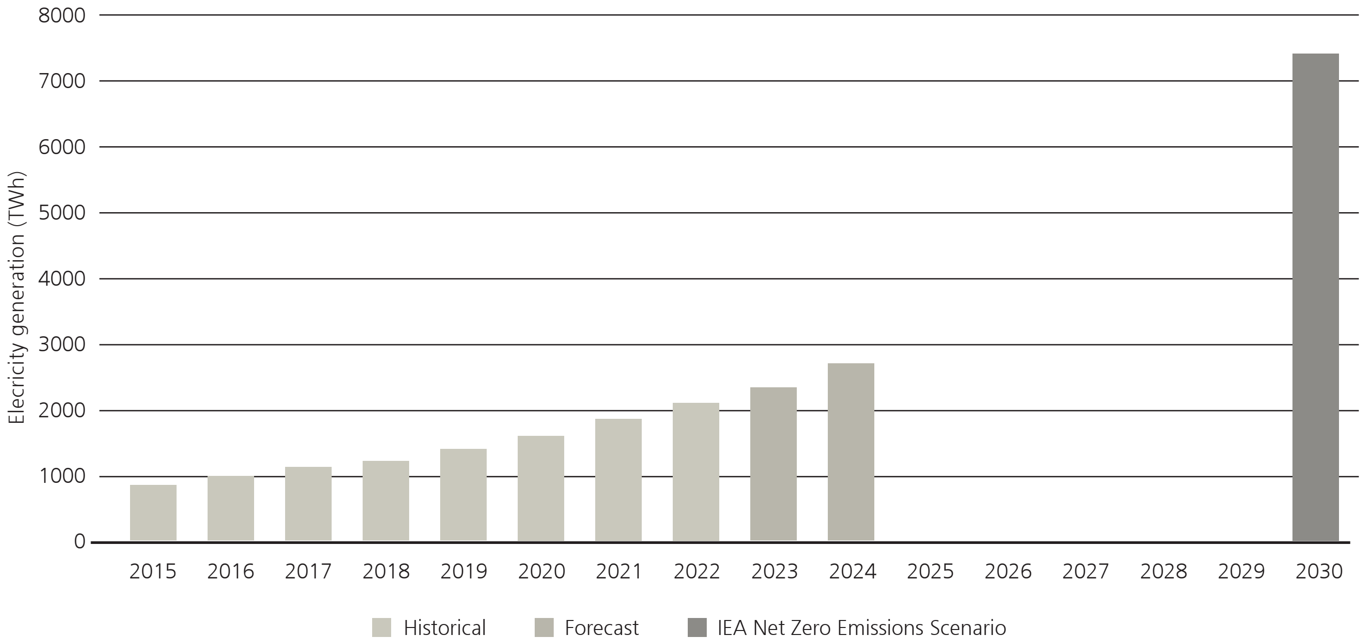
Material Impact: Wind turbine blades are currently the largest non-recyclable element of wind turbine infrastructure, as they are made from composite materials. Techniques for recycling composite materials are currently under development and are yet to be implemented at commercial scale.

Best practice: Companies demonstrate that they are focus on reducing waste in the first place by extending the useful life of wind turbine blades through refurbishment and reuse wind farm lifetime extension activities. More forward-looking companies are supporting the development of solutions focused on creating turbine blade materials that may be easier to recycle into more turbine blades, while other less impactful options broadly mean downcycling turbine blades into materials that can be used in other sectors.

State of play and future demand

Wind is currently a major source of renewable energy and is projected to be a key energy transition technology alongside Solar PV. Onshore and offshore wind turbines generated 7.6% (over 2,100 TWh) of the world's electricity in 2022, more than double the share in 2015 (3.5%).[143] Wind power generation increased by a record 17% in 2022, and this trend will need to continue to meet the IEA's Net Zero Emissions Scenario trajectory, which envisages wind power reaching 21% of global energy generation by 2030.[144]

Figure 9: Wind power generation in the IEA Net Zero Scenario, 2015-2030



Source: IEA (2023)

Onshore wind has developed rapidly in the last five years with increased turbine efficiency which allows for sites with lower wind speeds. Currently over 90% of total wind power generation is onshore, but the share of offshore is set to increase as it becomes more efficient and cheaper to deploy.[145] Onshore wind power is now cheaper than generating electricity from fossil fuels in most countries.[146]

Investments in wind power increased by 20% in 2022 to a record USD 185 billion, rebounding after a slowdown in 2021.[147] This is the second largest amount of investment among all electricity generation technologies (including fossil fuels) after solar PV,[148] and it is expected to grow significantly in future years, driven by ambitious government targets, policy support and a highly competitive market.

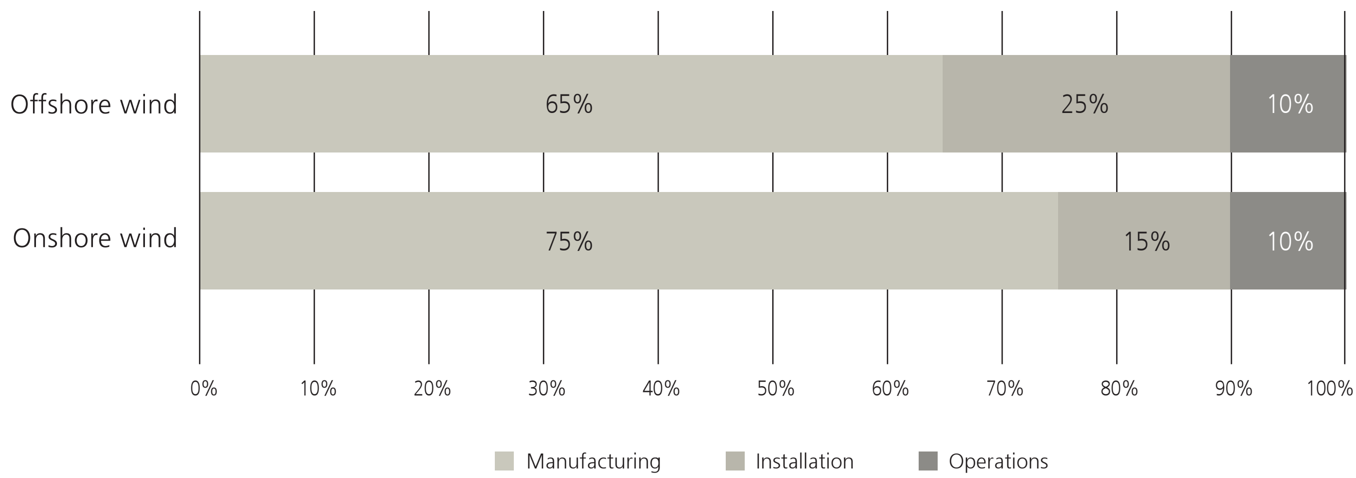
Wind power is set to develop more quickly in some countries and regions than others. China is currently on track to see the largest growth in wind power in the mid-term, followed by the EU and the US, driven by supportive policies.[149] In contrast, little wind power generation has been established in Middle Eastern and African countries and most countries in these regions do not have the policy or regulatory support in place to drive growth in the medium term.

What are the most material natural capital impacts for wind power?

Estimates for environmental impacts for the lifetime of a wind power project vary depending on a variety of factors, including: whether a wind facility is onshore or offshore, the turbine technology, the assumed lifetime of a project, turbine size and capacity factor. For examples, offshore wind farms require more steel for turbine foundations than onshore wind farms, resulting in a greater overall natural capital impact. Different turbine technologies use different volumes and types of materials, with heavier, more metal-intensive technologies having bigger environmental impacts. Newer, bigger turbines are more efficient.

Overall, however, wind power is estimated to have the lowest natural capital impact compared to fossil fuels, solar PV and other renewable energy technologies.[150] A study by the UNECE found that wind power demonstrated the lowest impact compared to all other energy sources across categories such as land and water use, materials use and climate change. However, as the number of wind farms increases, these impacts will become more material. Research on the environmental impacts of a wind power facility show that across the full life cycle, manufacturing wind turbines creates the most significant impacts (when including both carbon and natural capital impacts).[151] Offshore wind installation impact is increased by the shipping vessels required to transport turbines to wind farm sites.

Figure 10: Estimated average lifecycle natural capital impacts from onshore and offshore wind



Source: Torres, Jaime Fernández, and Fontina Petrakopoulou. "A Closer Look at the Environmental Impact of Solar and Wind Energy." Global Challenges 6, no. 8 (2022): 2200016.

Greenhouse gas emissions (carbon dioxide and methane) are the most significant natural capital impact of wind power across its lifecycle,[151] driven by the fossil fuel intensive production of steel (and iron ore) for turbine towers, composite turbine blade materials (fibre-glass reinforced resins or plastics) and cement foundations. Over 12 million tons of steel were estimated to have been used to produce wind turbines in 2021,[153] which amounts to less than 1% of total global steel demand.[154] However, lifecycle CO_2 emissions from wind power are minimal compared to fossil fuel-based energy production. CO_2 emissions from producing and installing a modern wind turbine are paid back within 6 months of operation for onshore facilities and in less than a year for offshore facilities.[155] As such, CO_2 emissions are not considered material for this sector.

Beyond emissions, the most significant natural capital impacts of wind power are habitat loss and damage from mining metals (copper and iron ore); wildlife impacts from operating wind turbines; and end-of-life waste in the form of turbine blades which are made from composite materials that cannot currently be recycled;

Environmental lifecycle assessments of wind power usually include other less significant natural capital impacts from producing steel and composite turbine blade materials, which produces sulphur dioxide and nitrogen oxide emissions that contribute to acid rain and eutrophication (nitrogen oxide emissions only), as well as toxic substance pollution all of which cause ecosystem damage.

Overall, however, wind power's contribution to these issues is minimal compared to other sectors, such as heavy industries and agricultural production, and makes a minimal contribution to these three broad issues: acid rain is mainly driven by burning fossil fuels, most toxic pollution is also caused by burning fossil fuels, as well as heavy and chemical industries and eutrophication, is largely driven by agricultural production.

Natural capital impacts can create real risks to business, including legal and regulatory risks that may pause or halt wind power projects, and supply chain risks where natural capital impacts are embedded in wind turbine component production. A recent study found growing opposition to wind energy projects across North America over time: between 2000 and 2008, 13% and 8% of wind projects in the United States and Canada, respectively, experienced opposition; these numbers grew to 19% and 21% between 2009 and 2016.[156] The reasons for opposition remain varied, including project characteristics such as farm size and height of the turbines as well as perceived noise and disruption to the landscape. However, the study found that a direct impact on wildlife (or a perception of such impact), can also serve as a predictor of community opposition to projects.

Our analysis found many mature and emerging mitigation solutions have been developed to reduce or minimize the natural capital impacts and associated risks across the lifecycle of wind power. Some natural capital impact mitigation solutions, like risks to bird and bats in wind farm operations, are baked into legal restrictions or regulatory requirements in some more advanced jurisdictions, such as within the EU. This could provide an indication of how regulation will develop in jurisdictions that are beginning to deploy wind power.

Some mitigation options can reduce multiple natural capital impacts. For example, when wind turbines reach their end of life, there are significant circular economy opportunities which may reduce the need for mining raw materials to produce the same amount of power, including lifetime extension (upgrading existing components), repowering (replacing old turbines with fewer new ones) and recycling materials when turbines reach their end of life. Recycling alone can reduce the natural capital impacts from manufacturing wind turbines by at least a third.[157]

Mining-related habitat loss and damage caused by wind power

Habitat loss and damage, driven by land use change, is one of the most significant natural capital impacts over the lifecycle of a wind power facility. Little direct land/seabed is required for wind turbines themselves. Onshore wind turbines typically take up less than 10% of the area of a wind farm[158] and the land between turbines can be used for other activities, including nature positive solutions.

Our analysis shows the majority of habitat loss and damage is driven by indirect land use change caused by mining for the iron ore (for steel) used to create wind turbine towers and copper for turbine generators, which generates electricity as the turbine blades turn.[159] Habitat is lost and damaged in clearing land for mine sites and extracting materials, as well as clearing land for supporting infrastructure.

As steel (made from iron ore) makes up 80%-90% of the mass of a wind turbine, this is the most material metal to focus on in terms of understand mining-related habitat loss and damage. Iron ore production in Brazil, which makes up about 18% of total global supply,[160] has been highlighted as having a particularly high impact on biodiversity-rich habitats.[161] The worst impacts are concentrated in the Amazon rainforest – one study showed that iron ore mining accounted for only 8% of the area occupied by mining in the Amazon, it made up over 60% of the value of traded production in 2017 (just over 8 billion USD).[162]

Copper mining in Chile has the most impact on biodiversity-rich habitats, followed by Peru and Indonesia, mainly due to mining in tropical forests. Where materials for wind turbines are sourced in or near these sensitive areas, the impact of habitat loss and damage will be greater, including biodiversity loss.[163]

> Where materials for wind turbines are sourced in or near these sensitive areas, the impact of habitat loss and damage will be greater, including biodiversity loss.

Risks to business caused by mining-related habitat loss and damage.

There are a range of risks for businesses throughout the wind power value chain posed by mining-related habitat loss and damage. Downstream companies, such as project developers, may be exposed to supply chain risks where environmental permitting causes delays in bringing new mines into operation or stops mining projects from going ahead. Companies may face reputational risks from sourcing from mines in sensitive (protected, biodiverse or wild) areas, which could become legal risks if local communities or NGOs take legal action against such projects.

An example of this is First Quantum Minerals' Cobre Panamá open pit copper mine in Panama, located in a biodiverse area of jungle on Panama's Atlantic coast, which was one of the largest copper mines opened globally in the last decade.[164] The Government of Panama announced the closure of the mine in November 2023, after its Supreme Court ruled that the 20 year concession granted to First Quantum Minerals was unconstitutional.[165] The mine had triggered mass protests, including concerns on the mine's environmental impact on the biodiverse jungle and depleted water in the area.[166] Protesters were also concerned that the concession favoured the mining company over providing revenue for Panama.[167] The mine began producing copper in 2019, accounting for around 1% of global copper output.[168] Protesters created road and sea blockades which eventually forced First Quantum Minerals to suspend its operations in early November.[169]

Mitigation opportunities for mining-related habitat loss and damage

A range of mature and emerging solutions exist to mitigate the impact of mining-related habitat damage and loss within wind turbine value chains. Solutions that aim to reduce the need to mine virgin materials in the first place can have the most significant impact on reducing mining-related ecosystem loss and damage. These include wind farm lifetime extension activities and manufacturing turbines from recycled materials. Where mining is still required, mitigation options focus on minimizing habitat loss and damage caused by mining, mainly: repowering wind farms which replaces old turbines with fewer new ones and supporting best practice environmental standards for mining operations. These metals supply chains are often relatively short, with wind turbine manufacturers having direct relationships with the companies that both mine and manufacture metals.[170] This presents an opportunity an opportunity for direct engagement on assessing risks and developing mitigation opportunities for mining-related habitat loss.

Figure 11: Key mitigation options for reducing mining-related habitat loss and damage from wind turbine manufacturing

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Wind farm lifetime extension activities: Existing turbine components are upgraded to extend windfarm lifetime from 20-25 years up to 35 years.[171]	■■■■■■■■■■■■■ **High:** Significantly reduces the need for mining virgin materials, by increasing the capacity and efficiency of existing wind farms. Also reduces need to new wind farms and associated impacts.	**Already used in commercial operations.** Lifetime extension of 5-10 years is projected for half of Europe's existing wind farms.[172]	■■□□□□□□□□□□□ **Low:** Estimates from Germany and Spain range from EUR 5,000 – EUR 15,000 per turbine,[173] compared to EUR 1.1 – EUR 4.5 million[174] for one onshore wind turbine.	Not all wind turbines are suitable for lifetime extension, particularly older technologies where replacement parts are no longer manufactured. Uncertainty over future electricity spot market prices which determine the economic feasibility of lifetime extension.
Using recycled materials to manufacture wind turbines. Particularly steel which comprises 80%-90% of a turbine's material mass. For minimum impact, recycled metals can be manufactured using renewable energy.	■■■■■■■■■■■■■ **High:** Reduces the need for mining some virgin materials, particularly iron ore. Recycled steel is currently suitable for use in entire onshore turbine towers (52% lower emissions than conventional steel) and the top section of offshore turbine towers.[175]	**Commercial scale use scheduled for 2025.** E.g., Vestas will be using recycled green steel supplied by ArcelorMittal in its Baltic Power Offshore Wind project in Poland.[176]	**No data available**	Limited supply of recycled steel made with renewable energy and limited or non-existent supply of other recycled materials for turbine components. Recycled steel can currently only be used in the top section of offshore wind turbine towers.
Repowering wind farms by replacing old turbines with (fewer) new, larger, more efficient ones on the same site.	■■■■■■■□□□□□□ **Medium:** Reduces the number of turbines on existing sites by 27% on average[177] while increasing energy output and reducing need for new wind farm sites. However, virgin materials are still required to make new turbines.	**Already used in commercial operations.** E.g., ACCIONA Energía is replacing 90 old turbines with 13 new ones in Tahivilla, Spain.[178]	■■■■■■■■■■■■■ **High:** Initial costs are high e.g., ACCIONA Energia is investing EUR 120 million in its Tahivilla project.	Getting permits for repowering can be resource intensive and take many years in some jurisdictions. Getting regulatory approval and funding to upgrading electricity grid connections for more powerful turbines can be challenging.
Sourcing from metals and mining companies enforcing best practice environmental standards for setting up, operating and rehabilitating mines.	■■□□□□□□□□□□□ **Low:** Where possible sourcing materials from companies that comply with environmental legal standards and requirement for mining, or third-party sustainability initiatives such as The Initiative for Responsible Mining Assurance. These aim to minimize some environmental impacts of mining, but operations will still cause significant ecosystem loss and damage.	**Varied:** There are significant gaps in monitoring or enforcement of environmental legal standards globally and low uptake of sustainable mining initiatives. Most mine rehabilitation is a process of trial-and-error, due to the lack knowledge of how ecosystems function.[179]	■■■■■■■■■■■■■ **High:** Limited data available on the cost to companies of implementing environmental standards. The cost to the Australian government of rehabilitating 50,000 abandoned mines[180] is estimates to be over AUD 1 billion.[181]	Environmental regulations for mining may be ignored by companies. E.g., there exist over 50,000 abandoned mines in Australia,[182] over 161,000 abandoned mines in the US[183] and over 10,000 abandoned mines in Canada.[184] All these jurisdictions have world-leading environmental regulations for mining.[185]

Source: Planet Tracker.

Nature positive opportunities for wind power: habitat creation and restoration

While habitat loss and damage occur over the lifecycle of wind power facilities, there are also opportunities to restore and even create new habitats.

Onshore wind farms provide opportunities to create wildlife corridors or habitats for pollinators or other species due to reduced human traffic and increased availability of food.[186] The nature positive management of onshore wind power sites on agricultural land can also include reducing pesticide or fertilizer use.[187]

Offshore wind farms have a stronger potential to create new habitats, where the submerged parts of turbines act like artificial reefs which can increase the abundance of certain species, including local rare species and habitat-forming species that further increase habitat complexity.[188] Species may also include nonindigenous ones that are extending their spatial distributions or increasing their populations. While wind farms cause the loss of seabed in their direct footprint, the reef effect they produce has been shown to attract more fish than natural reefs.[189] This positive impact is more significant when turbines are located in homogenous low biodiversity areas of sea bed where turbines provide hard surfaces to create reefs and attract more biodiversity.

Offshore wind farms also prohibit bottom trawling fishing and stop other vessels from accessing the surrounding area, which can protect marine wildlife, creating de facto marine reserves.[190] This has been shown to boost fish populations and can increase catches in surrounding fisheries by 7%.[191]

Wildlife impacts from installing and operating wind farms

Most studies and regulation on the nature impacts of both onshore and offshore wind farms have focused on injury and mortality to birds and bats caused by collision with wind turbines.[192] However, little is known about how species may be affected at a population level and there is a limited understanding of how wind turbines might impact other wildlife taxa, including non-flying animals.[193]

The main impacts to birds and bats are injuries and fatalities from collision with onshore and offshore turbines.[194] While this has received much attention in discussions, policies and regulations, existing research shows wind turbines cause only a tiny fraction of total bird and bat fatalities. The actual bird and bat mortality from collisions with wind turbines is not easily quantifiable and estimates vary significantly. The average number of collisions per wind turbine per year were estimated to be 8 in Canada,[195] 7 in France[196] and 3 in Japan.[197] A 2013 study estimated that between 140,000 and 328,000 birds were killed by onshore wind turbines annually in the United States,[198] accounting for an estimated 0.007% of total bird mortalities nationally.[199] On the flip side, an estimated 95% fewer birds are killed by wind turbines versus the impacts of climate change.[200] Other factors, such as collisions with vehicles and cars, impacts from agriculture, pollution and urban expansion are much larger contributors to bird and bat mortality.[201] Recently, turbines have become taller, with larger areas swept by turbine blades and with turbines placed further apart. Despite larger blades, newer turbines usually have a lower collision rate per MW for birds than older, smaller models.[202 203]

There are several factors that might increase the risk of bird and bat collisions with onshore and offshore wind turbines. Birds that are larger and less agile (and are therefore less able to change direction to avoid wind turbines) face greater collision risk,[204] as do those that fly in low light conditions at dawn or dusk, as there is less chance they will detect and evade wind turbines.[205 206] Collision risk is also greater around heavily used flyways (including migration routes) or areas regularly used for feeding and roosting.[207] The natural capital impact of bird and bat collisions are also higher where wind farms are located in areas that contain rare or endangered species. At a species level, bird species that face the biggest risk are those that are rare or endangered, have long lifespans and are slow to reproduce.

Much less is known about bats' wind turbine collisions, particularly for offshore wind farms, and most studies have been carried out in northern temperate regions where the species most at risk are those adapted to foraging insects in open spaces, high above the ground, far from vegetation.[208] There is very little known about the collision risk faced by fruit and nectar feeding species.

For offshore wind power, the high noise volumes caused by constructing wind farms can disturb and disorientate some marine mammals.[188] This impact is limited to the construction phase of offshore projects and has a minimal impact across the whole lifecycle of a wind farm.

There is still a lack of information, and more research is needed to draw conclusions for the direct impact on fauna. The lack of conclusive data, however, does not preclude companies from operating with care.

Risks to business caused by negative wildlife impacts from installing and operating wind farms

In more mature jurisdictions, such as the EU, spatial planning constraints stop or impose operational restrictions on wind power developments within protected areas, or those that contain rare or endangered bird and bat species.[209] Businesses may face risks as regulation and policy aimed at minimizing or managing wind turbine impacts on birds and bats changes, or, develops, in jurisdictions beginning wind power deployment. For example, in California, new guidelines for wind developments recommend environmental reviews for each project to assess impacts on birds and bats, and are required by government agencies on a case-by-case basis.[210] Mitigation measures might be required to reduce impacts on wildlife, and specific studies are needed to understand potential impacts better. Meanwhile in Canada, especially in Ontario, wind energy projects must comply with the Endangered Species Act and the Environmental Protection Act, including specific guidelines to protect birds and bats.[211] Projects undergo rigorous review to ensure minimal impact on local wildlife, including migration patterns and habitats. Other countries that have adopted regulations and guidelines for wind power projects in relation to bats and birds include Scotland,[212] Germany[213] and Australia.[214]

Companies may face legal action over the risk of harm to birds and bats. This could delay wind farm developments or even stop them from going ahead. One example is the Altamont Pass Wind Farm in California, which was subject to legal action and regulatory scrutiny because of perceived high levels of bird fatalities, particularly raptors like golden eagles.[215] The controversy led to significant operational changes and retrofitting of turbines to reduce bird deaths.

Mitigation opportunities for wildlife impacts from installing and operating wind farms

A range of mature and emerging solutions exist to mitigate the impacts to wildlife caused by installing and operating wind turbines. Solutions implemented at the project design phase may focus on changing the layout of wind farm infrastructure (termed 'micro-siting') which can help to avoid, or minimize, impacts on wildlife, particularly the risk of birds and bats colliding with turbines. These measures focus on locating windfarms or turbines and other infrastructure away from sensitive areas for wildlife and altering wind farm layouts to minimize barriers to movement with the overall aim of decreasing risk of mortality and injury for wildlife. Micro-siting measures mainly focus on reducing bird and bat collisions and include giving greater consideration to:

- The minimum distance between turbines
- Aligning turbines parallel to main bird migration routes
- Creating corridors between turbines to provide avian wildlife a passage through the site
- Avoiding important nesting, roosting and foraging areas
- Planning around landscape features that concentrate bird or bat movements, e.g., ridges and escarpments for birds and rivers and forest edges for bats.

During wind farm operation, key mitigation solutions focus on modifying wind farm infrastructure itself or temporarily shutting down turbines to minimize impacts on wildlife.

Figure 12: Key mitigation options for reducing collision risk for birds and bats during wind farm operation

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Raising wind turbine cut-in speed* to minimize bat collisions, particularly in the high-risk period from late summer to early autumn. * Wind speed at which turbines begin producing electricity into the power grid	■■■■■■■■■■■■■■ **High:** A study at the Casselman wind project in Pennsylvania, US, found up to 93% reduction in bat fatalities.[216] A study in Germany showed 50% fewer bat fatalities where turbine cut-in speeds were raised by 4 meters/second (m/s).[217] Studies in the US and Canada showed at least 50% reduction in bat fatalities when cut-in speed was increased to 1.5 m/s above the manufacturer default.[218]	**In commercial use.** Required by law in some European jurisdictions since 2010, e.g., Germany.[219]	■■□□□□□□□□□□□□ **Low:** Limited data on power loss and economic costs of raising turbine cut-in speed. Research suggests <1% of total annual power output would be lost if cut-in speed is raised only during high-risk period for bat fatalities.[220]	Cannot be implemented on older and small to medium turbine models where there is no way to remotely control or change cut-in speed.[221] No evidence that this solution works for plan-visiting bats species.[222]
Increasing visibility of wind turbine blades by painting one of the three blades making it easier for birds to detect them.	■■■■■■■■■■■■■■ **High:** Painting two-thirds of one wind turbine blade black in the Smøla wind farm in Norway reduced total annual bird fatalities by over 70% and white-tailed eagle (Haliaetus albicilla) fatalities by 100% compared to unpainted control turbines.[223]	**One commercial scale study** has been run to test this solution at Statkraft's Smøla wind farm in Norway, funded by the Research Council of Norway.[224]	**Varied:** In the Smøla study, painting the blades while in-place was resource intensive and the cost would be reduced by painting before wind turbines are constructed.[225]	There may be regulatory restrictions to painting turbine blades where specific colouring is required. Painting turbine blades after construction is technically challenging and expensive. Communities may object to the visual impact of painting turbine blades.
Installing acoustic devices to deter bats from wind turbines. Devices emit high frequency sounds within the range of bat call frequencies, masking echo perception or deterring bats from airspace around turbine rotor swept areas.[226]	■■■■■■■□□□□□□□ ■■■■■■■■■■■■■■ **Medium – high:** Acoustic deterrent devices at Los Vientos wind farm in Texas, US, reduced overall bat fatalities by 50%. Results varied by species: there was a 54% and 78% reduction in fatalities for the Brazilian free-tailed bat and hoary bat, respectively. Acoustic devices appeared to be less effective for bats with high frequency calls.[227]	**One commercial scale study** at Duke Energy's Los Vientos wind farm in Texas, US, in collaboration with Texas Parks & Wildlife Department, Duke Energy, NRG Systems, Bat Conservation International and Vestas.	■■□□□□□□□□□□□□ **Low:** Small, relatively low-cost devices.	It is unclear how well acoustic devices can withstand extreme weather conditions and over longer time periods. More testing is needed to understand how well acoustic devices deter other bat species. Acoustic devices might be less effective for bats with high frequency calls.

Source: Planet Tracker.

Figure 12 (continued): Key mitigation options for reducing collision risk for birds and bats during wind farm operation

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Automated image detection technology for wind turbine shut-down-on-demand to prevent bird collisions. Daylight/thermal imaging cameras mounted on turbines or similar structures identify birds in flight and issue a warning sound or automatically shut down turbines based on preset criteria (e.g., distance from turbine).	■■■■■■■■■■■■■ **High:** DTBird technology detected >80% of bird flights when tested at the Manzana wind project, California, US.[228] Warning sounds from DTBird reduced collisions risk zone bird flights by 38%-60% in trials in Sweden and Switzerland.[229] IdentiFlight technology showed 96% detection rate in trials at Duke Energy's World Windpower Project in Wyoming, US.[230]	**In commercial use.** IdentiFlight is installed at sites in Australia, northern Germany and the US.[231] DTBird is installed at 90 existing/projected onshore/offshore wind farms in 16 countries.[232]	■■■■■■■□□□□□□ **Medium:** Costs estimates at 0.5%-2.0% of project investment and 0.5%-2% of annual turnover of a wind farm.[233]	No data public data on the cost of these technologies. Warning sounds to deter birds require more testing to understand efficacy across bird species and wind farm sites. The impact to humans of warning sounds might limit deployment opportunities for these technologies.
Radar technology for wind turbine shut-down-on-demand to prevent bird and bat collisions. Radar systems detect and track birds and turbines can automatically be shut down based on predefined rules.	■■■■■■■■■■■■■ **High:** BirdTrack technology used at the E.ON Barão de São João wind farm resulted in zero fatalities over a five year period and only two fatalities over the first 10 years of operation from 2010-2019.[234] BirdTrack technology deployed in Egypt has resulted in only 5-7 fatalities from around 370,000 birds passing through the wind farm each season when combined with human observers.[235]	**In commercial use.** Used at the E.ON Barão de São João wind farm since 2010.	■■■■■■■□□□□□□ **Medium:** Robin Radar Max technology estimated to cost > USD 500,000.[236]	Radar use may be restricted by national military or aviation regulations.[237] Some technologies have only been tested with human observers, increasing cost.

Source: Planet Tracker.

End-of-life waste from wind turbine blades

85%-90% of wind turbines total mass can be recycled[238] when they reach the end of their life, including the foundation, tower, and nacelle which can be recycled using well established practices. However, the rotor blades of wind turbines are currently not widely recycled. They are made of composite materials (usually fiberglass reinforced plastics/resins) which need to be strong and lightweight to function well in harsh weather conditions. This durability makes such materials difficult to recycle cost efficiently without creating more carbon emissions than using raw materials.[239] They often end up in landfill, or are incinerated which can produce toxic emissions harmful to nature. It is important to highlight that this is a cross-sectoral challenge: composite materials are used by the transport, aeronautics and construction sectors and it is estimated that wind power will account for only 5% of total composite waste by 2025.

However, as wind power deployment increases and many old turbines come to the end of their life, this will become an increasingly material issue for downstream wind power companies. With this in mind, the industry body Wind Europe has called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025, committing the industry to reuse, recycle or recover all decommissioned blades by this date.[240]

Risks to business caused by end-of-life waste from wind turbine blades

Around 14,000 wind turbines blades globally are reaching the end of their usable life within the next two to three years and this figure could increase tenfold by the end of the decade.[241] With the rise in blade waste, wind power companies are likely to come under increasing scrutiny in terms of improving the circularity of their products. Dealing with blade waste in some jurisdictions may become increasingly expensive, and regulation may become more stringent as the issue develops.

Circularity solution to end landfill for turbine blades

Turbine blades are hard to recycle due the presence of epoxy resin, a widely used chemical substance that is challenging to break down. The market has been trying to find alternatives, but meanwhile tens of thousands of tons of wind turbines (manufactured with epoxy-based resin) are reaching the end of their lives and need to be recycled.

Danish wind manufacturer, Vestas, has partnered with other value chain actors on developing a novel chemical process that can chemically break down epoxy resin into virgin-grade materials. These so-called new epoxies can be used in wind turbine blades. The company is now focussed on scaling this process commercially.

Mitigation opportunities for end-of-life waste from wind turbine blades

Circular economy strategies are key for reducing the volume of end-of-life waste for wind turbine blades. The most impactful (and mature) solutions focus on reducing waste in the first place by extending the useful life of wind turbine blades through refurbishment and reuse and wind farm lifetime extension activities. Most other solutions are yet to be made available at commercial scale and remain in pilot and testing phases.

Composite material recycling technologies may be relevant across other sectors that are big users of such materials, and there could be opportunities for cross-sectoral partnerships to develop recycling solutions that could provide a feedstock for the composite materials value chain.

Figure 13: Key mitigation options for improving the circularity of wind turbine blades.

Mitigation method / technology	Level of impact	Level of development	Level of investment	Key barriers to scaling
Turbine blade refurbishment and reuse in wind farm lifetime extension activities: Existing turbine components are upgraded to extend windfarm lifetime from 20-25 years up to 35 years.[242]	■■■■■■■■■■■■■■ **High:** Significantly extends the life of turbine blades with minimal additional resource requirement. Additional benefit of, increasing the capacity and efficiency of existing wind farms. Also reduces need to new wind farms and associated impacts.	**Already used in commercial operations.** Turbine manufacturer Vestas already refurbishes and reuses the majority of turbine components and commits to 55% refurbishment by 2030, and 75% by 2040.[243] Lifetime extension of 5-10 years is projected for half of Europe's existing wind farms.[244]	■■□□□□□□□□□□□□ **Low:** Estimates from Germany and Spain range from EUR 5,000 – EUR 15,000 per turbine,[245] compared to EUR 1.1 – EUR 4.5 million[246] for one onshore wind turbine.	Not all wind turbines are suitable for lifetime extension, particularly older technologies where replacement parts are no longer manufactured. Uncertainty over future electricity spot market prices which determine the economic feasibility of lifetime extension.
Developing novel commercially viable turbine blade material which can be recycled. The Circular Economy for Thermosets Epoxy Composites (CETEC) initiative is developing a novel two-step recycling process where novel blade materials can be disassembled into fibre and epoxy, before the epoxy is broken down into base components similar to virgin materials.[247][248]	■■■■■■■■■■■■■■ **High:** Where wind turbine blades cannot be refurbished and reused in turbines, CTEC's novel blade materials could see turbine blades recycled into new blades or similar objects, eliminating waste sent to landfill. The CETEC initiative involves wind turbine manufacturer Vestas, Epoxy supplier Olin and research institution partners.	**Laboratory / pilot-scale.** The CECT initiative aims to create a full scoped solution ready for industrial adoption by 2024.[249] Wind turbine manufacturer Vestas aims to create a fully recycled rotor (including blades) by 2030.[250]	**No data available**	New technology is at a very early stage of development and may not become available commercially for some time.
Pyrolysis degasification processing of turbine blade materials into other useful (but less valuable) materials. Materials are heated in an oxygen free atmosphere, converting resins into liquids, gases and solids which can be used for other applications.	■■■■■■■□□□□□□□ **Medium:** Resins are converted into liquids (used as fuel or as chemical industry feedstock), gas (used for heating or electricity) and solid materials (glass fibres, carbon fibres, ash, used in industries like cement).[251] Some of these products, mainly solid materials are lower quality than virgin materials	**Laboratory / pilot-scale.** The DecomBlades project based in Denmark carried out laboratory tests and developed a pilot plant in 2022 for processing turbine blades.[252]	■■■■■■■■■■■■■■ **High:** Pilot studies show this process is not yet economically viable for turbine blade processing.[253]	Not yet economically viable. Currently no industrial scale pyrolysis installation is processing common turbine blade materials. Fibre products from pyrolysis are often degraded, reducing their value and limiting uses. Risk of toxic gases leaking from waste treatment chambers.
Cement co-processing: Shredded blade material can be burnt to contributing to the heat needed for cement production and the resulting waste and ash can be used as alternative fuel or as a material in cement.	■■■■■■■□□□□□□□ **Medium:** Cement co-processing for turbine blade waste is potentially highly scalable and could process large quantities of blades with no waste left over. However, it transforms blades into lower value products, and refurbishment and recycling could be better options for retaining blade value.	**Laboratory / pilot-scale.** The DecomBlades project based in Denmark began testing the feasibility of cement co-processing in 2021.[254]	■■□□□□□□□□□□□□ **Low:** Pilot studies show this process could be low-cost at commercial scale.[255]	Produces lower-value products from turbine blades. Can create toxic substance pollution and particulate matter emissions.

Source: Planet Tracker.

Engagement questions for minimizing natural capital impacts from wind power

Figure 14: Minimizing natural capital impacts from wind power

Recommended questions

1

What actions are being taken to engage with metals and mining companies to assess and minimise habitat loss in relation to sourcing wind turbine materials and components?

To what extent are wind farm lifetime extension activities being planned to reduce reliance on virgin materials?

How much recycled material is currently being used in new wind turbines and what investment is planned to increase this?

2

What actions have been taken to assess and mitigate bird and bat collision risk during wind farm operations when projects are proposed and designed?

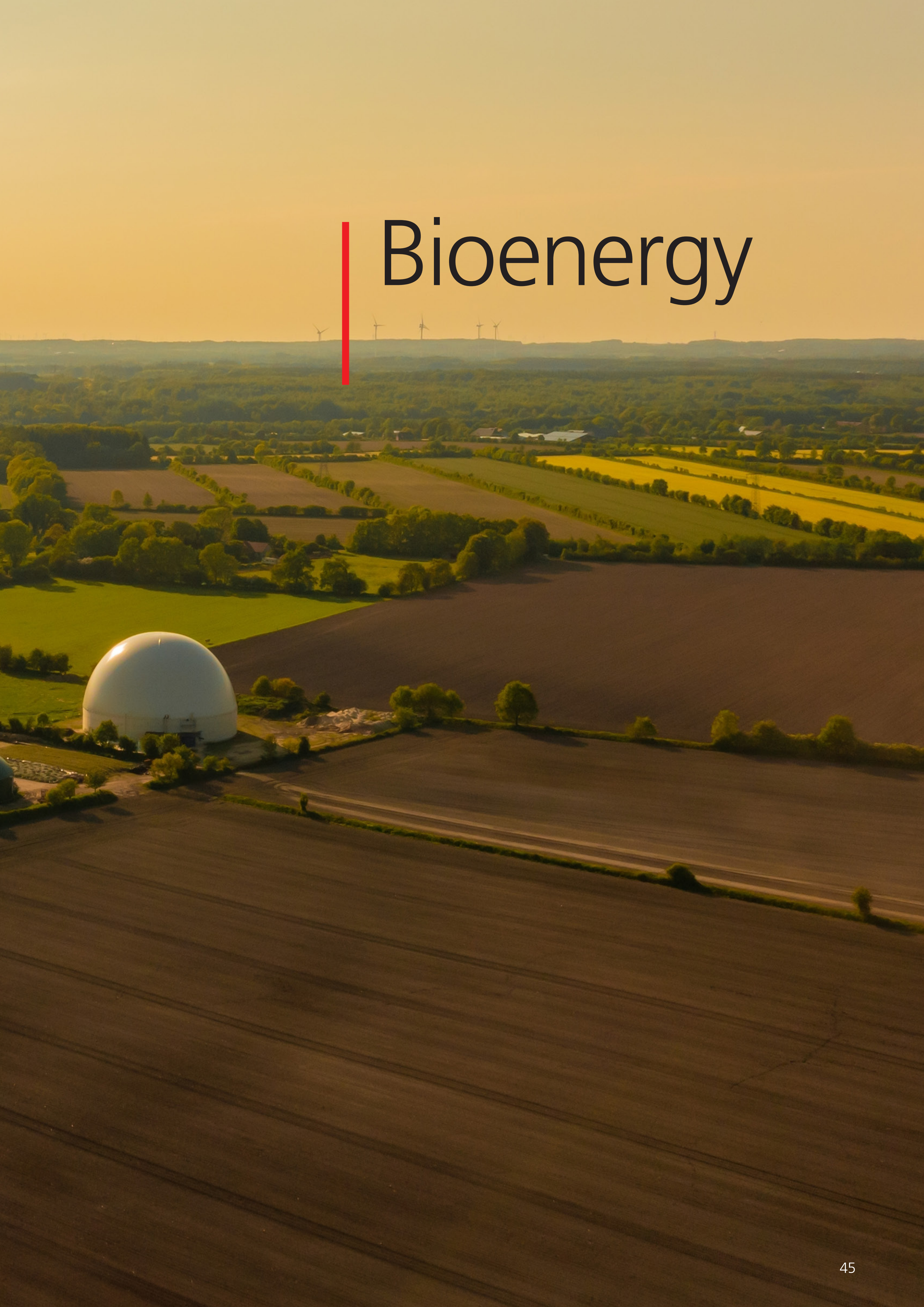
What action is being taken to minimize bird and bat collisions during wind farm operation, whether legally required or not?

3

What measures are being taken to refurbish and reuse wind turbine blades for use in lifetime extension activities?

What research and development is planned for wind turbine blade recycling?

Bioenergy



Bioenergy

Material impact: Second-generation bioenergy feedstocks can contribute directly and indirectly to land use change and associated habitat and biodiversity loss. Direct land use change occurs where second generation bioenergy is derived from non-edible biomass crops and trees, which require land to be grown. The expansion of second-generation bioenergy crop production could lead directly to the conversion of natural ecosystems, causing the loss and damage of habitats and biodiversity. Second-generation bioenergy can also drive indirect land use change where the production of feedstocks displaces the production of crops or livestock to other locations.

Best practice: Companies may adopt certification schemes and sustainable procurement policies including policies that restrict or prohibit sourcing high land use change risk crops or sourcing from high-risk locations.

Material impact: Many studies show that the carbon emissions of second-generation biofuels are often significantly underestimated, especially where they are counted as zero or negative emissions by regulation.

Best practice: Companies should conduct full third-party lifecycle assessments on all potential feedstocks, including all stages of a product lifecycle, particularly emissions from producing bioenergy feedstocks, even if they are counted as zero or negative emissions by regulation.

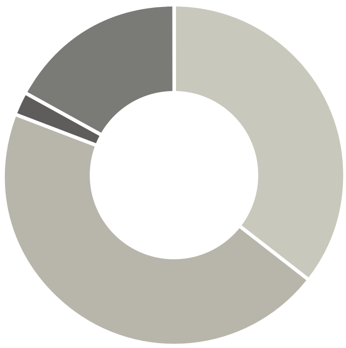
Material impact: Research has shown that the decomposition of crop and forestry wastes and residues within forests and fields is important to the long-term sustainability of agriculture and forestry ecosystems, and there may be a range of negative impacts from removing these materials, including declining soil health and soil carbon stocks.

Best practice: Due to the current lack of research and guidance, the main opportunities for companies aiming to mitigate ecosystem impacts from removing wastes and residues is to support more research into this area, alongside the development of best practice standards. Second generation bioenergy could also deliver positive climate outcomes when the aim of biomass removal is to improve ecosystems, for example through wildfire risk reduction and alien invasive species removal, or when biomass is gown on degraded, low-carbon stock land that would otherwise not be used.

State of play and future demand

Bioenergy is energy produced from organic material (biomass) and industrial and municipal waste.[256] Modern bioenergy makes up around 6%[257 258] of total primary energy supply globally. It is used as fuel for transport, to produce electricity, as a source of heat in buildings and industry, and as a chemical feedstock, and will play a role in the low carbon energy transition in the coming decades.

Figure 15: Bioenergy final energy consumption by sector in 2020



	% of total
Buildings	35%
Industry	45%
Other energy use	2%
Transport	17%

Source: IRENA (2023).

The Net Zero Emissions by 2050 (NZE) Scenario sees a rapid increase in the use of bioenergy to displace fossil fuels by 2030. Use of modern bioenergy has increased on average by about 3% per year between 2010 and 2022 and remains on an upward trend. However, to accelerate modern bioenergy deployment in line with the NZE Scenario, deployment needs to increase by 8% per year between 2022 and 2030, while simultaneously ensuring that bioenergy production does not have a negative impact on natural capital.[259]

Bioenergy feedstocks: first to fourth generation

Bioenergy is produced from a variety of feedstocks and can generally be categorized into first to fourth generation bioenergy.

Figure 16: Bioenergy feedstock examples

1st Generation bioenergy

Food crops:
- Corn
- Wheat
- Sugar beet
- Sugar cane
- Palm oil
- Soya bean oil
- Sunflower oil

2nd Generation bioenergy

Non-edible crops:
- Miscanthus
- Switch grass
- Poplar trees
- Willow trees
- Jatropha
- Camelina

Waste streams:
- Municipal solid waste
- Industrial waste
- Forestry residues
  Agricultural residues (e.g., manure, corn stover, straw)
- Food industry waste (e.g., used cooking oil)

3rd Generation bioenergy

- Microalgae
- Cyanobacteria biomass

4th Generation bioenergy

- Genetically engineered microalgae

Source: Jeswani et al. (2020),[260] Cavelius et al. (2023).[261]

First generation bioenergy: socially and environmentally unsustainable

First generation bioenergy is typically produced from food or animal feed crops to produce liquid biofuels – bioethanol and biodiesel[262] – through microbial fermentation with well-established technologies and processes including fermentation, distillation and transesterification.[263]

First generation bioenergy feedstocks have become associated with significant negative social and environmental impacts. These energy crops are in direct competition with food production, and models estimate massive areas of agricultural land would be required to produce relatively limited amounts of biofuel,[264] potentially leading to food security issues. Increased demand for edible crops (e.g., corn) for biofuels has driven price rises in these foods, causing food security issues.[265] For example, various studies have highlighted the price of maize rose 21% in the US in 2009, when 26% of the country's maize was used for ethanol production.[266]

Increase in the market values of biofuel crops such as palm oil has also led to deforestation of tropical rainforests, in Indonesia for example, which have been cleared to establish biofuel plantations, releasing more CO_2 emissions than the emissions saved by those biofuels.[267] Future increases in demand for biofuel in emerging markets in particular has the potential to increase the risk of deforestation in some of the planet's last intact forests.[268] When the whole production cycle is taken into account, biodiesel from food crops can emit an average of 1.8 times more CO_2 than fossil fuel equivalents,[269] with palm oil and soy feedstocks among the worst performers. In 2022, a study in the Proceedings of the National Academy of Sciences found that the carbon intensity of corn-based ethanol produced under the US Renewable Fuel Standard was no less than gasoline, and could be up to 24% higher.[270]

There are also concerns about the use of freshwater and synthetic fertilizers and pesticides required to produce first generation biofuels, all of which have negative natural capital impacts on surrounding ecosystems.[271] For example, even feedstocks that are typically thought to have a low risk of direct and indirect land use change, such as rapeseed oil, still have a significant greenhouse gas footprint driven by the use of synthetic fertilizer, pesticides and herbicides and agricultural machinery.[272]

A 2018 analysis of biofuel policy estimated the use of 10.7 million tonnes of palm oil, just under 1/5th of global production. In a scenario where global demand for palm oil from biofuel policies increases to 67 million in 2030, that could result in 4.5 million hectares of deforestation, 2.9 million hectares of peat loss and 7 billion tonnes of CO_2 emissions, vis-à-vis a scenario eliminating use of palm oil as a biofuels feedstock. These issues have prompted regulatory action, with the EU making palm oil-based biodiesel ineligible for fulfilling renewable transport targets after 2030.

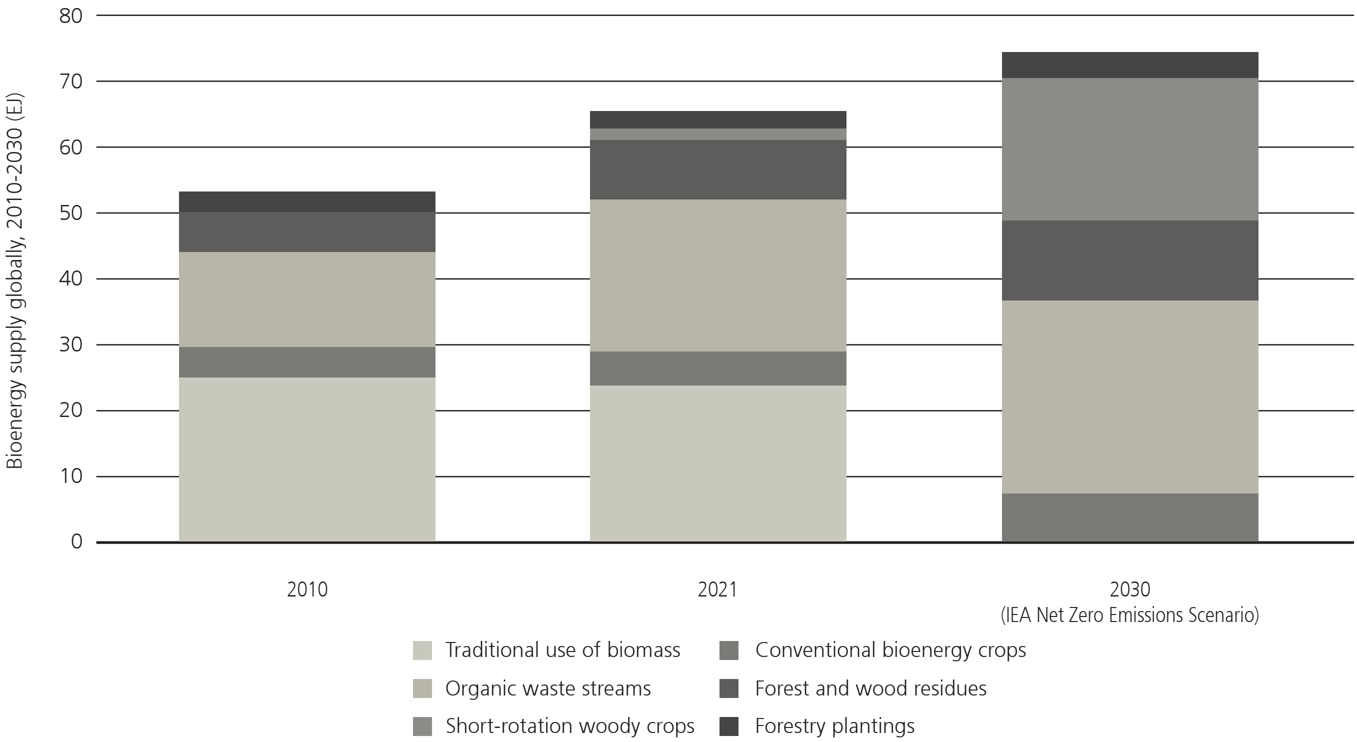
Source: Malins, Chris. "Driving deforestation" 2018

Second generation bioenergy: state of play and future projections

Second generation bioenergy feedstocks, sometimes called ‘advanced feedstocks’, were developed in response to the issues associated with first generation bioenergy. Feedstocks for second generation bioenergy include agricultural, food industry and forestry wastes and residues and inedible crops, including lignocellulosic (woody) crops such miscanthus and switchgrass and oily crops like camelina and carinata. Other waste streams such as municipal solid waste, industrial waste and water treatment wastes are also included in second generation biofuels.

The IEA estimates that in 2021 48% of bioenergy supply came from organic waste streams (36%), forest and wood residues (13%),[273] which can be classed as second-generation bioenergy feedstocks. The IEA’s Net Zero Emissions Scenario requires the significant growth in feedstocks from organic waste and agricultural and forestry residues, which are projected to grow from 48% in 2021 to 56% in 2030 and 75% in 2050.[274] This scenario also includes short-rotation woody crops as sources of advanced bioenergy and requires these to grow from 3% to 30% of bioenergy supply from 2021 to 2030.

Figure 17: Bioenergy supply globally in the IEA Net Zero Emissions Scenario, 2010 to 2030



Source: IEA (2023).

Bioenergy is expected to play a particularly important role in the low carbon energy transition in the transport sector, particularly for aviation, shipping and potentially heavy-duty trucking where other decarbonization options (e.g., green ammonia and hydrogen) will not be developed in the near-to mid-term.[275] Biofuels currently make up 4% of liquid transport fuel globally, and around 12% of this is estimated to come from advanced second generation feedstocks, mainly from residue oils, fats and grease such as used cooking oil.[276] Biofuels from first and second generation feedstocks are required to grow to 10% of liquid transport fuel globally in 2030 under the IEA's Net Zero Emissions Scenario.

Biogas and biomethane, produced from crop residues, manure, municipal and industrial waste and sewage sludge, are also projected to play a role in providing flexible dispatchable power for electricity grids and potentially as a future transport fuel.[277] Europe is the world's most mature biogas market, and Germany in particular has developed large scale biogas use, with biomethane contributing to 22% of the natural gas-based power supply in 2021, around 75% of which is based on energy crop feedstocks.[278] Most growth in biogas is expected to be in Europe and North America due to established infrastructure and policies, which could enable near-term growth in production.[279] China and India also have ambitious biogas expansion plans, but the lack of infrastructure is likely to limit growth to the end of the decade.

The IEA states that there needs to be a significant acceleration in the deployment of advanced second-generation bioenergy to meet the requirements of the Net Zero Emissions Scenario. However, there are questions around whether the high costs of advanced bioenergy could hinder the uptake of these technologies. One study found that the price of many advanced biofuels were higher than those of first generation biofuels and even higher than those of fossil fuels, which has limited their spread.[280] The lack of centralized collection systems for disparate waste and residue streams both increases costs and creates a logistical barrier to scaling waste-based bioenergy.[281] Waste streams can also represent more complex feedstocks than first generation bioenergy crops, and can require costly and time consuming pretreatment steps to turn them into biofuels.[282] [283]

In the United States, Brazil, Europe and Indonesia, high adoption rates of bioenergy has been driven largely by financial and policy incentives as well as regulation and technical standards.[284] The EU has led the way in developing policy that encourages the uptake of advanced second generation bioenergy through its Renewable Energy Directive III,[285] although first generation bioenergy feedstocks still dominate.[286] Other major markets could adopt similar pro-second generation bioenergy measures in the mid-term.Analysis from the IEA has shown that financial incentives such as subsidies will be essential to scaling second generation bioenergy in the mid term.[287]

As well as the financial cost, questions have been raised about whether increasing second generation bioenergy production is sustainable from a natural capital and climate perspective. In response to these sustainability concerns, research and development is underway for third and fourth generation bioenergy feedstocks.

Third and fourth generation bioenergy: under research and development

Third and fourth generation biofuels are not currently commercially available. Third generation biofuels are produced from microalgae and cyanobacteria biomass, which are used to generate alcohol and lipids which can be transformed into biodiesel and other high energy fuel products.[288] Wastewater or salt water can be used to grow algae, so in theory it would not compete with arable land or freshwater. Algae cultivation also requires a direct supply of CO_2 which could be sourced from industrial emitters or atmospheric carbon capture.[289] However third generation biofuel production technologies remain at the research and development or pilot stage and are currently too energy-intensive and costly to be commercially viable.[290]

Fourth generation bioenergy uses genetically modified microalgae to capture larger amounts of CO_2 and increase biofuel productivity.[291] This technology remains at the research and development stage and so far can only be applied to a small number of microalgae species due to limited genetic and biological information.[292]

What are the most material natural capital impacts of second generation bioenergy?

While second generation bioenergy feedstocks are often framed as solutions to the sustainability issues associated with first generation bioenergy crops, concerns have emerged about the natural capital impacts arising from these sources of bioenergy.

Our analysis has identified three key areas of natural capital impacts from second generation bioenergy feedstocks.

These natural capital impacts pose real risks to business, including rising fraud. There is a significant risk of cheaper, more readily available, less sustainable first-generation bioenergy feedstocks entering second generation feedstock supply chains, which can pose regulatory and reputational risks to businesses. For example, in the Netherlands in 2019, one of the largest markets for used cooking oil biodiesel, criminal investigators found that a third of used cooking oil feedstock could in fact be virgin oil biodiesel.[293]

1. The potential for significant direct and indirect land use change and associated habitat and biodiversity loss from producing second generation bioenergy crops and trees, including as cover crops.

2. Challenges associated with accounting for carbon emissions, where emissions from so-called waste and residue feedstocks are often underestimated and emissions from forestry residues may produce significant near-term emissions with long carbon pay-back periods.

3. Ecosystem impacts from removing ‘wastes’ and ‘residues’ from agriculture and forestry production systems for use as biofuels, including potentially reducing soil health and carbon sequestered in the soil.

There is also a risk of encouraging 'lock-in' to higher carbon second generation bioenergy feedstocks, where carbon accounting underestimates the lifecycle carbon footprint of these materials which could expose companies to the risk of stranded assets. This is particularly the case where waste and land-intensive pellets are being used to extend the life of coal-fired power plants through cofiring, which is already happening around the world including in Europe and Indonesia. Carbon capture technologies have been proposed as a solution to capture combustion emissions from bioenergy used in power plants, with pilots for BECCS (bioenergy with carbon capture or storage) underway in the UK, Europe and US.

Extracting some agricultural and forestry wastes and residues for use as biofuels can harm the long-term health sustainability of these ecosystems, for example through reducing soil health, soil carbon content and overall biodiversity.[294] This could cause decreases in productivity on farms[295] and in forests[296] which could have a financial impact on businesses reliant on these production systems.

Our analysis found that opportunities to mitigate the natural capital impacts associated with second generation bioenergy are evolving and companies will face challenges to improve their effectiveness and scale. This includes the diffuse nature of the production of many second-generation bioenergy feedstocks and a lack of value chain traceability and transparency.

Land use change, habitat and biodiversity loss from second generation biofuels

Second generation bioenergy feedstocks can contribute directly and indirectly to land use change and associated habitat and biodiversity loss. Direct land use change occurs where second generation bioenergy is derived from non-edible biomass crops and trees, which require land to be grown. The expansion of second generation bioenergy crop production could lead directly to the conversion of natural ecosystems, causing the loss and damage of habitats and biodiversity.[297] These impacts are greater where high-biodiversity value ecosystems are converted to monoculture bioenergy crop production and it could take centuries to restore these ecosystems to their natural state.[298] Land use change also produces CO_2 emissions, where carbon stocks in biomass and soils are released when natural habitats are removed and replaced with lower-carbon agriculture or forestry production.[299]

Second generation bioenergy can also drive indirect land use change where the production of feedstocks displaces the production of crops or livestock to other locations.[300] One example of this is agricultural cover crops, which are grown after a main crop has been harvested and before the next season's crop has been sown and can include second generation bioenergy feedstocks crops. Cover crops are widely used in traditional and modern agricultural systems and are promoted in agricultural policies (e.g., the EU Common Agricultural Policy[301] and Brazil's SPD[302]) as a form of sustainable land management. This practice incorporates crops that improve soil health (including leaving plant residues on fields), crops for food, livestock feed and bedding.

Biofuels are already being made from 'cover crops' such as camelina and carinata by companies like Neste[303] and Nuseed.[304] However, replacing cover crops that produce food and feed with biofuel cover crops means those food and feed crops have to be produced elsewhere, potentially on land newly converted from natural ecosystems.[305] Where cover crops and their residues improve soil health by reducing soil erosion, improving nutrient retention and carbon sequestration, replacing these with biofuel crops or removing these crop residues for use as biofuels could reduce soil fertility, increase reliance on carbon intensive synthetic fertilizers and even increase carbon emissions from soil.[306 307] For example, one study[308] found removing corn residue for biofuel across the United States could add 30 to 90g of CO_2 per megajoule of biofuel, making the total lifecycle emissions of biofuel from this feedstock on average 7% more than that of gasoline. Another study[309] found that in some cases, cover crops can reduce the yields of primary crops such as soy. This could lead to a shortfall in the supply of primary cops which in turn can drive the expansion of cropland to meet demand.[310]

Risks to business from land use change, habitat and biodiversity loss

Companies could face regulatory risks as awareness grows around the potential for direct and indirect land use change caused by second generation bioenergy crops. The EU's Renewable Energy Directive now includes measures to try and phase out the use of the first-generation bioenergy feedstocks such as crude palm oil that have a high risk indirect land use change[311] and the increasing scale of second generation bioenergy crop production could expose them to similar regulatory pressure in the future.

With an increased demand for second generation bioenergy in general and due to supply chain complexity and lack of traceability and transparency, there is a high risk that unsustainably sourced feedstocks may be procured by companies, even with non-crop based feedstocks. For example, a study by Transport & Environment found that Europe was reliant (80%) on imports, mainly from Asia, for used cooking oil for bioenergy, the consumption of which doubled between 2015 and 2022.[312] The report highlights a significant exposure to the risk of fraud with these imported used cooking oil, as supplies are very tight. Meeting the IEA's forecast for global bioenergy feedstocks from 2022 to 2027 would require 100% of estimated used cooking oil and animal fats supplies, or 65% of global supply if other agricultural wastes (e.g., tall oil and palm oil mill effluent) are used.[313] The report highlights that much of the EU's used cooking oil is likely to be repurposed virgin palm oil, which is associated with a high risk of deforestation and peat habitat destruction, and a number of countries such as Germany and Ireland have launched official investigations into this issue.

Mitigation opportunities for land use change, habitat and biodiversity loss

Third party sustainability certification schemes have emerged as a key mitigation option for tackling bioenergy-related land use change. Schemes such as ISCC[314], RSB[315] and FSC,[316] provide third party chain of custody certification (including to meet regulatory requirements) that aims to ensure the bioenergy feedstocks are not sourced from high biodiversity or carbon value ecosystems, such as primary forests, protected areas, or threatened or endangered ecosystems. These schemes aim to ensure traceability across bioenergy feedstock supply chains, which is inherently challenging because it is hard to tell whether biofuels are made from the raw material cited when analyzing the properties of the final fuel.[317]

However, supply chain complexity and lack of traceability and transparency can mean that even in jurisdictions with high rates of certification like the EU, unsustainably sourced feedstocks may still be procured by companies, even with non-crop based feedstocks. To tackle the risk of fraud, companies should develop procurement policies that aim improving supply chain traceability and transparency, including third party chain of custody certification (including the schemes mentioned above). Technologies like blockchain have been used to create centralised digital databases for tracking biofuels sourcing, chain of custody and greenhouse gas emissions data, as piloted by the Roundtable on Sustainable Biomaterials (RSB) and BioLedger[318] and commercialised by the start-up Circularise.[319] Digital supply chain databases (using blockchain or otherwise) can use solutions such as biometric authentication, photos, signatures, and geolocation data to increase the strength of evidence and minimize the risk of errors and fraud for each data point collected.

Alongside certification, companies can reduce the risk of land use change from second-generation bioenergy with policies that aim to avoid high-risk land conversion feedstock crops, such as soy cover crops, or sourcing from regions which have a high rate of agriculture-related biodiversity-risk natural habitat loss, such as Brazil and Indonesia. The exact crops and countries covered in each policy may change with time as new trends in second generation biofuels and agricultural production emerge. However, the same challenges remain around the lack of transparency and traceability in supply chains when it comes to verifying the content and source of final bioenergy products.

Carbon emissions from wastes and residues

The lifecycle carbon footprint of second generation bioenergy feedstocks is usually considered to be significantly lower than that of fossil fuels.[320] Estimates here vary considerably, from carbon negative to more carbon intensive than fossil fuel equivalents, reflecting the diversity of feedstocks and production routes, life cycle assessment assumptions and methodological differences.[321] However, our analysis found that many studies show that the lifecycle carbon emissions of second-generation biofuels are often significantly underestimated.[322]

Reid, et al.'s[323] study identified four factors that contribute to greenhouse gas emissions over the lifecycle of bioenergy: 1) emissions from production, harvest, transport and processing; 2) the carbon debt from converting an ecosystem to bioenergy production (in some cases carbon sequestration may be increased if degraded lands are planted with bioenergy crops); 3) the payback period for an area of bioenergy production to return to preharvest carbon stocks and; 4) the loss of the carbon sequestration that would have occurred if the area had not been used for bioenergy production. However, not all of these factors are fully accounted for in many mainstream carbon accounting methodologies for second generation bioenergy, including those enforced by regulation, potentially leading to an underestimation of the climate impact of these feedstocks.

Waste and residue greenhouse gas emissions uncovered

This analysis uncovered that regulations in many countries effectively treat waste and residue bioenergy feedstocks at low- or zero-carbon, or provide favorable accounting under carbon pricing regimes for meeting national and corporate climate targets.[324] For example the EU's RED III regulation considers wastes and residues "to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials",[325] with the assumption these feedstocks are generally not considered to be the intended product of a given production system.[326]

However, our analysis found that the production systems for some feedstocks classed as wastes and residues may be carbon intensive, particularly where they drive large scale land use change of high carbon stock ecosystems. For example, the increased use of palm oil derivatives such as palm fatty acids (PFAD) in biofuels in the EU has received significant attention as they are classed as 'low-carbon' wastes and residues, but their production is associated with wide-spread land use change.[327]

PFAD can be used to make candles, soaps, other oleochemical products, as well as animal feed and could be more accurately described as by-products of the palm oil industry.[328] Due to competition with these existing uses, the high demand for PFAD for biofuels can increase demand for unsustainable palm oil associated with deforestation and peatland conversion in Indonesia and Malaysia in particular. When the carbon emissions from this land use change are fully accounted for, the emissions from producing PFAD biofuels can reach up to 221 gCO_2e/MJ, more than twice the emissions of fossil fuel diesel.[329] The mainstream use of carbon accounting that fails to consider the emissions from producing PFAD for biofuels runs the risk of creating significant negative climate impacts, particularly as demand for these feedstocks rises.

Another waste bioenergy feedstock which has gained significant attention is the use of manure to produce biomethane (also known as renewable natural gas), particularly in California.[330] Here, livestock manure, mainly from dairy farms, is collected in biodigesters which capture the nearly pure stream of methane released, which is almost identical to natural gas and can be blended into the energy grid among other uses.

Under California's clean fuels policies, which class manure as a waste rather than a byproduct of the dairy industry, the renewable natural gas from dairy farms is the only fuel designated as having a negative carbon footprint, between -109 gCO_2e/MJ and -762 gCO_2e/MJ.[331] As a result, dairy and energy companies can earn avoided methane credits for energy produced from cow manure. A study commissioned by the Union of Concerned Scientists found that methane capture could make up nearly 40% of the total profits from mid- to large-sized dairy farms in California and could incentivize farms to increase herd sizes to boost manure production.[332]

However, regulators fail to factor in any of the emissions from producing manure in the first place, including raising animals and the emissions associated with cow burps, which produce roughly the same methane emissions as manure,[333] as well as emissions from transport and significant methane leaks from biomethane supply chains.[334] Indirect emissions from raising animals include deforestation-related emissions from soy-based feed, much of which is sourced from converted biodiversity rich habitats in the Brazilian Amazon and Cerrado regions.[335] Synthetic fertilizer used to grow animal feed (domestically or overseas) poses another indirect climate impact, from the nitrogen emissions created by excess fertilizer left on cropland.[336] Again, failing to account for the emissions from dairy cow manure-based biomethane could drive significant negative climate impacts, particularly if farmers and energy companies continue to receive financial incentives to expand production.

Carbon debt and carbon payback for forest biomass

Studies have shown that the growth in forest biomass, including forestry waste and residue feedstocks, could create a ‘double climate problem’ by simultaneously driving near-term carbon emissions (or carbon debt) that can be greater than fossil fuels, with long carbon payback periods ranging from decades to over a century for carbon stocks to be replenished to their preharvest state.[337 338] In addition, the extraction of first and second generation forestry bioenergy may reduce the ability of forests to fix carbon.[339]

This is particularly an issue if wood products (whether classed first-generation feedstocks or forestry residue second generation feedstocks) are used to co-fire coal power stations. In this case, because of the lower energy density of wood based bioenergy[340] and because combustion and processing efficiencies for wood are less than coal, studies have found that wood burnt in power plants produces greater immediate atmospheric CO_2 than coal.[341 342]

Regulators, such as in the EU, consider second-generation wood waste and residue zero emissions, which has contributed to and increased in demand for these feedstocks.[343] The use of wood pellets to extend the life of coal-fired power plants through co-firing is already happening across Europe[344] and Indonesia,[345] with the risk of encouraging lock-in to emissions intensive power production.[346]

Risks to business from underestimating carbon emissions from second generation bioenergy

As the negative climate impacts of high-carbon waste and residue feedstocks gain increasing attention, companies may face reputational risks and even the risk of stranded assets from using or investing in these products. NGOs such as Transport & Environment[347] and the Union of Concerned Scientists[348] are campaigning to change the regulatory carbon accounting for these wastes and residues, and if regulation does change to incorporate emissions from producing these products, companies could face regulatory risks. This could include the risk of stranded assets if regulators stop effectively subsidizing the production of second-generation biofuels.

Mitigation opportunities for underestimating carbon emissions from second generation bioenergy

This analysis found that there are opportunities for businesses to fund studies or conduct lifecycle assessments to gain a better understanding of the potential range of lifecycle carbon emissions from second generation bioenergy feedstocks, which they wish to consider in procurement and investment decisions. This is particularly important for waste and residue streams, or other feedstocks classed as ‘zero-‘ or ‘negative-emissions’ by regulations. Therefore, lifecycle assessments may include recategorizing wastes and residues to byproducts where appropriate to understand where there might be a significant risk of emissions from producing these bioenergy feedstocks in the first place.[349 350]

The challenge here is that there are an increasing number of feedstocks that could potentially be assessed, and to improve the accuracy and utility of research, variations caused by factors like location and production route/process should be considered.

Carbon capture technologies have been proposed as a solution to capture combustion emissions from bioenergy used in power plants, with pilots for BECCS (bioenergy with carbon capture or storage) underway in the UK, Europe and US. According to the IEA, based on projects currently in the early and advanced stages of deployment, capture on biogenic sources could reach around 60 Mt CO_2/yr by 2030, which falls far short of the approximately 185 Mt CO_2/yr captured from biogenic sources by 2030 in the Net Zero Emissions by 2050 (NZE) Scenario.

Case study

Global shipping company Maersk has listed biofuels as one of the four priority future fuels for climate friendly emissions shipping. They have a stringent sustainability policy for bio feedstocks and biofuels governed by three pillars:

Certification and proof of sustainability

All biofuels must have a proof of sustainability (POS) under a RSB or ISCC mass balance to support any emissions saving claims made against a fuel.

1

Feedstocks

Maersk only accepts wastes, residues, and by-products as feedstocks. Forestry waste and residues must originate from FSC certified forest or equivalent..

2

Lifecycle GHG savings

Maersk sees life cycle assessments as a useful decision-making tool for evaluating new feedstocks. All feedstocks must meet the minimum reductions in Article 29(10) of the EU Renewable Energy Directive (2018/2001) which is about 65%-70% depending on the fuel type and production plant age compared to fossil reference fuel. The analysis also considers geographical usage (whether the waste in fact has value in certain geographies) and consequential usage, linked to additional demand risks.

3

Ecosystem impacts from removing wastes and residues

Our analysis has found that more consideration is needed in determining which bioenergy feedstocks are truly wastes and residues, as demonstrated in the case of carbon accounting in the previous section. Research has shown that the decomposition of crop and forestry wastes and residues within forests and fields is important to the long-term sustainability of agriculture and forestry ecosystems, and there can be a range of negative impacts from removing these materials.[351 352 353]

The removal of wastes and residues for use as bioenergy has been argued to reduce carbon emissions that would be released as they decompose,[354] however, not all residues can be expected to decompose quickly. Stenzel, et al.'s study showed that some forest residues can take several decades to release all the sequestered carbon.[355] Extracting crop and forest residues can risk reducing soil carbon content, soil health and overall ecosystem biodiversity.[356] For example, one study found that the removal of corn residue both decreased soil organic carbon content and increased overall CO_2 emissions as residue carbon in biofuels is oxidized to CO_2 at a faster rate than when crop residues are incorporated into soil.[357]

One major area of concern is that regulation and certification often does not set any maximum extraction levels for forest residues and recommended sustainable extraction levels for agricultural residues vary too widely to be effective.[358]

Mitigation opportunities for ecosystem impacts from removing wastes and residues

Due to the current lack of in-depth research and guidance, the main opportunities for companies aiming to mitigate ecosystem impacts from removing wastes and residues is to support more research into this area, alongside the development of best practice standards.

While there are considerable risks of unsustainable waste and residue extraction for use as bioenergy, there are also opportunities for bioenergy feedstocks to be sourced from activities that promote good ecosystem stewardship.

In some circumstances, the carbon storage capacity of natural ecosystems can be improved by removing biomass, for example to prevent forest fires. There is an increased risk of forest fires as climate change causes more extreme weather events,[359] including droughts, and serious forest fires around the world had resulted in significant greenhouse gas emissions.[360] A study by the Chinese Academy of Sciences found that forest fires emitted 33.9 billion tons of CO_2 globally between 2001 and 2022, more emissions annually than Japan produced from burning fossil fuels in one year – the world's sixth largest emitter.[361] Selective forest thinning has been shown in some instances to reduce the risk of wildfires,[362] and this biomass could be used to produce bioenergy. However, there are many other industries, including pulp and paper, construction and furniture that compete for these forestry 'wastes' and 'residues', which could provide better use of these materials from a climate perspective.[363] For example, waste timber can be used to produce composite materials for the construction industry, which can both keep carbon in use for longer and replace CO_2 emissions intensive materials like steel.[364]

There are also opportunities for bioenergy feedstock production to contribute to ecosystem restoration. Biomass can be removed from ecosystems to tackle the problem of alien invasive plant species, which need to be removed in order to restore ecosystem health and functioning. An example of this is the Working for Water program in South Africa, a study on which showed that the cost of alien invasive plant removal and landscape restoration could be substantially offset when the alien invasive woody biomass was used as a bioenergy feedstock.[365] Similarly, high-diversity grass species for bioenergy feedstocks have been used to enhance the biodiversity of abandoned agricultural lands and were shown in one study to improve net primary productivity of the grassland.[366]

Second generation bioenergy could deliver positive climate outcomes when the aim of biomass removal is to improve ecosystems, for example through wildfire risk reduction and alien invasive species removal, or when biomass is grown on degraded, low-carbon stock land that would otherwise not be used. However, ensuring these criteria are met faces challenges from a lack of traceability and transparency in second generation bioenergy supply chains, which makes their development even more vital.

Engagement questions for minimizing natural capital impacts from second generation bioenergy

Figure 18: Minimizing natural capital impacts from second generation bioenergy

Recommended questions

1

What actions are being taken to assess the risk of direct and indirect land use change in second generation bioenergy supply chains?

What actions are being taken to improve traceability and transparency in second generation bioenergy supply chains, including procurement policies and practices?

Is certification being used to mitigate the risk of direct and indirect land use change in second generation bioenergy supply chains? Are there any targets for certification levels?

2

Do you conduct lifecycle carbon footprint assessments of second generation bioenergy feedstocks? Does your carbon accounting include emissions from producing bioenergy feedstocks, even where this is counted as zero- or negative-emissions in regulation, e.g. for wastes and residues?

What actions do you take to minimise the climate impact of bioenergy feedstocks, including policies and targets.

3

What measures are being taken to understand the risk of ecosystem impacts from removing wastes and residues from agricultural and forestry systems?

What measures are being taken to mitigate the risk of ecosystem impacts from removing wastes and residues from agricultural and forestry systems?

What investment is planned in bioenergy feedstocks that aim to enhance or restore ecosystem functioning, e.g., reducing wildfire risk, or restoring low-carbon stock lands?

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